Geographic Information Systems and Geostatistics in the Design and Validation of Regional Plant Virus Management Programs

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ABSTRACT

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A regional management plan was designed and implemented for a multivirus, multivector, disease complex in tomatoes in the Del Fuerte Valley, Sinaloa, Mexico. The viruses include tobacco etch and cucumber mosaic with aphid vectors, a geminivirus complex with whitefly vectors, tomato spotted wilt with thrips vectors, and tomato mosaic with no known vector. Although the viruses and their vectors are biologically diverse, all are transmitted by flying insects, with the exception of tomato mosaic, and all except tomato mosaic are known to have alternate hosts among weeds and other crop plants in the area. Because of these similarities, we developed a risk-assessment process based on general virus infection hazards rather than specific viruses. The risk assessment helped to focus on actions that could be taken both locally and regionally to reduce early and damaging infections. Risk assessment and virus disease-incidence data were collected from 53 fields during 1990–1991 and 60 fields during 1991–1992. A geostatistical analysis of risk and incidence showed that both were spatially dependent variables with a variogram range of 20 to 25 km. Moving spatial averages (computed by kriging) indicated that the area east of Los Mochis was higher in risk and incidence than the area near Guasave during both seasons. Qualitative observations consistent with observed patterns of incidence suggest there are underlying landscape features more conducive to endemic plant virus diseases in the Los Mochis area than in the Guasave area.

Virus diseases of vegetable crops along the west coast of Mexico and contiguous areas in southern Arizona and California have been long-standing problems. Since 1980, these problems have increased due to the whitefly-transmitted geminivirus complex (1,2,6,27) and the thrips-transmitted tomato spotted wilt virus (TSWV, tospovirus group) in many crops in the southern and western United States and northern Mexico. The emergence of these diseases during the last 15 years as potentially limiting factors in tomato production in the Del Fuerte Valley, Sinaloa, Mexico (Fig. 1) coincided with similar situations in other parts of Mexico (21) and the world (5,8,28). Prior to 1980, virus diseases described in this area were primarily aphid-transmitted mosaic diseases (9,12,16,24–26). The recent experience of serious virus diseases in the tomato industry in various parts of Mexico has been a concern of both the fresh and processing tomato industries.

Preliminary observations of virus symptoms in the Del Fuerte Valley suggested that there was a consistent spatial pattern of virus infection in tomatoes on a regional scale. Spatial characteristics of a plant disease are amenable to study on any scale (3) including regional. Geographic information systems (GIS) and geostatistics are tools that can be used to analyze and manage disease data at this scale. The approach and vocabulary of GIS and geostatistics have been well described in recent articles reviewing their use in applied insect ecology (17,20). We are aware of only within-field analyses of plant diseases using geostatistics (4,18,19,30,32,34).

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 (5). From a biological standpoint, the tomato virus diseases identified in the Del Fuerte Valley form a diverse group. These include aphid-transmitted tobacco etch virus (TEV), pepper mottle virus (PepMoV), cucumber mosaic virus (CMV), thrips-transmitted TSWV, whitefly-transmitted geminiviruses (including yellows and leaf curl types), and tomato mosaic virus (TMV). With the exception of TMV, these viruses all fall into a general ecological type characterized by a dynamic aerial vector with multiple sources of virus for infection in a climate in which alternate hosts of both virus and vector exist year round. Virus diseases of this type may show consistent spatial structure from year to year (25). The development of culturally acceptable resistant varieties for components of this disease complex is difficult, and it is doubtful that any will be available in the foreseeable future. Consequently, a cultural management approach is needed in which a series of actions is taken that collectively delays infection and suppresses disease spread. A classic example of a disease that has been managed for many years with this concept (i.e., multiple management actions) is leafhopper-transmitted curly top in California (10).

The Del Fuerte Valley agricultural area is approximately 60 × 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. The Los Mochis area is by far the most extensive urban area in the valley. The program focused on processing tomatoes—approximately 30% of the tomatoes grown in the valley. The tomato crop is planted from September through January during normal years, with the most serious virus infections occurring during the September and early October plantings. During September, the whitefly vectors of the geminiviruses are associated primarily with the maturing soybean crop and various weed species that become senescent during the time 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) results in early, heavy virus infection. A program was developed to assess the 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. A preliminary report of this research has been published (23).

Fig. 1. Map of Mexico with a rectangular box outlining the study area in the Del Fuerte Valley in northern Sinaloa, Mexico.

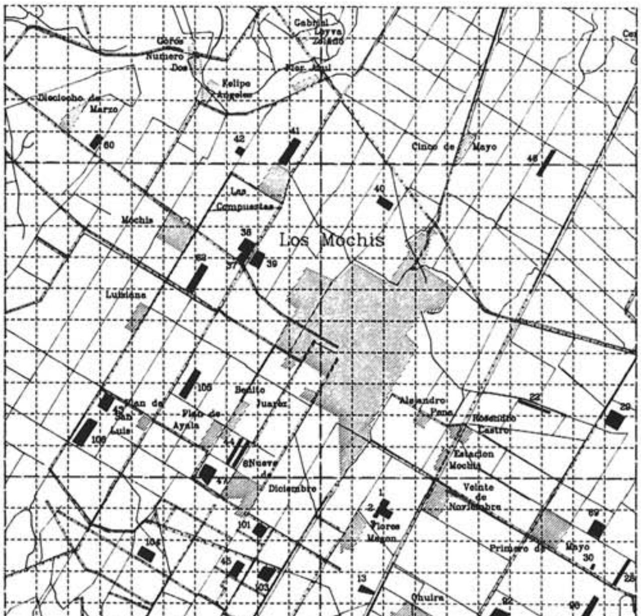

Fig. 2. Example of a map used to assign universal transverse mercator (UTM) coordinates to fields (solid black rectangles) near Los Mochis. The UTM coordinate system is a metric equivalent of latitude and longitude that divides the earth into zones within which points are located by x- and y-coordinates in meters. The grid lines are 1,000 m apart. Fields are sketched on the map based on their location with respect to roads and canals. Because the UTM coordinates for the grid lines are known, the coordinates of the center of a field can be accurately estimated within approximately 200 m. Thirteen such maps were used to estimate coordinates for fields throughout the region.

MATERIALS AND METHODS

Risk assessment. During 1990–1991 and 1991–1992, fields to be planted to tomatoes were identified and located on GIS maps (Fig. 2). 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. Representative plants (weeds and wild plants) with geminivirus-like symptoms were identified by R. Vega-Viña (University of Sinaloa, Culiacán, Mexico), and geminiviruses were diagnosed by R. L. Gilbertson (University of California, Davis).

Risk variables were derived from a numerical scoring system based on observations of adjacent fields and ditches (within 50–100 m) in each direction from the field including the corners (eight directions). Scores were assigned as follows: 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. The variable "risk-total" was computed by adding the scores for all eight directions. The variable "risk-north" consisted of the sum of the scores for the three northerly directions (northwest, north, and northeast). Similarly, variables "risk-east", "risk-south", and "risk-west" were computed. The variable "risk-symptoms" was simply the number

TABLE 1. Variables used to characterize tomato fields in the risk-assessment program

Variable	Description
x	x-coordinate of center of field in meters (UTM[a] system).
y	y-coordinate of center of field in meters (UTM[a] system).
Nplants	Number of plants surveyed in the field.
Dayseas	Days from July 1 to the date of planting the field.
Gap	Days from planting to evaluation for incidence.
Area	Area of the field in hectares.
Risk-total	The sum of risk scores in all eight directions.
Risk-north	The sum of risk scores for north, northwest, and northeast of the field.
Risk-east	The sum of risk scores for east, northeast, and southeast of the field.
Risk-south	The sum of risk scores for south, southeast, and southwest of the field.
Risk-west	The sum of risk scores for west, southwest, and northwest of the field.
Risk-vectors	Number of adjacent fields with aphids, whiteflies, and thrips.
Risk-symptoms	Number of adjacent fields with plants showing virus symptoms.
Risk-weeds	Number of adjacent fields with weeds.
Risk-1990-inc	For 1991, kriged incidence in 1990 of the block containing the 1991 field
Risk-combo	For 1991, a weighted sum of risk-total, risk-1990-inc and (184 − dayseas).
Incidence-gem	Percentage of plants surveyed with geminivirus symptoms.
Incidence-mos	Percentage of plants surveyed with mosaic symptoms.
Incidence-sw	Percentage of plants surveyed with spotted wilt symptoms.
Incidence-all	Percentage of plants surveyed with any virus disease symptom.

[a] The universal transverse mercator (UTM) coordinate system is a metric equivalent of latitude and longitude that divides the earth into zones within which points are located by x- and y-coordinates in meters.

of directions from the field in which there were plants with virus symptoms. The variables "risk-weeds" and "risk-vectors" were the number of directions in which fields or ditches contained weeds or insect vectors, respectively. Risk-symptoms, risk-weeds, and risk-vectors ranged from zero to eight. A risk variable was created for the 1991 season, based on incidence in 1990, by assigning a risk value proportionate to the block kriging estimate of 1990 incidence for the 5 × 5 km block containing the field. This is variable "risk-1990-inc." All variables used to characterize fields are described in Table 1. Although a wide variety of risk variables was analyzed, risk-total was the primary risk-assessment variable used. The risk-assessment process functioned as a predictive system for virus infection.

Virus disease assessment. Virus incidence was evaluated by scoring approximately 1,000 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 viruslike symptoms but type uncertain. PepMoV was identified in some samples during the diagnostic phase of the program but because of the close relationship to TEV was not considered separately (26). Plants from all categories were used in the final analysis to determine percent incidence. Fields were divided into nine blocks (usually on a 3 × 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 during 1988 and 1989 provided background that allowed them to recognize certain symptom types as dominant. In addition, samples from plants characteristic of geminivirus symptoms were periodically sent to R. L. Gilbertson (University of California, Davis) for evaluation. Representative plants with TSWV were checked by the enzyme-linked immunosorbent assay (ELISA) system (AGDIA, Elkhart, IN). The results of the study, however, are based on field symptoms, because this was the only practical way of evaluating the large number of fields required for the study. Therefore, in the Results and Discussion

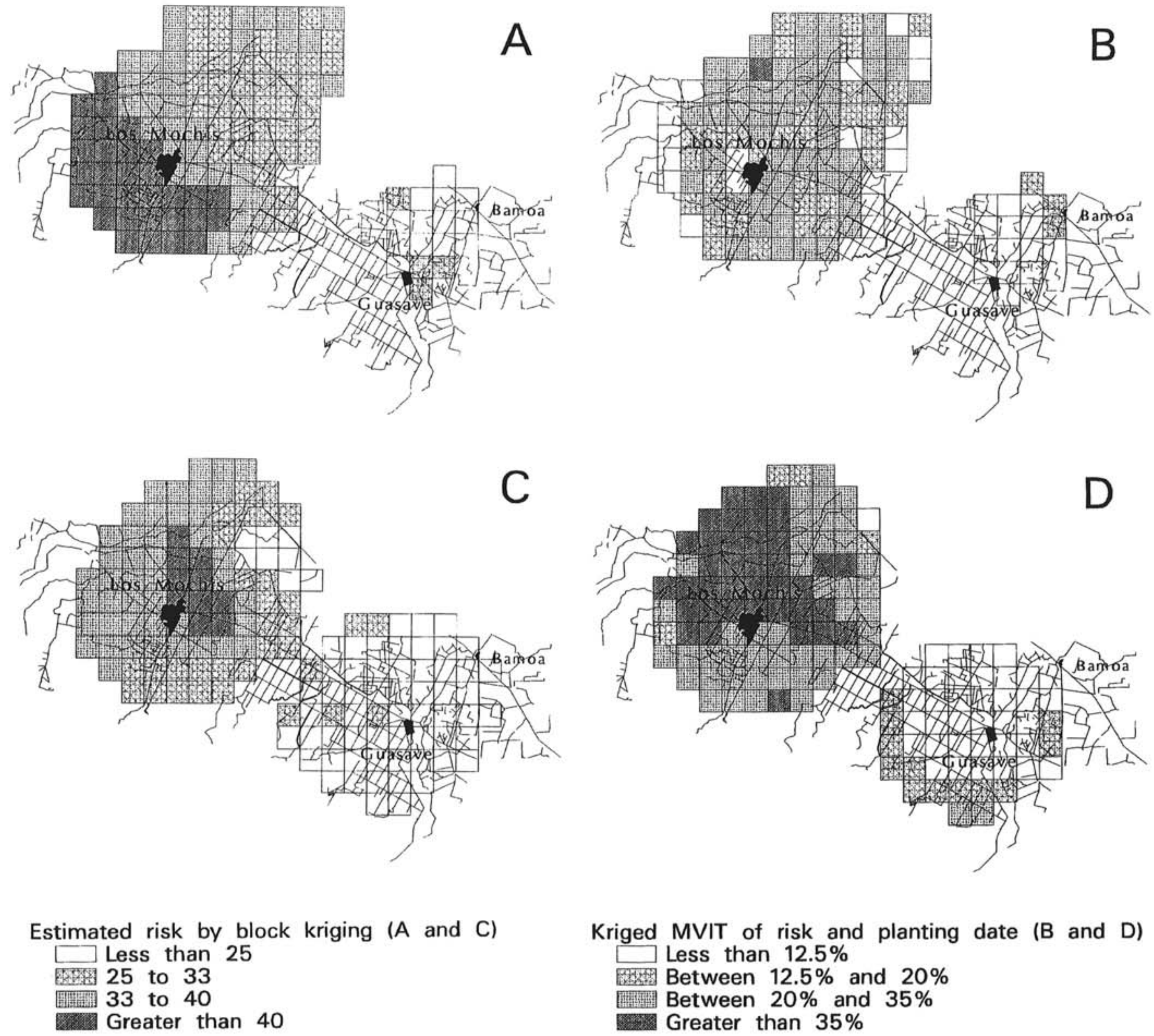

Fig. 3. Spatial pattern of tomato virus disease risk assessments in the Del Fuerte Valley, Sinaloa, Mexico, during 1990–1991 (**A and B**) and 1991–1992 (**C and D**). Assignment of risk scores is described in the text. **A and C**, Ordinary block kriging of the risk data and **B and D**, ordinary block kriging of a multiple variable indicator transformation of risk and planting date, described in the text, show that risk is generally higher in the Los Mochis area than the Guasave area.

sections of this paper, the word "incidence" refers to the incidence of virus symptoms (generic) as observed in the field. Infected plants with no symptoms are not included in our estimates of incidence.

Geographic information systems (GIS). Commercially available topographic maps (1:50,000) produced by the Instituto Nacional de Estadistica Geografia e Informatica (Mexico City) were obtained and digitized by 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. The UTM system is a metric translation of latitude and longitude whereby the earth is divided into zones within which locations are determined by x- and y-coordinates in meters. In a geostatistical study, it is necessary to have x- and y-coordinates for the objects of the study (in this case, tomato fields). Thirteen detailed maps were developed with a 1 × 1 km grid in such a way that UTM coordinates of the center of the fields could be accurately estimated within approximately 200 m (Fig. 2). Although variations in the size and shape of the tomato fields can be seen on the detailed map (Fig. 2), for regional analyses the fields were considered as points. This provided sufficient accuracy, because the spatial structure of regional importance had a range of several kilometers. The PC version of ARCVIEW (ESRI) provided interactive access to the GIS database. For a hard copy printout of maps, we used the PC version of ARCVIEW (ESRI).

Geostatistical analysis. GeoEAS (USEPA EMSL-LV, EAD, Las Vegas, NV) was used for a standard geostatistical analysis of the variables risk-total and incidence-all for both 1990 and 1991 (22). Both directional and omnidirectional sample variograms were examined. Ordinary block kriging (14,22), with fitted variograms and the sample data, gave estimates of risk and incidence for 5 × 5 km blocks throughout the region. Because the distributions for the incidence variables were highly skewed, indicator variogram models and indicator kriging also were used to produce block estimates (29). Cutoff points of 1, 5, 10, 15, and 25% incidence were used with the 1991 data for the indicator kriging of incidence. A multiple variable indicator transformation (MVIT) (13) of the variables dayseas and risk-total was scored 1 if the planting date was prior to November 1 and risk-total

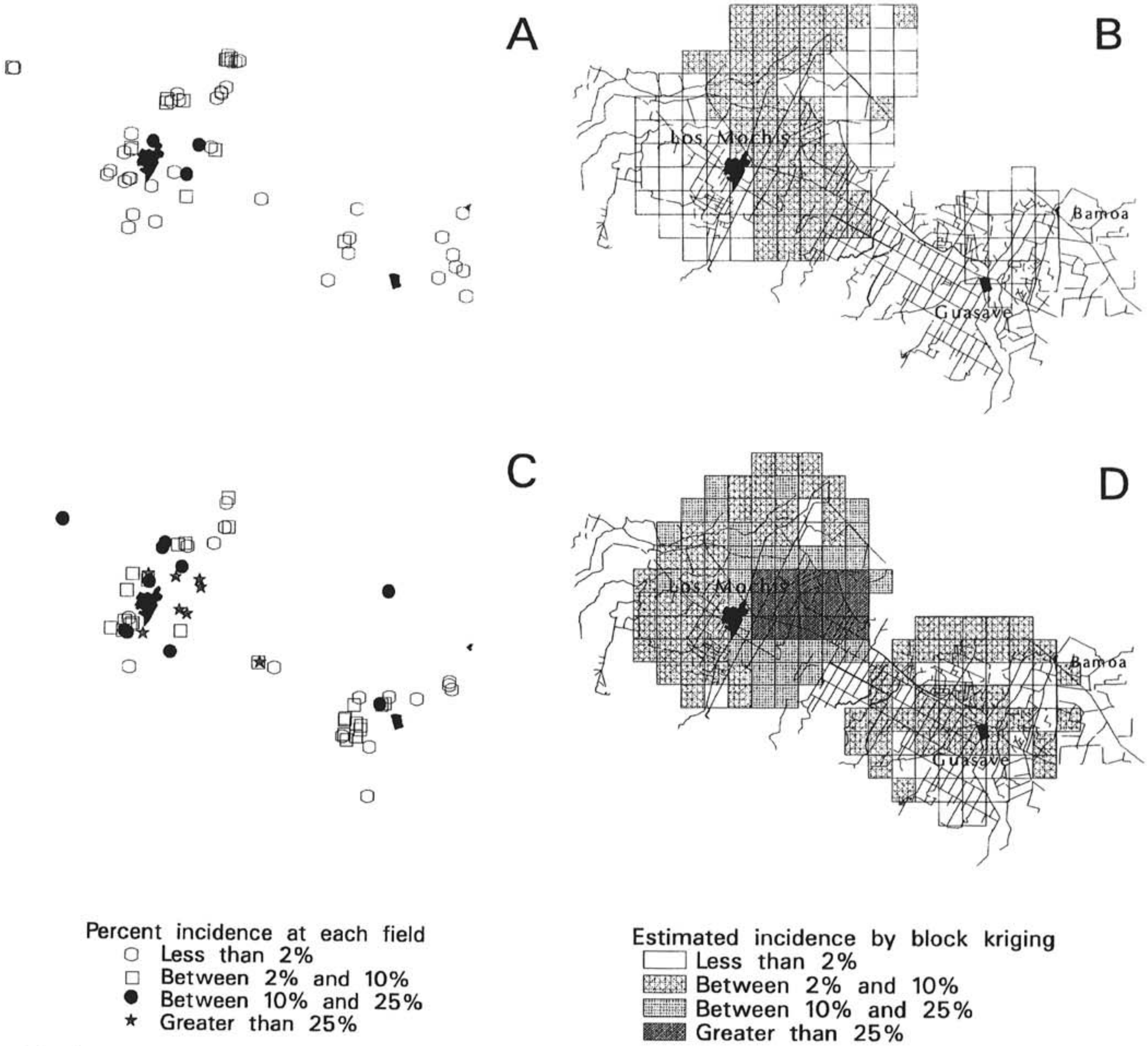

Fig. 4. Spatial pattern of tomato virus disease incidence in the Del Fuerte Valley, Sinaloa, Mexico, during 1990–1991 (**A and B**) and 1991–1992 (**C and D**). **A and C**, Percent incidence by field location and **B and D**, moving spatial averages of the incidence data by ordinary block kriging. Kriged incidence did not exceed 10% during 1990–1991 (**B**), but exceeded 25% east of Los Mochis during 1991–1992 (**D**). Incidence was higher in the fields east of Los Mochis than the fields around Guasave during both years.

was greater than 33; otherwise it was scored 0. Kriged maps of the MVIT were prepared for both growing seasons.

The large number of variables characterizing each field (Table 1) were clustered by the professional module of SPSS/PC+ (SPSS, Chicago). A dendrogram of the variables was generated from a similarity matrix of Spearman coefficients of rank correlation (31) by the unweighted pair group average method.

RESULTS

The principal result of the analysis is a set of maps showing the regional patterns of risk and incidence; these patterns are useful in crop management. GIS representations of the results of ordinary block kriging show that the area east of Los Mochis was higher in both risk and incidence of virus disease than the area around Guasave (Figs. 3 and 4), both during 1990–1991 and 1991–1992. Maps of incidence data by field position show the point data used to obtain the moving spatial averages by kriging (Fig. 4A and C). Incidence during 1990–1991 (mean 2.3%, median 0.8%) was much lower than during 1991–1992 (mean 11.5%, median 6.3%), but the spatial pattern of incidence was similar during both years (Fig. 4). The correlation of risk and incidence within the Los Mochis area was greater during 1991–1992 (Figs. 3C and D with 4D) than during 1990 (Figs. 3A and B with 4B).

Sample variograms and variogram models for risk and incidence during 1990–1991 and 1991–1992 show that these variables were spatially dependent (Fig. 5). The variograms have a range of 20 to 25 km, indicating underlying spatial autocorrelation of the risk and incidence variables within this range. No clear evidence of directional effect was found, so isotropic variogram models were used throughout. Because of the skewed probability distribution of incidence in 1991–1992, the spatial structure of incidence also was studied by a series of indicator variograms at various cutoffs (1, 5, 10, 15, and 25% incidence) (Fig. 6). These cutoffs correspond to 17, 45, 70, 78, and 87th percentiles, respectively, for the variable incidence-all. No spatial structure was apparent when virus incidence of 1% was used as a cutoff; the variogram model was a pure nugget represented by a horizontal line (Fig. 6A). This means that when fields were categorized as + or −, depending on whether or not incidence was above or below 1%, there was no detectable clustering of +'s or −'s. The situation changed when 10, 15, or 25% were used as cutoffs. There is a well-defined structure to the sample variograms with a range of about 17 km (Fig. 6C–E). The range did not decrease with increasing cutoff values, so there was no indication that the highest incidence was found near the center of the clusters (i.e., no evidence for point spread) (34). Indicator kriging of the variable incidence-all for 1991–1992 by a 10% cutoff value (not shown) revealed a pattern similar to that in Figure 4D.

A dendrogram based on Spearman's coefficient of rank correlation for all pairs of variables for 1991–1992 shows that the risk variables cluster together as do the incidence variables (Fig. 7). The correlations between the incidence variables and the risk variables were significant pairwise with the caveat that the assumption of independence among observations was not strictly met because of the spatial autocorrelations. Correlations between incidence and risk variables were not significant in 1990 probably because incidence was quite low.

DISCUSSION

Our results suggest that tomato virus disease incidence has two principal sources: hazards immediately surrounding the field, represented by the risk variable, and area-wide landscape features conducive to virus persistence, observed but not quantified. During the 1991–1992 growing season, the regional risk pattern was similar to the regional pattern of incidence, and there was a positive correlation between risk assessment and incidence for each field. This supports the conclusion that reducing hazards

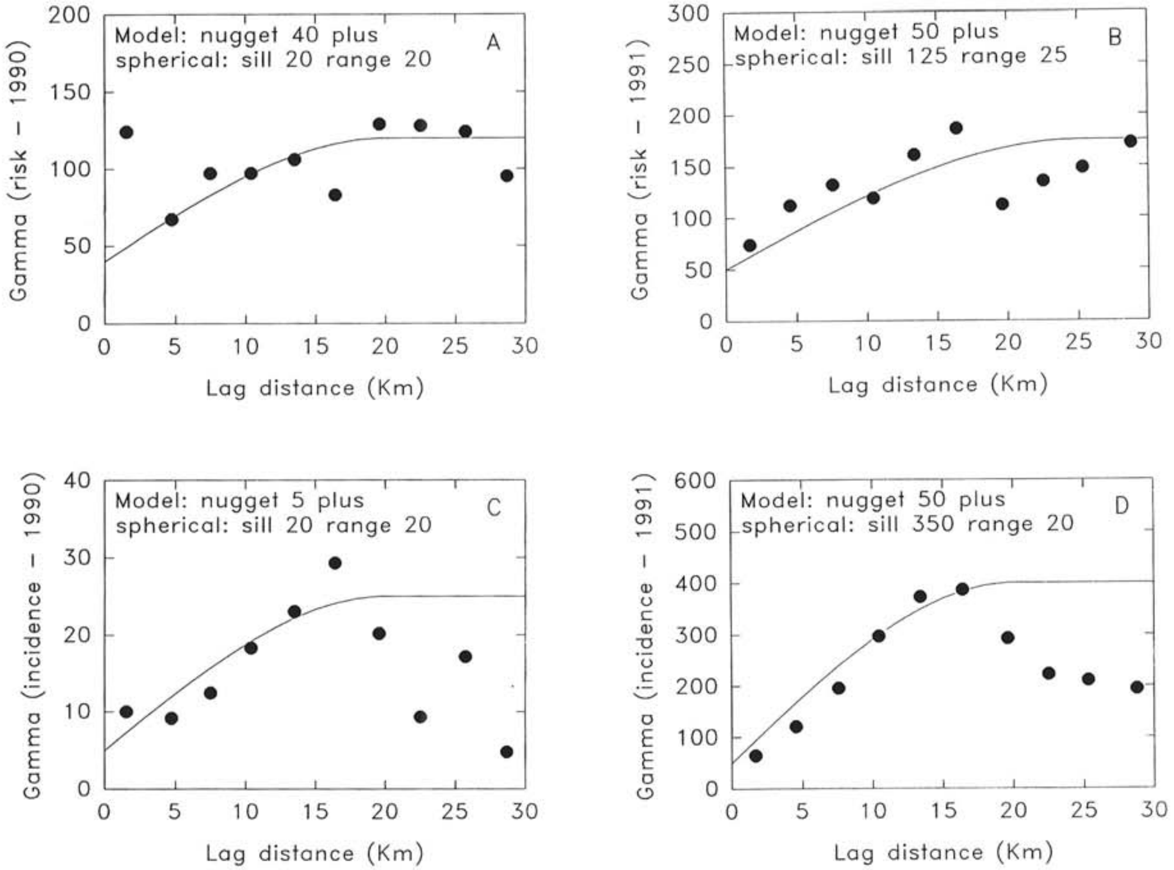

Fig. 5. Sample variogram values (dots) and variogram models (lines) of the variables risk-total for **A**, 1990–1991 and **B**, 1991–1992 and incidence-all for **C**, 1990–1991 and **D**, 1991–1992.

immediately surrounding a field is important. During 1990–1991, the area east of Los Mochis was higher in risk and incidence than the Guasave-Bamoa area, but fields south and west of Los Mochis had high risk scores with low incidence; this is a caution against over-generalization. Incorporating the planting date with risk using a MVIT (Fig. 3B) somewhat improves the comparison between risk and incidence during 1990–1991 in the Los Mochis area and suggests that later planting south and west of Los Mochis is a partial explanation for the lower incidence there during 1990–1991. The risk assessment might be thought of as a measure of potential problems not fully realized during 1990–1991 due to more general regional factors associated with low incidence that year. The positive correlation between risk and incidence during 1991–1992 is evidence that in a year of moderate virus incidence, areas immediately surrounding a field are critical.

Area-wide landscape features probably interact with the hazards surrounding the fields to produce the regional spatial patterns of virus disease incidence observed. Qualitative observations reveal that the landscape in the Guasave-Bamoa area differs from the Los Mochis area. Bamoa is located about 20 km northeast of Guasave in a low-risk, low-incidence area. The Guasave-Bamoa area has larger fields (150–300 ha versus 20–150 ha), more grain fields, fewer vegetable fields, and fewer embedded rural homesteads than the Los Mochis area has. 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. In general, irrigation and drainage ditches in the Guasave-Bamoa area are lined with concrete, whereas in the Los Mochis area they are not. There appears to be a richer flora along the ditch banks near Los Mochis. Representative plants with

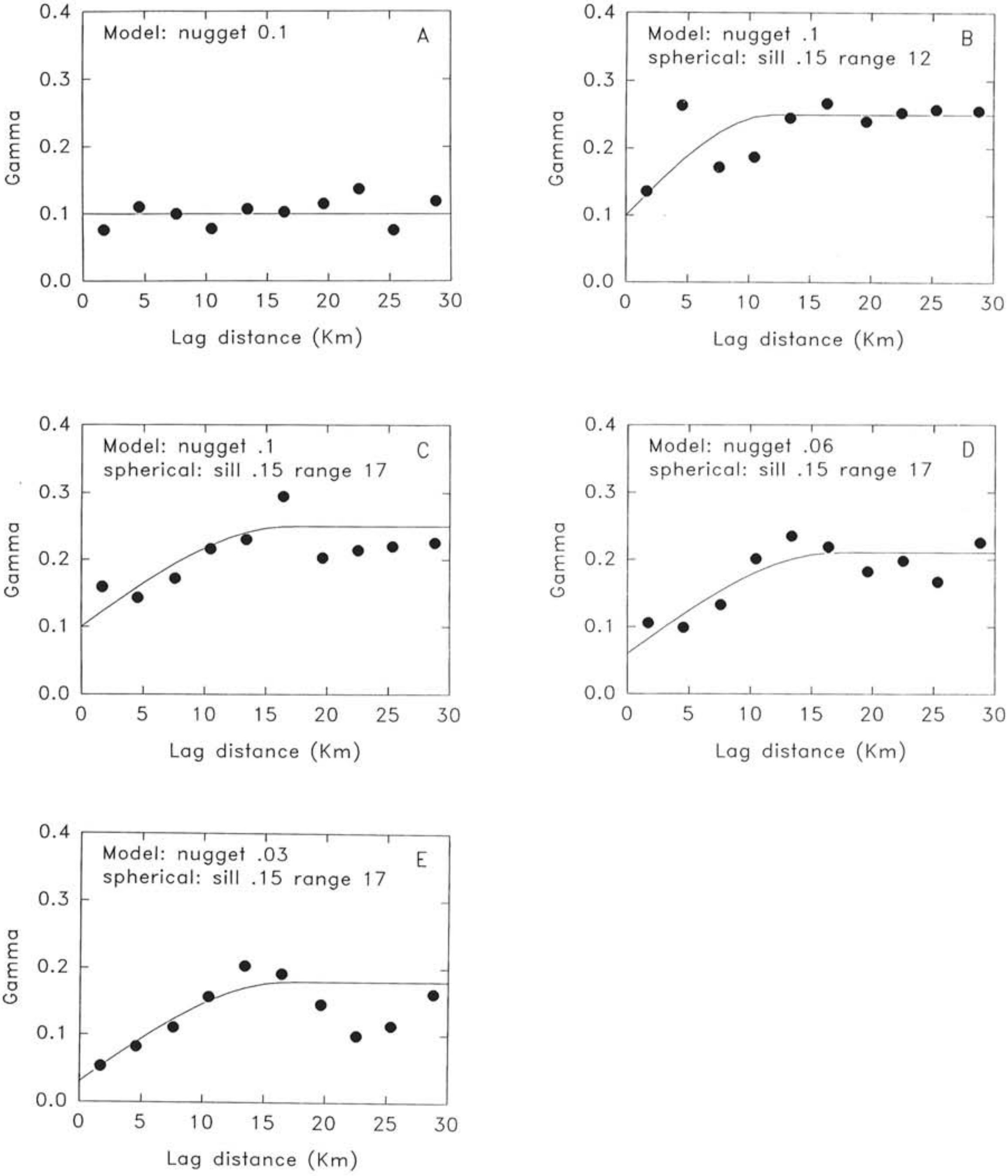

Fig. 6. Sample variogram values (dots) and variogram models (lines) based on indicator transformations of the variable incidence-all during 1991–1992 using cutoff points of **A,** 1, **B,** 5, **C,** 10, **D,** 15, and **E,** 25% incidence. The sample variograms for the 10, 15, and 25% incidence cutoff values are more well defined than are the sample variograms for the 1 and 5% incidence cutoff values.

symptoms of geminiviruses have been identified and assayed with a generic geminivirus probe (Table 2). Two plant species that were positive for the presence of geminiviruses (*Melochia pyramidata* and *Koteletzkya depressa*) were more abundant in the Los Mochis area than in the Guasave-Bamoa area. *Nicotiana glauca*, a host for TEV and CMV, also was more common in Los Mochis than in Guasave-Bamoa. These landscape differences were examined retrospectively, after the general pattern of virus incidence was clarified by the GIS analysis.

The landscape differences between the Los Mochis area and the Guasave-Bamoa area suggest that plant virus disease epidemiology could benefit from the ideas of landscape ecology (33). A full implementation of a landscape ecology approach is beyond the scope of the present work, but the contrasting observations described above suggest that there are more- and less-conducive landscapes for infection of tomatoes by viruses. Borrowing from terminology used in the biological control of soilborne pathogens ("conducive and suppressive soils" [7]), we suggest the term "conducive landscape" to describe this difference. Conducive landscape is not meant to imply that all fields in an area are at uniform high risk of virus incidence. For example, although the Los Mochis area (particularly the area east of Los Mochis) is considered a conducive landscape, not all fields have a high risk and incidence. In a conducive landscape, fields have a higher probability of serious virus disease incidence, but the final outcome will still be influenced heavily by conditions in the immediate vicinity of the field.

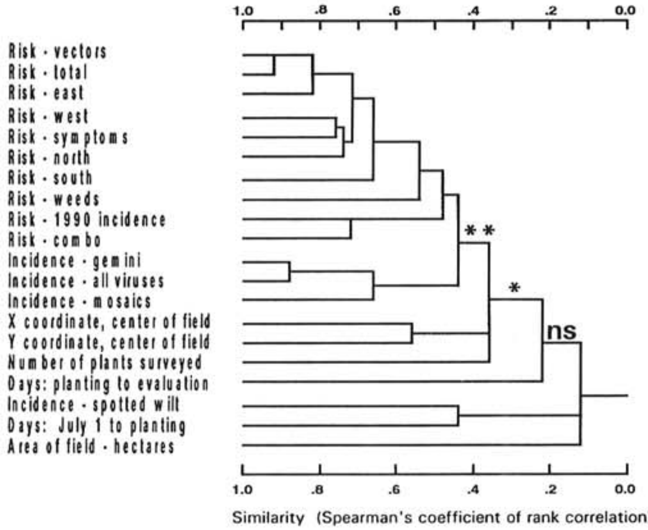

Fig. 7. Dendrogram of tomato field variables using the unweighted pair group average method with the absolute value of the Spearman coefficient of rank correlation as a measure of similarity for clustering. The diagram is not designed for hypothesis testing, but the critical values for statistically significant correlation at $P = 0.01$ and 0.05 and not significant in a pairwise test are indicated by **, *, and ns, respectively, as reference points. With the exception of spotted wilt, the incidence variables clustered together. The risk variables also clustered together and, as a whole, risk and incidence were better correlated with each other than with the other variables.

The geostatistical analysis of risk and incidence shows that, in the Del Fuerte Valley, both are spatially dependent variables with a variogram range of 20 to 25 km. The data on virus incidence emphasize the spatial aspects of disease and not the temporal. Past studies of disease increase in general and virus diseases specifically have placed heavy emphasis on temporal data collection and analysis (15). Because both the date of planting and the time between planting and evaluation influence incidence to some degree, there is the possibility that the staggered plantings could confound the results. However, we were looking for a general pattern, not a high-resolution picture. The overall spatial pattern in the two years of the study (Figs. 3 and 4) is consistent with preliminary observations made during the two years prior to the study. Demonstrating that virus disease incidence is a spatially dependent variable on a regional scale (tens of kilometers) has implications for crop loss-assessment strategies. A geostatistical approach, which takes into account spatial autocorrelation, should be considered for assessments of crop loss.

The GIS/geostatistical technology was useful for communicating with the growers concerning management practices that promote or inhibit virus disease. The ability to visualize the regional situation and the association of the high risk factors with high disease incidence resulted in modifications in the management approach and spatial/temporal arrangement of plantings. By focusing attention on the high-incidence, high-risk areas, classical virus management strategies could be promoted more effectively. These strategies included the control of alternate hosts near fields, delayed plantings in high-risk, high-incidence areas, avoidance of major hazards such as maturing pepper fields, and control of volunteer or surviving tomato plants during the off-season. The combination of classical virus management strategies with the focus provided by the GIS analysis was used by one grower to eliminate pesticide spraying to control vectors as part of an integrated pest management strategy. 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 (11), but without easily communicated alternatives, it can be difficult to convince growers to resist pressure to use insecticides for virus control.

One of the principal reasons for this project was the concern that virus diseases would negatively impact the stability of tomato production in the Del Fuerte Valley as they had other regions of Mexico. Experiences of professionals in other parts of Mexico with serious virus disease problems in tomatoes contributed to this concern (21). A conclusion of this project is that, for the region as a whole, the current virus problem is less serious than originally estimated. The original assessment was based on observations of heavily infected fields around Los Mochis. The project worked for the tomato processors in the Del Fuerte Valley, in part, because of the presence of staff with the education and experience to participate and implement this approach to virus disease management and because of the flexibility of the companies involved in changing the spatial and temporal placement of tomato fields. Future efforts in virus management will focus on the Los Mochis area. The ground-work laid in the virus management project is now being applied to other pests and diseases to better understand spatial relationships with an ultimate goal of integrating several additional disease and pest problems into an overall management program.

TABLE 2. Uncultivated plants with virus symptoms that tested positive for the presence of geminiviruses with a generic geminivirus probe[a]

Spanish name	Scientific name	Family	Comments
Malva	*Malvastrum coromandelianum*	Malvaceae	Common throughout region
Malva vellosa	*Koteletzkya depressa*	Malvaceae	Common in Los Mochis; Rare in Guasave-Bamoa
Malva flor azul	*Melochia pyramidata*	Stericuliaceae	Common in Los Mochis; Rare in Guasave-Bamoa
Lechosa	*Euphorbia heterophila*	Euphorbiaceae	Common throughout region
Sambe-Sarambe	*Boerhaavia coccinea*	Nyctaginaceae	Common throughout region
Frijolillo	*Rhynchosia minima*	Leguminosae	Common in Los Mochis and Guasave; Rare in Bamoa

[a] Plant Identification by R. Vega-Viña (Univ. Sinaloa, Culiacán, Mexico) and virus diagnosis by R. L. Gilbertson (Dept. Plant Pathol., Univ. Calif., Davis).

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