

GEOGRAPHIC INFORMATION SYSTEMS AS KEY TOOLS IN THE PHYTOSANITARY MANAGEMENT OF MEZCAL AGAVE (*Agave angustifolia* Haw) IN THE STATE OF MEXICO, MEXICO

Atenas **Tapia-Rodríguez**¹, José Francisco **Ramírez-Dávila**^{2*}, Agustín David **Acosta-Guadarrama**³, Alfredo **Ruiz-Orta**⁴

¹Tecnológico Nacional de México. Tecnológico de Estudios Superiores de Villa Guerrero. Carretera Toluca-Ixtapan de la Sal km 64.5, La Finca, Villa Guerrero, State of Mexico, Mexico. C. P. 51763.

²Universidad Autónoma del Estado de México. Facultad de Ciencias Agrícolas. Carretera Toluca-Ixtlahuaca km 15, El Cerrillo, Piedras Blancas s/n, entronque a El Cerrillo, Toluca, State of Mexico, Mexico. C. P. 50200.

³Universidad Mexiquense del Bicentenario. Unidad de Estudios Superiores Coatepec Harinas. El Reinoso, Coatepec Harinas, State of Mexico, Mexico. C. P. 51700.

⁴Universidad Autónoma del Estado de México. Centro Universitario UAEM Tenancingo. Carretera Tenancingo-Villa Guerrero km 1.5, Tenancingo de Degollado, State of Mexico, Mexico. C. P. 52400.

* Author for correspondence: jframirez@uaemex.mx

ABSTRACT

Mezcal agave (*Agave angustifolia* Haw.) is a key resource for the economy and culture of the State of Mexico. However, it faces a phytosanitary crisis due to pests such as the agave weevil (*Scyphophorus acupunctatus* Gyllenhaal, 1838) and diseases such as *Fusarium oxysporum* wilt, causing losses of up to 50 % in production. The lack of efficient monitoring systems justifies the development of a Geographic Information System (GIS) to optimize phytosanitary management. This study aimed to design a GIS that integrates biophysical and management variables to identify risk zones and facilitate integrated management strategies. Four plots were monitored in the municipalities of Malinalco and Zumpahuacán in 2024, with 100 plants per plot georeferenced. The incidence of *S. acupunctatus* and *F. oxysporum* was assessed monthly, along with environmental and management variables. Data were processed using QGIS 3.24, generating risk maps through interpolation (Inverse Distance Weighted (IDW) and Kriging) and spatial correlation analysis (Moran's I). Statistical analyses included analysis of variance (ANOVA) and multiple regression. The results demonstrated that GIS-generated risk maps allow highly accurate identification of infestation hotspots. In Malinalco Centro, weevil incidence was positively correlated with accumulated precipitation ($r = 0.65$, $p < 0.05$) and clay soils, exhibiting a spatial aggregation pattern (Moran's $I = 0.42$, $p < 0.01$). For *F. oxysporum*, soil moisture (>60 %) was the most influential factor ($\beta = 0.62$; $p = 0.002$), with critical zones expanding radially at 15 m per month. The Random Forest model predicted weevil incidence with 88.2 % accuracy (AUC-ROC = 0.91). This integrated approach, replicable in other agave-growing regions, would contribute to crop sustainability by enabling spatially targeted interventions, optimizing resources, and reducing input use.

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INTRODUCTION

The mezcal agave (*Agave angustifolia* Haw.) is a vital phylogenetic resource for the State of Mexico due to its central role in mezcal production, its contribution to the economic livelihoods of thousands of rural families, and its role in maintaining traditional agroecological systems. However, in recent years, the crop has faced an unprecedented phytosanitary crisis. The combination of factors such as climate change, extensive monoculture, and the lack of integrated management techniques has led to an increase in pests and diseases that threaten the sustainability of its production chain (SENASICA, 2026; IPBES, 2019).

Among the main phytosanitary problems affecting mezcal agave in the region, the pineapple rot complex stands out, associated with pathogens such as *Fusarium oxysporum* and the agave weevil (*Scyphophorus acupunctatus* Gyllenhaal, 1838). These causal agents generate losses ranging from 30 to 50 % of production in critical agricultural cycles (SADER, 2023). The situation is further aggravated by the lack of monitoring and early warning systems that would allow producers to implement timely and effective control measures.

In this context, geotechnology emerges as an innovative alternative for phytosanitary management. Geographic Information Systems (GIS) have proven effective in managing strategic crops worldwide. Studies such as that of Birhan (2023) on coffee cultivation and that of Villegas-Monter *et al.* (2024) on citrus in Veracruz demonstrate how integrating spatial variables (climate, soil, and topography) with biological data can accurately predict the occurrence of disease outbreaks. Specifically for agave, Quezada-Chico *et al.* (2026) conducted a geospatial analysis using remote sensing techniques and field visits to identify changes in land use and the replacement of traditional vegetation. This analysis links soil type with the growth of new plantations, exploring how agave has taken over areas that were once used for local crops.

Despite these advances, a technological gap persists in the State of Mexico regarding geospatial management applied to mezcal agave. The few existing systems are limited to agricultural land registries (SIAP, 2023) and do not incorporate key phytosanitary variables. This limitation hinders both the implementation of effective public policies and the optimization of resources by producers.

This work is based on the hypothesis that developing a specialized GIS that integrates biophysical and phytosanitary information layers through predictive models will allow the identification of epidemiological risk zones in mezcal agave cultivation. This, in turn, can facilitate the implementation of integrated management strategies adapted to the specific conditions of the State of Mexico. The overall objective of the study is to design a GIS for the phytosanitary management of mezcal agave that enables visualization of the spatial distribution of key pests and diseases and serves as a basis for implementing spatially differentiated integrated management.

The relevance of this research extends beyond the academic sphere, as it is framed within critical economic, social, and environmental dimensions for the state. This study aligns with the 2017–2023 State Development Plan, specifically its “Sustainable Rural Development” focus, and directly contributes to Sustainable Development Goals (SDGs) two (Zero Hunger), nine (Industry, Innovation and Infrastructure), and 15 (Life on Land).

MATERIALS AND METHODS

Study area

The study was conducted in the municipalities of Malinalco and Zumpahuacán, located in the State of Mexico. These regions are known for their significant activity in agave cultivation (Secretaría del Campo, 2022). The climatic and edaphic conditions are typical for agave cultivation, with altitudes ranging from 1500 to 2000 m and a semi-warm sub-humid climate (INEGI, 2022; Municipio de Malinalco, 2025).

Experimental design and sampling

Four plots belonging to cooperating producers (two per municipality) were selected using targeted, non-random sampling, prioritizing those with a history of phytosanitary problems. In Malinalco, the selected plots were Malinalco Centro (18° 56′ 43.5″ N, 99° 29′ 38.2″ W) and El Caporal (18° 57′ 15.8″ N, 99° 30′ 1.5″ W), while in Zumpahuacán, San Gaspar (18° 48′ 22″ N, 99° 33′ 45″ W) and La Perla (18° 49′ 10.5″ N, 99° 34′ 20.1″ W) were included. Monitoring was conducted throughout 2024 via monthly assessments. In each plot, 100 randomly selected plants were georeferenced using a high-precision GPS (Garmin GPSMAP 64s; error ≤ 3 m) (INEGI, 2022).

Variables evaluated

The incidence of the agave weevil (*S. acupunctatus*) was evaluated by counting the number of affected plants and, in a subsample, determining the number of insects per plant. Symptoms associated with *F. oxysporum* wilt, such as yellowing and leaf collapse, were also observed. The severity of the wilt was assessed using the scale developed by Jiménez-González *et al.* (2017), which rates damage on a scale from 0 to 100 % for each plant.

Additionally, environmental variables were analyzed, including climatic data such as precipitation and temperature obtained from local stations. Soil characteristics, including texture, pH, and electrical conductivity, were determined through laboratory analyses conducted at the Faculty of Agricultural Sciences of the Autonomous University of the State of Mexico. Management variables, including irrigation type and plant density, were also considered.

Data processing and thematic map creation

Data were organized in an Excel matrix and processed using QGIS 3.24. For spatial representation, monthly thematic maps were generated using Inverse Distance Weighted (IDW) interpolation for *S. acupunctatus* and ordinary Kriging for *F. oxysporum*, allowing visualization of incidence and severity. Spatial autocorrelation was assessed using Moran's I index.

For predictive analysis of *S. acupunctatus* incidence, the Random Forest algorithm was applied. The model was trained and validated in RStudio using the caret and randomForest packages. Predictor variables included environmental and management factors. The dataset was split into 70 % for training and 30 % for validation, and model performance was evaluated based on accuracy and the area under the receiver operating characteristic curve (AUC-ROC).

Statistical analysis

Analysis of variance (ANOVA) was used to compare incidence across municipalities and months, followed by Tukey's test ($p \leq 0.05$) using Minitab 21.4. Multiple regression analyses were conducted to evaluate the influence of environmental variables on wilt severity.

RESULTS AND DISCUSSION

Spatiotemporal analysis of the agave weevil (*S. acupunctatus*) and *F. oxysporum* wilt across four plots in Malinalco and Zumpahuacán revealed clear spatial structure in their distribution. Thematic maps generated through GIS-based interpolation (IDW and Kriging) (Appendices 1 and 2) showed pronounced heterogeneity in incidence and severity. When integrated with statistical and predictive modeling, these spatial outputs enabled the detection of aggregation patterns, their associated environmental drivers, and the dynamics of their spread. The interpretation of these patterns is fundamental for transitioning from uniform management to integrated, site-specific crop management.

The mapping of weevil incidence using the Inverse Distance Weighted (IDW) method (Appendix 1) revealed marked heterogeneity both between and within the sampled plots. In the Malinalco Centro plot, the map corresponding to June 2024 clearly shows the formation of "hotspots," or areas of high infestation, with values reaching up to 4.5 insects per plant on average during the peak of the rainy season (June–September). This visual pattern was statistically confirmed by a positive and significant Moran index ($I = 0.42$, $p < 0.01$), indicating an aggregated spatial distribution of the pest. The areas of greatest aggregation were located in zones with steep slopes (>15 %) and clay soils, conditions that, combined with accumulated rainfall greater than 800 mm, generate microhabitats with high soil humidity favorable for the insect's biological cycle.

This spatial behavior is not an isolated finding. Recent studies in the same region, such as that of González-Dávila *et al.* (2024), which used the Spatial Analysis of Distances Index (SADIE) in plots in Malinalco, corroborate the aggregated nature of *S. acupunctatus* populations, reporting aggregation indices (Ia) consistently higher than 1. The agreement between different methodologies (SADIE versus Moran indices and IDW interpolation) applied in the same geographic area lends considerable robustness to this conclusion: the agave weevil is not randomly distributed but instead forms stable foci of infestation in space.

Furthermore, González-Dávila *et al.* (2024) documented the short-term temporal stability of these hotspots, a phenomenon that, while not explicitly quantified in this study, aligns with the observed persistence of hotspots in Malinalco Centro throughout the sampling period. The practical implications are significant: if high-risk areas are spatially predictable and remain stable over time, it becomes both feasible and advisable to prioritize and efficiently direct monitoring and control efforts, such as applying biocontrol agents or removing infected plants, toward these areas. This approach would optimize resource use and minimize environmental impact.

In contrast, the El Caporal plot, also in Malinalco, showed a different spatial pattern. The incidence map (not shown) revealed an early infestation in June, but with more isolated outbreaks and less subsequent dispersal, with fewer than one insect per plant in 75 % of the area. This contrast, made evident through GIS, suggests that local factors such as sandy loam soil (which promotes faster drainage and reduces persistent soil moisture) and management practices such as crop rotation acted as barriers to the spread and establishment of large pest aggregations. In Zumpahuacán, the San Gaspar and La Perla plots showed moderate and dispersed incidence, without the formation of defined “hotspots” in the interpolation maps. The lack of clear aggregation may be associated with lower overall environmental and soil humidity, as well as landscape fragmentation, which could hinder insect mobility and colonization.

The correlation analysis (Table 1) quantified the influence of these factors. Accumulated precipitation showed the strongest positive correlation with weevil incidence ($r = 0.65$,

Table 1. Correlation analysis between environmental variables and the incidence of the agave weevil in Malinalco and Zumpahuacán, State of Mexico.

Environmental variable	Range/data	Correlation coefficient (r)	Significance (p-value)
Accumulated precipitation	>800 mm (vs. <500 mm)	0.65	<0.05
Soil type (clay)	pH 6.5–7.0 (vs. sandy-loam)	0.58	<0.05
Slope	>15 % (vs. <5 %)	0.52	<0.05
Mean temperature	20–25 °C (vs. 15–18 °C)	0.32	>0.05
Altitude	1500–2000 m	-0.41	<0.05
Moran index	0.42 (Spatial aggregation)	-	0.01

$p < 0.05$), followed by clay soil type ($r = 0.58$, $p < 0.05$) and slope ($r = 0.52$, $p < 0.05$). These results reinforce the hypothesis that soil moisture, enhanced by topography and soil texture, is the main epidemiological factor explaining the aggregated distribution of *S. acupunctatus* in the study region.

The application of ordinary Kriging to model the severity of *F. oxysporum* allowed the generation of highly accurate risk maps, such as that for a plot in Zumpahuacán in September 2024 (Appendix 2). This map not only locates diseased plants but also interpolates risk across the spatial continuum, clearly identifying three critical zones or “hotspots” with severity greater than 25 %. The underlying geostatistical analysis (with nugget values = 0.12 and sill values = 0.85) indicated a high degree of spatial structuring of the disease.

By incorporating the temporal dimension, these hotspots expanded radially at a rate of 15 m per month ($R^2 = 0.89$), reflecting a centrifugal expansion pattern typical of soilborne pathogens with limited dispersal mechanisms, such as *Fusarium* spp. The ability of GIS to visualize and quantify this spatiotemporal dynamic is crucial, as it allows anticipation of disease trajectories and the establishment of sanitary barriers or containment zones around hotspots before further expansion.

The robustness of this methodological approach is supported by extensive research in geostatistics applied to phytosanitary problems. Pioneering work by the group at the Autonomous University of the State of Mexico has consistently validated the use of these techniques. For example, Rivera-Martínez *et al.* (2017) used Kriging to model Thysanoptera distribution in avocado, demonstrating that even when the pest is present throughout a plot, density maps allow the identification of areas with higher pressure, enabling targeted control measures and more efficient resource use.

Similarly, Rivera-Martínez *et al.* (2022) applied geostatistics to characterize the spatial behavior of the avocado seed weevil *Copturus aguacatae*, concluding that this approach significantly improves understanding of pest dynamics and, consequently, management strategies. Martínez-Martínez *et al.* (2021) determined the aggregated distribution of *Hemiberlesia lataniae* in ‘Hass’ avocado using density maps and fitted semivariograms to theoretical models (spherical and exponential) to describe spatial structure. The present study on agave aligns with this body of knowledge and extends it to a crop of high economic and cultural importance, demonstrating the replicability and analytical strength of geostatistics for site-specific management of phytosanitary problems.

The multiple regression model (Table 2) identified the factors associated with wilt severity. Soil moisture (>60 %) emerged as the most influential variable ($\beta = 0.62$; $p = 0.002$), followed by a temperature range of 18–22 °C ($\beta = 0.41$; $p = 0.016$) and low values of the Normalized Difference Vegetation Index (NDVI < 0.35; $\beta = -0.55$; $p = 0.001$). The model explained 78 % of the observed variability (adjusted $R^2 = 0.78$). The strong negative correlation with NDVI is particularly revealing, suggesting a negative feedback loop in which plant stress and reduced vigor (reflected by low NDVI values) increase susceptibility to infection, or conversely, that infection itself leads to a rapid

Table 2. Multiple regression model for the severity of *Fusarium oxysporum* in mezcal agave plots.

Variable	Coefficient (β)	<i>p</i> -value	Confidence interval (95 %)
Soil moisture	0.62	0.002	0.51, 0.73
Temperature (°C)	0.41	0.016	0.29, 0.53
NDVI	-0.55	0.001	-0.67, -0.43
Plant density	0.19	0.042	0.05, 0.33

NDVI: Normalized difference vegetation index.

decline in plant vitality. This finding highlights NDVI, a variable readily obtained through remote sensing, as a potential early indicator of epidemiological risk.

The predictive model developed using Random Forest for the incidence of *S. acupunctatus* showed excellent predictive capacity, with an overall accuracy of 88.2 % and AUC-ROC of 0.91, indicating strong discrimination between the presence and absence of the pest. A novel and particularly interesting finding was the high relative importance of soil electrical conductivity (EC), which contributed 23 % to the model's accuracy. This factor has been little explored in the ecology of the agave weevil. High EC may be associated with greater concentrations of salts and nutrients, potentially influencing plant physiology and making plants more attractive or susceptible to insect attack. Alternatively, it may act as an indicator of higher soil moisture or compaction. The model-derived hypothesis opens a new and relevant line of research that targeted studies should further explore.

However, the model also revealed an important limitation, as its accuracy decreased markedly in areas with steep slopes (>25 %), with a corresponding increase in root mean square error (RMSE = 4.7). This reduction in performance is attributable to topographic shadowing and geometric distortion affecting satellite imagery in rugged terrain, a problem well documented in the literature (Matese and di Gennaro, 2015). While this limitation does not invalidate the model, it calls for caution when applying it under complex topographic conditions and points to a clear avenue for improvement. The integration of complementary technologies, such as unmanned aerial vehicles (drones) equipped with multispectral sensors, would enable low-altitude data acquisition, minimizing shadow effects and providing higher spatial and spectral resolution, thereby improving predictive accuracy in these areas.

Taken together, the results demonstrate that GIS is not merely a visualization tool but a robust analytical platform capable of quantifying the spatial heterogeneity of phytosanitary problems (Tapia-Rodríguez *et al.*, 2025). The maps serve as central evidence to guide decision-making, supporting a transition from uniform and indiscriminate management to site-specific strategies. Interventions such as the application of biocontrol agents, including *Trichoderma harzianum*, whose effectiveness against *Fusarium* has been reported at up to 83 % in tequila agave by Silva *et al.* (2022), as

well as improved drainage in clay soils or irrigation adjustments, can be concentrated in identified “hotspots” and their surrounding areas. This approach not only increases control effectiveness, as observed in Malinalco Centro with a 60 % reduction in weevil incidence following targeted interventions, but also reduces the use of chemical and biological inputs, contributing to both economic and environmental sustainability. The persistence of low levels of pests and disease even after intervention indicates that management must be continuous, preventive, and genuinely integrated. As noted by Martínez-Martínez *et al.* (2021), understanding spatial distribution is only the first step and must be followed by the development of integrated management programs combining targeted biological control with cultural practices at both plot and landscape scales. These include drainage management, agroecosystem diversification, the use of trap plants, and continuous training for producers. Community participation in monitoring, supported by the interpretation of simplified risk maps, represents a critical step for scaling up this approach and ensuring its long-term adoption, thereby strengthening the sustainability of the mezcal agave production chain under increasing climate and phytosanitary pressures.

CONCLUSIONS

The distribution of weevil (*Scyphophorus acupunctatus*) and the incidence of *Fusarium oxysporum* wilt in mezcal agave in the State of Mexico were determined by a specific combination of soil and climatic factors and management practices, with soil moisture standing out as the main epidemiological driver. The risk maps allowed visualization and quantification of the spatial aggregation of these problems, identifying hotspots with high precision. This capacity for spatial localization is fundamental to designing and implementing spatially differentiated integrated management strategies, optimizing resource use and increasing control effectiveness. Predictive models such as Random Forest offer considerable potential for anticipating risk zones, although their accuracy may be constrained under complex topographic conditions. The identification of soil electrical conductivity as a relevant variable in weevil modeling opens new perspectives for research on the mechanisms underlying infestation. The implementation of artificial drainage practices in clay soils is recommended to reduce soil moisture, along with irrigation adjustments based on the spatial risk of wilt. Future research should incorporate continuous monitoring through sensors and information and communication technologies, as well as metagenomic analyses to improve early pathogen detection. In addition, integrating socioeconomic variables into predictive models will enable the development of adaptive strategies that combine local knowledge with technological innovation, thereby strengthening the sustainability of mezcal agave cultivation.

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Appendix 1. Thematic map of the incidence of *Scyphophorus acupunctatus* in Malinalco, State of Mexico, in June 2024 (prepared by Inverse Distance Weighted (IDW) interpolation in QGIS 3.24).



Appendix 2. Thematic map of the incidence of *Fusarium oxysporum* in Zumpahuacan, State of Mexico during September 2024 (prepared by ordinary Kriging in QGIS 3.24).