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Geostatistical analysis for mapping soil salinity in the Lajas Valley Agricultural Reserve, southwestern Puerto Rico[1,2]

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ABSTRACT

Studies were conducted in the 1950s to evaluate the degree and spatial extent of soil salinity and sodicity in the Lajas Valley in southwestern Puerto Rico. Problem areas were identified and most of these were remediated with the establishment of irrigation and drainage infrastructure, resulting in a four-fold increase in agricultural production over a 10-year period. The area is now an important agricultural region (known as the Lajas Valley Agricultural Reserve). But soil salinity and sodicity are important concerns among farmers. In this paper we used published data and re-created the spatial distribution of soil salinity and sodicity using geostatistical analysis with Geographic Information Systems (GIS). An Ordinary Kriging method was applied to map the spatial distribution of soil salinity and to classify soils in four classes: (i) Normal, (ii) Saline, (iii) Saline-Sodic, and (iv) Sodic. The original hand-drawn maps were digitized using the Georeferencing Tool in ArcGIS, guided by a recent aerial photo of the Lajas Valley. Salinity and sodicity isopleths were created using Surface Generation to map the spatial distribution and to compare the newly

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[2]The *.shp files are available upon request to the corresponding author. We acknowledge soil scientist Manuel Matos, USDA-NRCS Caribbean Area, for providing the electronic soils database.

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created data to the original maps. The relative error in aerial estimate between the old and new maps for Normal, Saline, Saline-Sodic, and Sodic surface soils was between 1 and 5 percent. The new maps developed with geostatistical analysis can predict soil problem areas with a 94% coincidence compared with the hand-drawn maps. The highest proportion of soils classified as Normal was found in the upper soil layers and the proportion of soils affected by salt and sodium increased with depth. The combination of geostatistical analysis and GIS is a cost-effective and trustworthy method for analyzing similar datasets that would otherwise be costly and involve lengthy time commitments.

Key words: soil salinity, soil sodicity, GIS, geospatial analysis, ordinary kriging

RESUMEN

Análisis geoestadístico para mapas de salinidad de suelos en la Reserva Agrícola del Valle de Lajas, al suroeste de Puerto Rico

En la década de 1950 se realizaron estudios para evaluar el grado y distribución espacial de salinidad y sodicidad de suelos en el Valle de Lajas. Se identificaron áreas con problemas y la mayoría se remediaron con el establecimiento de una infraestructura de riego y drenaje, resultando en un incremento en la producción agrícola de 400% en un periodo de 10 años. El área es ahora una región agrícola importante (conocida como la Reserva Agrícola del Valle de Lajas). Sin embargo, la salinidad y sodicidad de los suelos están entre las mayores preocupaciones de los agricultores. En este trabajo utilizamos datos publicados y recreamos la distribución espacial de salinidad y sodicidad usando un análisis geoestadístico con un Sistema de Información Geográfico (SIG). Se utilizó el método kriging ordinario para producir los mapas y clasificar los suelos en cuatro categorías: (i) Normal, (ii) Salino, (iii) Salino-Sódico, y (iv) Sódico. Los mapas originales, hechos a mano, se digitalizaron usando la herramienta *Georeferencing* en ArcGIS. Para comparar los mapas creados con los mapas originales, se crearon isopletas de salinidad y sodicidad con la herramienta *Surface Generation*. El error relativo en términos de área entre los mapas viejos y nuevos para suelos Normal, Salino, Salino-Sódico y Sódico varió entre 1 y 5 por ciento. Las áreas con problemas pueden predecirse con una coincidencia de 94% comparado con los mapas viejos. La mayoría de los suelos en la categoría de Normal se encontraron en las capas superiores y la proporción de problemas con sales y sodio aumentó con la profundidad. La combinación de análisis geoestadístico y SIG es una metodología útil y confiable para analizar bases de datos similares que de otra manera costarían mucho tiempo y esfuerzo.

Palabras clave: salinidad de suelo, sodicidad de suelo, SIG, análisis geoespacial, kriging

INTRODUCTION

The planning, design and construction of an irrigation-drainage infrastructure project known as the Southwest Project, in the Lajas Valley on the southwestern coast of Puerto Rico were part of an effort during the 1950s and 60s to strengthen the island's economic development (Lucchetti, 1948; Koenig, 1953). Its goal was to intensify agricultural production by (i) providing irrigation to 10,526 ha; (ii) generate electricity to developing urban areas; (iii) protect urban and rural lands from flooding by constructing the Lucchetti and Loco reservoirs; and (iv) provide drinking water for area residents (Lucchetti, 1948; González-Chapel, 1965). Planning was initiated in 1945, and the construction of dams, water transfer systems, hydroelectric plants and irrigation-drainage channels was initiated in 1952. The first irrigation lines were opened to farmers in 1955 and completed in 1961 at an estimated cost of $9.5 million. The Southwest Project was visualized, planned and conceived considering the best available intellectual and technical resources with experts in the fields of engineering, irrigation, drainage, soils, economy and agronomy from local and international areas.

Initial planning studies included geomorphological reconnaissance surveys, soil sampling, soil physical and chemical analysis, leaching tests and infiltration rates (Bonnet and Tirado-Sulsona, 1950). Since one of the main findings was that some soils were affected by salinity, a detailed field survey and soil sampling program of the Lajas Valley was conducted by Bonnet and Brenes (1958). Some soil areas affected by high salt and sodium content coincided with areas that had an upward hydraulic gradient (Willardson, 1958). Thus, according to Lucchetti (1948) and Mitchell (1957), the total elimination of superficial water was of utmost importance to assure a reduction of salt and sodium accumulation in soils. The three main reasons for the accumulation of salts and sodium in the soil profile were: (i) use of groundwater for irrigation (ii) the upward movement of salts from the subsoil in areas characterized by high artesian pressures, and (iii) capillary movement of groundwater with high electrical conductivity from the subsoil and subsequent evapotranspiration (Bonnet, 1960; Gardner, 1954). It was foreseen and proven that uncontrolled irrigation without adequate drainage would cause soil salinization of some land areas (Bonnet and Brenes, 1958; Van der Molen, 1957; Willardson, 1958). By 1964, the success of the irrigation/drainage infrastructure was demonstrated; only 400 acres were estimated to be affected by salts, sodium or its combination (Rivera-Santos, 1964; González-Chapel, 1965).

From the 1950s to the 1970s sugarcane was the main crop in the Lajas Valley, but as the crop was gradually phased out during the 1980s, the land was converted to grow mostly improved forages for haylage and cattle grazing, rice and horticultural crops (Sotomayor-Ramírez and Pérez-Alegría, 2012). In some areas, there has been less irrigation and a gradual abandonment of the drainage channels, possibly leading to salt and sodium buildup in the soil profile. Thus, soil salinity and sodicity remain among the biggest concerns of farmers.

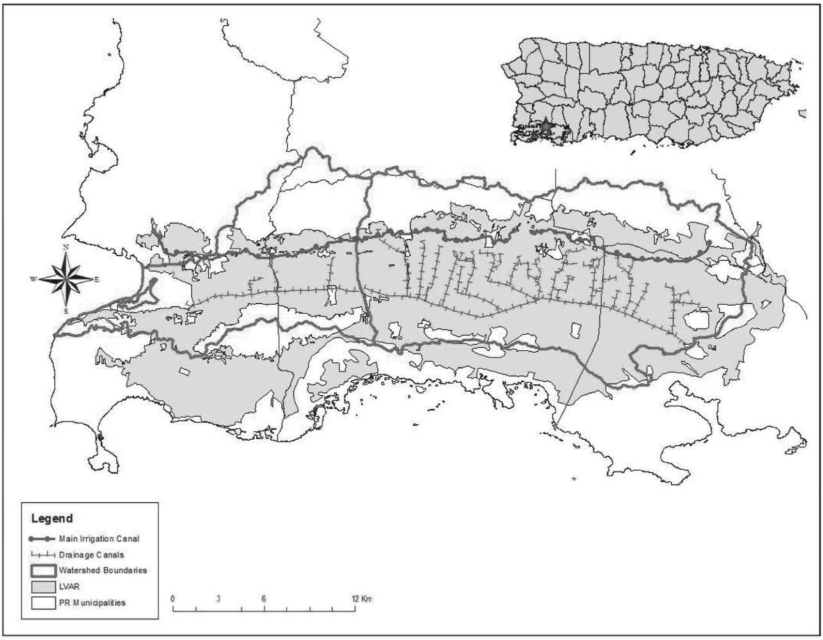
Since the work by Bonnet and Brenes (1958), soil salinity studies have not been conducted. Bonnet and Brenes (1958) provided hand-drawn maps that are difficult to interpret because they are not digitized and have low resolution. It is important to know the spatial locations where problem areas were initially identified to assess potential improvement or degradation of soil salinity by ground-truthing or with new mapping tools. This work was done with the objective of digitizing the data gathered by Bonnet and Brenes (1958), preparing spatial salinity maps and identifying the spatial distribution of soil salinity and sodicity problems using GIS tools.

MATERIALS AND METHODS

Study area. The Lajas Valley is a large plain in southwestern Puerto Rico (Figure 1)[6] that extends from Guánica municipality in the east to Bahía de Boquerón in the west. It includes parts of the municipalities of Yauco, Guánica, Sabana Grande, Cabo Rojo and Lajas, with a total area of about 41,000 ha (101,270 acres). The watershed divide that runs north to south is located 9.5 km east of Bahía de Boquerón near State Road 116. All of the land area east of State Road 116 has a drainage area of 15,028 ha (37,120 acres) and drains towards Guánica Bay; to the north is a chain of hills of maximum altitude of 300 m; to the south it is separated from the Caribbean Sea by a secondary ridge of hills of maximum altitude of 285 m (Graves, 1996). The Valley ranges from about 13 m above mean sea level (MSL) along the east-west drainage divide and then descends eastward to its lowest level of 1.1 m above mean sea level near the former Guánica Lagoon, which is now an important agricultural land area.

Precipitation in the Valley is bi-modal with maximum precipitation typically occurring during late August to early December and from April to June with 50-yr mean annual precipitation of 1,143 mm and pan evaporation of 1,100 mm (Harmsen et al., 2004; U.S. Department of Commerce, 1986). In general, the soils are considered of high fertility, clayey, with medium to low drainage capacity (Lugo-López and Pérez-Escolar, 1959; Lugo-López et al., 1959). The area has 50 identified soil series, but the predominant soils in the area are: Aguirre (Very-fine, smectitic, isohyperthermic Sodic Haplusterts), Cartagena (Fine, mixed, superactive,

[6]The colored version of the figures of this manuscript is available at: https://startnow259.files.wordpress.com/2018/05/figure_oliverasberrocalles_etal_2017.pdf.

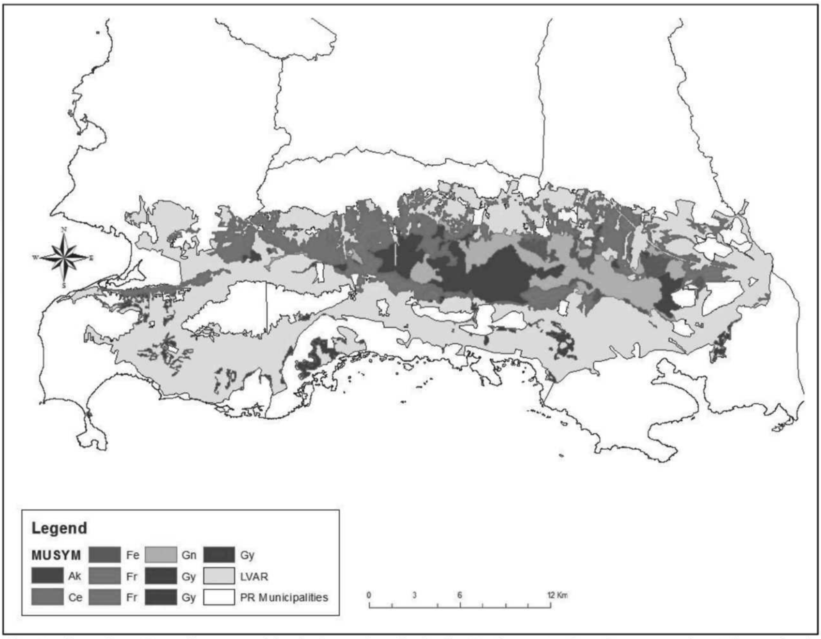


LVAR =Lajas Valley Agricultural Reserve

FIGURE 1. Map of the Lajas Valley in Southwestern Puerto Rico portraying the irrigation and drainage infrastructure of the area.

isohyperthermic Sodic Haplusterts), Fe (Fine, smectitic, isohyperthermic Sodic Haplusterts), Fraternidad (Fine, smectitic, isohyperthermic Typic Haplusterts) and Guánica (Fine, smectitic, isohyperthermic Typic Calciaquerts) (USDA-NRCS, 2008) (Figure 2).

Data source. A detailed field survey and soil sampling program of the Lajas Valley was conducted between 1 July 1954 and 15 March 1955 (Bonnet and Brenes, 1958). The location of the sampling sites was made by drawing a grid of 2.54-cm squares on a base map with a scale of 1:10,000. Each square represented an area of 6.45 ha (16 acres). Samples were collected from randomly selected points on the grid system from a corner of the selected square. Soil samples were taken with a soil auger at two depths, 0 to 20 cm and 20 to 60 cm (0 to 8 inches and 8 to 24 inches), respectively. For every four squares, or about 25.8 ha (64 acres), two more samples were also taken at depths of 60 to 122 cm (24 to 48 inches) and 122 to 183 cm (48 to 72 inches). Soil samples were also taken from under the shallow waters of the former Guánica lagoon at the eastern end of the Lajas Valley (Bonnet and Brenes, 1957), which was subsequently dried to im-



Ak- Aguirre clay (Very-fine, smectitic, isohyperthermic Sodic Haplusterts), Ce- Cartagena clay (Fine, mixed, superactive, isohyperthermic Sodic Haplusterts), Fe- Fe clay (Fine, smectitic, isohyperthermic Sodic Haplusterts), Fr- Fraternidad clay (Fine, smectitic, isohyperthermic Typic Haplusterts), Gn- Guánica clay (Very-fine, smectitic, isohyperthermic Typic Calciaquerts), Gy- Guayacán clay (Fine-loamy, mixed, superactive, isohyperthermic Typic Haplocalcids).

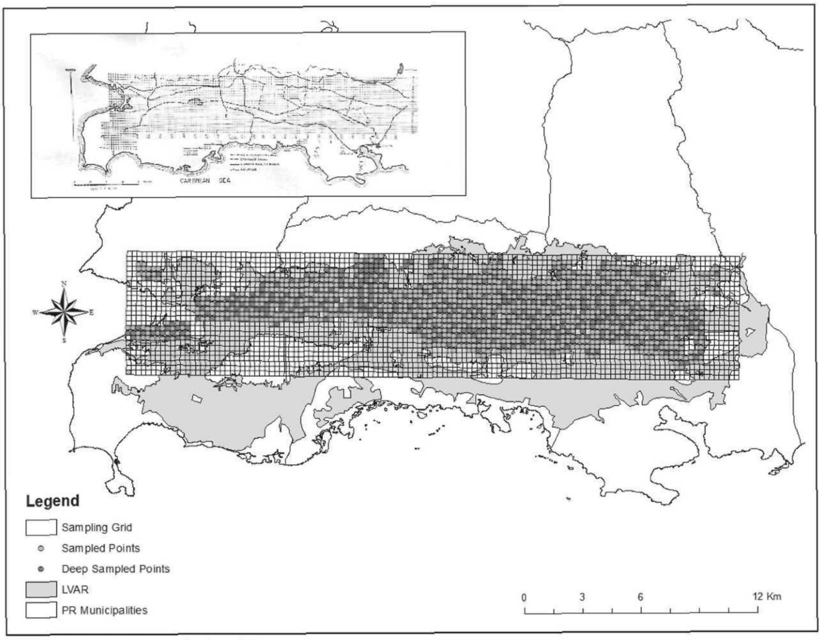
FIGURE 2. Predominant soil series association in the Lajas Valley Agricultural Reserve (LVAR) as described by the USDA-NRCS (2008). Soils having an area greater than 500 ha were included as the predominant soil series at the study area.

prove the drainage capacity of the soils of the Valley and to provide about 454 ha (1,123 more acres) within the irrigation project. Profile samples were taken for a total of 1,534 points from 0 to 60 cm, 440 from 60 to 122 cm and 422 from 122 to 183 depth intervals (Figure 3), representing a sampled area of about 9,937 ha (24,544 acres), which was about 25% of the total potential area.

The soil samples were prepared using saturated-paste and the extract analyzed for pH, free carbonates, and moisture at soil-saturation point, electrical conductivity (EC), and soluble sodium (Na), calcium (Ca), and magnesium (Mg) (Richards, 1954). The exchangeable sodium percentage (ESP) was calculated based on Na, Ca, and Mg normality concentration. The soils were classified as Normal, Saline, Saline-Sodic, and Sodic, based on the classification of Richards (1954). The distribution of the four soil classes to a depth of

60 cm (24 inches) were represented on a map that was hand-drawn (Bonnet and Brenes, 1958).

Analysis. A common grid-cell mapping system was used. A grid cell and its associated property attributes represent a spatial cell characterized by the dominant feature of that cell. The grid cell system is sufficient for mapping most soil properties because soil properties tend to change gradually over the landscape, making it difficult to establish a definitive boundary line for individual mapping units (Rhoades and Corwin, 1984). To increase spatial accuracy requires a reduction in grid cell size. But this increases the quantity of data. In a grid cell system, associated attributes are assigned to point groups rather than to a single cell or point. A mapping system requires a database of associated property attributes with x and y coordinates. Association of position and property attribute is accomplished by digitalizing the centroids of the grid cell, then relating the attribute to the corresponding point or centroid.



LVAR =Lajas Valley Agricultural Reserve

FIGURE 3. Sampling grid constructed by Bonnet and Brenes (1958) for the soil sampling at depths of 0 to 20, 20 to 60, 60 to 122, and 122 to 183 cm and the distribution of the sampling points taken.

A rectangular grid, similar to the original grid used in the salinity survey for the soil sampling, was constructed (Figure 3) in ArcGIS 10.2 (ESRI Corp, Redlands, CA)[7] using the dimensions described in the original publication by Bonnet and Brenes (1958). The soil EC, ESP and pH data were obtained from Bonnet and Brenes (1958) (Table 1) and transcribed to an electronic database. The electronic data was validated by randomly selecting samples and comparing them to the original data. The hand-drawn map made by Bonnet and Brenes (1958) was digitalized in ArcGIS with a georeferencing tool using control points of an actual aerial photo to achieve precise coordinates of the study area and sampled locations.

The spatial distribution of soil salinity, sodicity and salinity-sodicity was analyzed using ArcGIS 10.2 (ESRI, 2010). The Geostatistical Analyst module was used to model the spatial distribution of EC and ESP. The data was interpolated using the Ordinary Kriging method, which is a technique of making optimal, unbiased estimates

TABLE 1.—*Summary of soil properties by sampling depth within Lajas Valley as reported by Bonnet and Brenes (1958).*

Variable[1]	Units	-95% CI[2]	+95% CI	Mean
n= 1534		0 to 20 cm		
pH	pH	7.79	8.08	7.93
EC_e	dS/m	3.69	4.88	4.28
ESP	%	7.79	9.05	8.42
n= 1530		20 to 60 cm		
pH	pH	8.10	8.17	8.13
EC_e	dS/m	5.82	7.52	6.67
ESP	%	13.06	14.43	13.75
n= 440		60 to 122 cm		
pH	pH	7.76	7.92	7.84
EC_e	dS/m	4.37	7.74	6.06
ESP	%	9.55	12.25	10.90
n= 422		122 to 183 cm		
pH	pH	7.99	8.73	8.36
EC_e	dS/m	5.72	9.93	7.82
ESP	%	13.89	16.69	15.29

[1]ECe is saturated paste electrical conductivity; ESP is saturated paste exchangeable sodium percentage; n is the number of determinations.

[2]± 95% confidence interval

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[7]Company or trade names in this publication are used only to provide specific information. Mention of a company or trade name does not constitute an endorsement by the Agricultural Experiment Station of the University of Puerto Rico, nor is this mention a statement of preference over other equipment or materials.

of regionalized variables at un-sampled locations using the structural properties of the initial set of data values (David, 1977). Spatial interpolation for soil salinity data was performed using ArcGIS software by involving the following steps: Geostatistical Analyst (GA) tool, Ordinary Kriging method, exploratory data analysis and maps generation. The area corresponding to each soil attribute was calculated by digitalizing polygons and calculating the corresponding area using the calculate area tool in ArcGIS. The soil EC and ESP data were interpolated using GA tool by the Ordinary Kriging method in ArcGIS to create layers and combine them to produce the soil class classifications.

A weighted average of data from 0 to 22 and 22 to 60 cm for each sampling point was generated and spatial maps were created to compare with that by Bonnet and Brenes (1958). The areas calculated using Geostatistical tools were compared with the areas delineated by Bonnet and Brenes (1958). The relative error (RE) between the two maps was calculated using the theoretical area (A_t) which is the area reported on by Bonnet and Brenes (1958) and the experimental area (A_e) which is the area estimated with the Geostatistical analysis in ArcGIS, classified as Normal, Saline, Sodic, and Saline-Sodic as:

$$\%RE = \frac{(A_t - A_e)}{A_t} * 100 \qquad [1]$$

Using a sampling tool (Hawth's Analysis Tool) in ArcGIS, 20% (307) of the sampled points were randomly selected from the data sets to compare the geographical coincidence between the hand-drawn map and the new map generated with Geostatistical analysis. Further analysis included comparison of soils classified as having saline or sodic characteristics according to soil taxonomy and our estimates using Geostatistical analysis.

RESULTS AND DISCUSSION

Magnitude of soil salinity and sodicity. Soils to a depth of 0 to 22 cm classified as Normal, Saline, Sodic or Saline-sodic occupied 86, 5, 1, and 8% of the area, respectively. The extent of the problem increased with depth as soils classified as Normal, Saline, Sodic or Saline-sodic were 64, 8, 8, and 20% to a depth of 22 to 60 cm; 34, 11, 8, and 48% to a depth of 60-122 cm; and 23, 8, 11, and 58% deeper than 122 cm, respectively. The largest extent of soils classified as Normal was found in the upper soil layers (0 to 20, 20 to 60 cm), whereas the opposite was observed for saline, sodic or saline-sodic areas in the lower soil layers (60 to 122, 122 to 183 cm).

Data Interpolation. Ordinary Kriging as a simple predictor method does not require that the data have a normal distribution for the creation of predictive maps, but improvement in data prediction can be attained if the data is normally distributed (ESRI, 2010). Soil EC, ESP and pH parameters were highly skewed (skew 8.6, kurt 88.7); thus the data was $\log_{10}$ transformed. Graphical analysis between an east-west transect and skewness (kurtosis) was used to identify bias as a function of the geography of the area. In general, upside or downside U shapes represent more variability of the data as influenced by location. Monitoring soil salinity is complicated by changes in soil salinity on a small spatial scale (Rhoades and Corwin, 1984) and usually numerous samples are needed to adequately characterize an area. Also, adequate estimation is complicated by the dynamic nature of soil salinity, the influence of management practices, fluctuations in water table depth, soil permeability, consumptive water use, rainfall, topography and change in topography (Rhoades and Corwin, 1984). Graphical analysis revealed that the data had greater variability on the geographic extremes of the study area, in areas where soils did not necessarily have salinity or sodicity problems. A Second Order Trend Removal option was used to eliminate the variability of soil salinity data observed in the geographical extremes of the valley.

Surface Generation. After data transformation and trend removal, the data interpolation was made to create the raster layers. The classification of the layers was established based on two levels for EC (< 4 dS/m and > 4 dS/m) and ESP (< 15% and > 15%), and the surface was generated combining both layers to produce the maps. Figure 4 shows the spatial distribution of soil salinity, sodicity and salinity-sodicity by each sampling depth interval (0 to 20, 20 to 60, 60 to 122, 122 to 183 cm). The RE between the areas classified as Normal, Saline, Saline-Sodic, and Sodic soils by Bonnet and Brenes (1958) and by us using GA were 4%, 5%, 4%, and 1%, respectively.

The map produced by Bonnet and Brenes (1958) in Figure 5a is a visual representation of the spatial distribution of soils that were classified as Saline and Saline-Sodic at a depth of 0 to 60 cm, yet they did not report the original data corresponding to that depth interval. We generated a new map based on weighted averages of 0 to 22 and 22 to 60 cm, to visually compare the original hand-drawn map and our map (Figure 5b). The RE between the original study by Bonnet and Brenes (1958) and the new analysis performed with Geostatistical Analyst was on average 25% for the Saline and for the Saline-Sodic soils at a depth of 0 to 60 cm. These differences can be due to the way the hand-drawn maps were made based on the sampled locations. With Geostatistical Analyst the un-sampled lo-

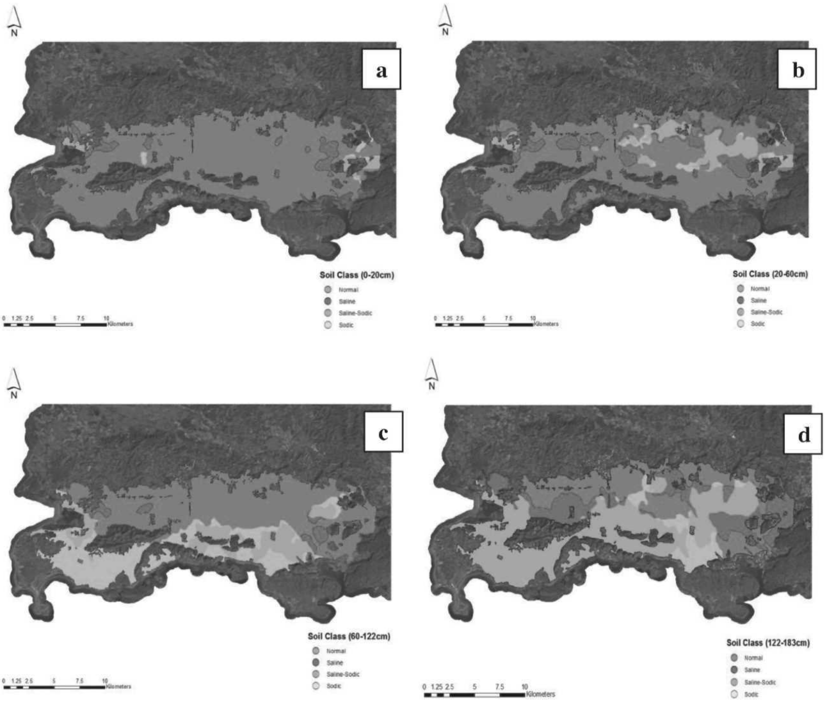

Figure 4. Map of the Lajas Valley with the spatial distribution of soil salinity or sodicity performed with Geostatistical Analyst by each sampling depth interval (a) 0-20, (b) 20-60, (c) 60-122, and (d) 122-183 cm.

cations are predicted based on the nearest sampled location. Also, with Geostatistical Analyst the prediction was extended to the entire area of the Valley.

The observed differences in the proportions of normal and saline-sodic soils as measured with site-specific data of Bonnet and Brenes and Geostatistical analysis can be due to the methodology used to calculate the percentage of each soil class. In the original publication, the area corresponding to each class was estimated from the number of samples classified under a soil class divided by the total number of samples collected at each sampled depth interval, with each sample having an area of 6.5 ha (16 acres). By contrast our analysis was made based on isopleths generated for each soil class, which provides improved resolution and spatial variation in the estimation. The latter may be a more objective procedure for estimating the soil area affected by soil salts and sodium.

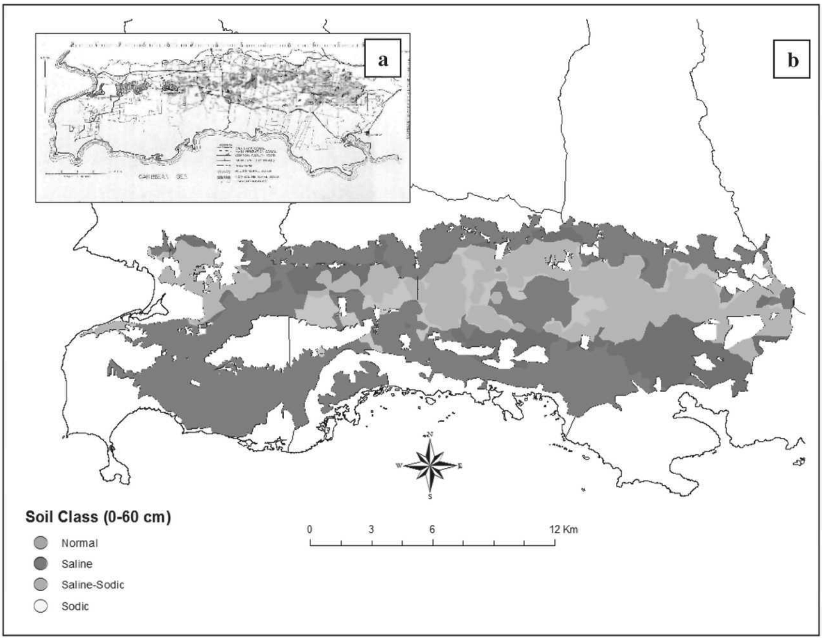

FIGURE 5. Map of the Lajas Valley that describes (a) areas with salinity problems as originally published by Bonnet and Brenes (1958) and (b) updated analysis performed with Geostatistical Analyst to a depth of 60 cm.

To examine the geographical coincidence between Geostatistical analysis and site-specific data, 289 points coincided within the same soil class. The results suggest that the new map developed with GA can predict the extent of saline or sodic areas with a 94% coincidence with the hand-drawn map.

Soil salinity and Soil taxonomy. Based on the study performed by Bonnet and Brenes (1958), the more problematic areas are those on the central and foot slope portions of the valley at the lowest topographic locations. As shown in Figure 2, these areas are associated with the soil series Aguirre (Very-fine, smectitic, isohyperthermic Sodic Haplusterts), Cartagena (Fine, mixed, superactive, isohyperthermic Sodic Haplusterts), Fé (Fine, smectitic, isohyperthermic Sodic Haplusterts), Fraternidad (Fine, smectitic, isohyperthermic Typic Haplusterts) and Guánica (Fine, smectitic, isohyperthermic Typic Calciaquerts), which, in general, are described by the USDA-NRCS soil survey as soils formed in depressions, fan skirts of basins and flood plains of the semiarid coastal plains. These are soils with clay texture, poorly drained, with very slow to slow permeability, moderate saline to saline soils, and slight alkaline to strongly alkaline throughout the soil profile (USDA-NRCS, 2008). Yet, none of the soils have saline or sodic subordinate designations at the surface layer that would classify them with these characteristics. This is so because in soil designation more than three suffixes are rarely used and suffix symbols "n" (accumulation of sodium) are not used with h, s, and w suffixes, and these soil series have "ss" (presence of slickensides) designations in their soil profile. Only Guánica and Fé series have the subgroup "z" (accumulation of salts) designation in the lower soil profile. At a depth of 0 to 60 cm the saline, saline-sodic and sodic areas were estimated at about 9,700 ha (23, 959 acres) and the area corresponding to soil series Guánica and Fe was estimated at about 8,000 ha (19, 760 acres). There is a spatial and area coincidence (82%) between the problematic areas mapped with Geostatistical Analyst and the soil series described with salinity problems by the soil survey.

The studies performed in the 1950s were the first attempt to identify and quantify the edaphic factors limiting agricultural production, such as salinity. Suitable inventories of soil salinity do not exist in Puerto Rico. At present, there are no structured planned or ongoing studies with the goal of monitoring areas with salinity problems, especially those that were identified more than 50 years ago in the area. A program to protect soils against salinization does not exist. Proper operation of viable permanent irrigated agriculture, which also uses water efficiency, requires periodic information on soil salinity. Some locations of the study area have very productive agricultural production systems; thus the Lajas Valley is an area with great agricultural potential for Puerto Rico. This work represents a new attempt to study the spatial extent of soil salinity in the Lajas Valley Agricultural Reserve, using new techniques that can be used to improve the soil quality in this area for the benefit of farmers.[8]

CONCLUSIONS

A spatial analysis of the extent of soil salinity and sodicity in the Lajas Valley of Southwest Puerto Rico was carried out from historical data and using ArcGIS GA Ordinary Kriging methods. The new map developed with ArcGIS Geostatistical Analyst can predict the extent of areas with salinity and sodicity problems with a 94% coincidence as compared with the site-specific data published in 1958. Visual analysis

[8]Since the article was submitted and approved, the authors have received extramural funding to update the origianl soil salinity maps by Bonnet and Benes (1958) using electromagnetic induction.

and quantitative comparison demonstrate that this methodology can be used to map soil properties relatively faster with an acceptable degree of error. ArcGIS Geostatistical Analyst provides a cost-effective, logical solution for the analysis of datasets that would otherwise cost considerable time and money to accomplish. From a single map, one can quickly obtain information about the spatial extent and areas affected by salinity. Further, this tool can be used to visualize the spatial variation in soil data especially when limited data is available. Also this data is amenable for use in gridded computer models, such as hydrologic models, which might be used to simulate the leaching of salts into the aquifer system or the concentration of salts at the surface through evaporation[9].

No recent inventory exists of soil salinity and sodicity of the Lajas Valley. Although recent empirically based soil EC and ESP data has not been gathered, it is expected that the current extent of saline and sodic areas will be less than in the 1950s, due in part to the irrigation and drainage infrastructure that was constructed and continues to be operational. Soil salinity data gathered by Bonnet and Brenes (1958) may be out of date because management, weather and water table conditions have changed since that study. Nevertheless, the information provided can be used by agronomists and consultants to identify potential areas that could be affected if future changes in the drainage and irrigation infrastructure occur in the area. The tool is also an important instrument that helps in the decision-making process regarding irrigation, water management, crop selection, crop establishment, location and intensity of salinity areas.

LITERATURE CITED

Bonnet, J. A., 1960. Edafología de los suelos salinos y sódicos. Universidad de Puerto Rico, Estación Experimental Agrícola. 1960. 337 pp.

Bonnet, J. A. and E. J. Brenes, 1958. Estudio detallado sobre salinidad en el Valle de Lajas. Univ. P.R. Agricultural Experiment Station, Río Piedras, Puerto Rico, Bulletin 141, 114 pp.

Bonnet, J. A. and E. J. Brenes, 1957. Salinity status of Lajas Valley soils. *J. Agric. Univ. P.R.* 41(1): 25-34.

Bonnet, J. A. and P. Tirado-Sulsona, 1950. Soil studies in Lajas Valley. Univ. P.R. Agricultural Experiment Station, Río Piedras, Puerto Rico, Bul. 86, 64 pp.

David, M., 1977. Geostatistical ore reserve estimation. Elsevier, Amsterdam.

ESRI, 2010. ArcGIS Explorer, California. Available in: http://www.esri.com/software/arcgis/explorer/index.html

[9]The GIS-based spatial layers can be obtained by request to the corresponding author, D. Sotomayor.

Gardner, R., 1954. Report on Soil and Water Control Problems of the Lajas Valley. Development Project, Mimeographed, University of Puerto Rico, Agricultural Experiment Station. 42 pp.

González-Chapel, A., 1965. Planificación e implementación de un programa de desarrollo en el Valle de Lajas. Univ. P.R. Agricultural Experiment Station, Río Piedras, Puerto Rico, Bulletin 192. 38 pp.

Graves, R. P., 1996. Atlas of ground-water resources in Puerto Rico and the U.S. Virgin Islands. *In:* Veve, T.D. and B.E. Taggart (eds) U.S. Geological Survey Water Resources Investigations Report 94-4198. San Juan, PR. 151 pp.

Harmsen, E. W., A. González-Pérez and A. Winter, 2004. Re-evaluation of pan evaporation coefficients at seven locations in Puerto Rico. *J. Agric. Univ. P.R.* 88: 109-122.

Koenig, N., 1953. A comprehensive agricultural program for Puerto Rico. USDA, in cooperation with The Commonwealth of Puerto Rico. US Govt. Printing Office, Washington, D.C. 299 pp.

Lucchetti, A., 1948. Proyecto del Suroeste de Puerto Rico. Autoridad de Fuentes Fluviales de Puerto Rico. San Juan, Puerto Rico, Marzo, 1948. 96 pp, con apéndices.

Lugo-López, M. A. and R. Pérez-Escolar, 1959. Hydraulic conductivity of subsoils of Lajas Valley. *J. Agri. Univ. P.R.* 43: 273-277.

Lugo-López, M. A., R. Pérez-Escolar, G. Acevedo and J. Juárez, Jr., 1959. Nature and properties of major soils of Lajas Valley. Bull. 86. Univ. P.R., Agricultural Experiment Station, Río Piedras, Puerto Rico. 60 pp.

Mitchell, Jr., D. S., 1957. Report on land classification of Lajas Valley Irrigation Project. Special Report, Water Resources Authority. Puerto Rico.

Rhoades, J. D. and D. L. Corwin, 1984. Monitoring soil salinity. *Journal of Soil and Water Conservation* 39:172-175.

Richards, L. A. (editor), 1954. Diagnosis and improvement of saline and alkali soils. USDA, United States Salinity Laboratory Staff. Agriculture Handbook No. 60. 160 pp.

Rivera-Santos, L., 1964. Breve historia de un gran proyecto: El Valle de Lajas. p. 5-20. Revista Café. Julio 1964.

Sotomayor-Ramírez, D. and L. Pérez-Alegría, 2012. Nutrient management and sediment source identification in Lajas Valley Agricultural Reserve and Guánica Watershed. Final Report of Project to National Fish and Wildlife Foundation. Performed under contract number 2010-0069-017. 67 pp. w/ appendices.

U.S. Department of Commerce, 1986. Climatological data annual summary – Puerto Rico and Virgin Islands: National Oceanic and Atmospheric Administration. 32: (13), 23 pp.

USDA-NRCS (United States Department of Agriculture-Natural Resources Conservation Service), 2008. Soil Survey of San Germán Area, Puerto Rico, Series 2008. 964 p.

Van der Molen, W. N., 1957. Report on salinity, irrigation and drainage conditions in the Lajas Valley development project, Puerto Rico. Special report, Puerto Rico Department of Agriculture, January.

Willardson, L. S., 1958. Lajas Valley drainage problems. Univ. P.R. Agricultural Experiment Station, Río Piedras, Puerto Rico, Bulletin 143.