Ecología Austral 30:472-483 Diciembre 2020
Asociación Argentina de Ecología
https://doi.org/10.25260/EA.20.30.3.0.1108

A geostatistical method in GIS to estimate the amount of seabird guano accumulated on islands and headlands of Perú

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Abstract. The 'guano of the islands' in Perú is the excrement of cormorants, boobies and pelicans (guano birds), accumulated in large deposits on islands and headlands. This guano is harvested and marketed by the governmental agency AGRORURAL to meet the demands of local organic agriculture. As part of its management and commercialization plans, AGRORURAL estimates the total quantity of guano built-up on the seabird colonies using a volumetric method. The objective of this research was to propose an alternative geostatistical method that uses the volumetric data collection as baseline but incorporates the slope of the terrain and makes estimations of the total amount and distribution of guano using an interpolation grid model in a Geographic Information System (GIS). The data of the slope of the terrain, depth of guano layer, guano density and proportion guano/rock of georeferenced sampling points (taken with a hand-held GPS) on the island/headland surface were used to interpolate the quantity of guano over the entire surface using a raster kriging model, so that each cell contained an estimated quantity of guano. For this study, six guano bird colonies were visited between June 2014 and February 2018. Based on the geostatistical method, the total quantity of guano estimated varied between 10921 t on Isla Mazorca and 26142 t on Isla Guañape Sur. The GIS grid maps showed that the quantity of guano deposits was not uniformly distributed over the island/headland surface. When the guano total quantity estimates based on the geostatistical method were validated with the amount of guano harvested, the estimation error was less than 18%. This error may decrease with the use of a submetric GPS, ground-penetrating radars and augers. An accurate method of guano volume quantification is crucial for budget, logistic and marketing planning of the guano islands and headlands of Perú.

[Keywords: fertilizer, Geographic Information System, guano harvesting, kriging interpolation, marine protected areas, Humboldt Current]

Resumen. Estimación de la cantidad de guano de aves marinas acumulado en islas y puntas de Perú mediante un método geoestadístico en SIG. El 'guano de las islas' en Perú es el excremento de cormoranes, piqueros y pelícanos (aves guaneras), acumulado en grandes depósitos en islas y puntas. Este guano es extraído y comercializado por la agencia gubernamental AGRORURAL para satisfacer las demandas de la agricultura orgánica local. Como parte de sus planes de gestión y comercialización, AGRORURAL estima la cantidad total de guano acumulado en las colonias de aves marinas utilizando un método volumétrico. El objetivo de esta investigación fue proponer un método geoestadístico alternativo que utiliza la recopilación de datos volumétricos como línea de base, pero incorpora la pendiente del terreno y hace estimaciones de la cantidad total y la distribución de guano utilizando un modelo de cuadrícula de interpolación en un Sistema de Información Geográfica (SIG). Los datos de la pendiente del terreno, profundidad de la corteza de guano, la densidad del guano y la proporción de guano/roca de puntos de muestreo georreferenciados (tomados con un GPS de mano) sobre la superficie de la isla/punta fueron usados para interpolar la cantidad de guano total usando un modelo ráster kriging, de tal forma que cada celda contuviera una cantidad estimada de guano. Para este estudio se visitaron seis colonias entre junio de 2014 y febrero de 2018. Según el método geoestadístico, la cantidad total de guano estimada varió entre 10921 t en Isla Mazorca y 26142 t en Isla Guañape Sur. Los mapas de cuadrícula SIG mostraron que la cantidad de depósitos de guano no se distribuía uniformemente sobre la superficie de la isla/punta. Cuando las estimaciones de cantidad total de guano basadas en el método geoestadístico se validaron con la cantidad de guano extraído, el error de estimación fue inferior al 18%. Este error debería disminuir con el uso de un GPS submétrico, un radar de penetración del suelo y barrenas. Un método preciso de cuantificación del volumen de guano en las islas y puntas es crucial para la planificación presupuestaria, logística y de mercadeo del guano de las islas guaneras y puntas del Perú.

[Palabras clave: fertilizante, Sistema de Información Geográfica, extracción de guano, interpolación kriging, áreas marinas protegidas, Corriente de Humboldt]

Editor asociado: Pablo Villagra
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Recibido: 17 de Febrero de 2020
Aceptado: 26 de Agosto de 2020

Introduction

The traditional term 'guano of the islands' in Perú refers to the substrate accumulated in large quantities on the desert islands and headlands. This guano is a product of the excrement of three species of seabirds, endemic to the Humboldt Current: the Guanay cormorant (*Phalacrocorax bougainvillii*), the Peruvian booby (*Sula variegata*) and the Peruvian pelican (*Pelecanus thagus*) (Coker 1919; Murphy 1936; Hutchinson 1950). It has been harvested in Perú since 1843 to be used as the best organic fertilizer in the world due to its high concentrations of nutrients compared with other natural fertilizers (Hutchinson 1950; Cushman 2013). In Perú, the guano is a renewable resource that is still harvested to suit the national demand for organic agriculture for products such as coffee, cocoa, quinoa and kiwicha (amaranth) (AGRORURAL 2019a). The governmental agency Programa de Desarrollo Productivo Agrario Rural (AGRORURAL) is in charge of the harvesting, processing and commercialization of guano from the islands. At present, the annual amount of guano harvested from the islands is ~27000 metric tons (t) (AGRORURAL 2019b), 74% of which is destined for national agriculture, and the remainder available for export (AGRORURAL 2018). To adequately comply with the annual management and commercialization plans, it is important first to establish the quantity of guano and distribution of the deposits on the harvesting sites.

The estimation of the volume of guano on the islands of Perú was of special interest since the beginning of its commercial harvesting due to its high economic value (Hutchinson 1950). In 1853, a team of researchers led by the French engineer Carlos Faraguet estimated a surplus of 11.4 million metric tons on the Chincha islands in central Perú (Piérola 1854), a quantity that was completely harvested by the end of 1871 (Villacorta 2003). With the creation of the Compañía Administradora del Guano (Guano Administration Company) in 1909, new methods for the calculation of the volume of guano on the islands were developed and implemented. The product of the excretion rate per bird and the total number of birds was used to calculate the amount of guano deposited during different time intervals (Hutchinson 1950; Schneider and Duffy 1988; Jahncke and Rivas 1998). Currently, AGRORURAL uses the volumetric method to estimate the quantity of guano (AGRORURAL 2019b), which consists in sampling several points on the colony surface and measure the density and depth of the guano crust. The mean of these measurements is then multiplied by the proportion of the area of the colony containing guano to obtain the total amount. This method assumes that all locations surveyed are flat, when in fact the relief of each island and headland is different. For this reason, the slope of the terrain must be taken into account for more precise estimations.

An accurate estimation of the quantity of guano is necessary to plan harvesting campaigns. It allows the adequate selection of the colony to be harvested, the number of guano workers to be hired and the duration of harvesting (AGRORURAL 2019b). Similarly, the spatial patterns of guano accumulation on an island or headland allows the identification of critical zones where guano harvesting activities may cause adverse effects on the seabirds (García et al. 2016; Carrasco and Meza 2017). The objective of this research was to evaluate an alternative method of quantifying guano based on a geostatistical model that incorporates the slope of the terrain and a grid configuration in a Geographic Information System (GIS). Six guano bird colonies were visited in Perú between 2014 and 2018 to 1) compare the depth of the guano layer to bedrock, guano density and total amount of guano deposited across the study sites, 2) generate raster or grid maps of the spatial distribution of the guano volumes at each location, and 3) validate the estimates from the geostatistical method with the harvesting quantities obtained at certain locations. We hypothesized that the calculations of the amount of guano at each location using the geostatistical method are similar to the quantities of guano harvested.

Materials and Methods

Period and study sites

The study was conducted between June 2014 and February 2018 at six locations within the Marine Protected Area 'Reserva Nacional Sistema de Islas, Islotes y Puntas Guaneras' (RNSIIPG): Isla Guañape Sur, Isla Mazorca, Isla Asia, Isla Chincha Norte, Punta San Juan and Punta Coles (Figure 1; Table 1). The permits to work in these sites were granted by the Servicio Nacional de Áreas Naturales Protegidas por el Estado (SERNANP): R.J N° 011-2016-SERNANP-RNSIIPG, R.J N°022-

Table 1. Date of evaluation and location of the islands and headlands visited in this study for data collection. The number of sampling points per study site, the total area of the island in hectares and the sampled area are also shown.

Tabla 1. Fecha de evaluación y ubicación de las islas y puntas visitadas en este estudio para la colecta de datos. Se muestra también el número de puntos de muestreo por localidad de estudio, el área total de la isla en hectáreas y el área muestreada.

Study site	Sampling date	UTM coordinates: zone (XY)	Number of sampling points	Total area (ha)[a]	Sampled area (ha)[b]
Isla Guañape Sur	15 Jun 2014	17S (724133, 9052634)	361	22.0	17.3
Isla Mazorca	20-21 May 2016	18S (200461, 8740173)	98	8.3	8.3
Isla Asia	22 May 2017	18S (323875, 8585235)	114	58.6	48.9
Isla Chincha Norte	27-28 Feb 2018	18S (349457, 8492919)	216	49.0	49.0
Punta San Juan	10-11 Jun 2016	18S (479613, 8301236)	150	52.1	27.7
Punta Coles	28-29 Jun 2016	19S (248275, 8041351)	113	155.6	26.0

[a] Surface area of the entire guano island or headland.
[b] Surface that was sampled and contains accumulated harvestable guano. In general, guano birds occupy only a portion of the total area of the island or headland, as in the case of Punta San Juan, Punta Coles and Isla Asia.
[a] Superficie de toda la isla o punta guanera.
[b] Superficie que se muestreó y contiene guano acumulado extraíble. Por lo general, las aves guaneras ocupan solo una porción del área total de la isla o punta, como en el caso de Punta San Juan, Punta Coles e Isla Asia.

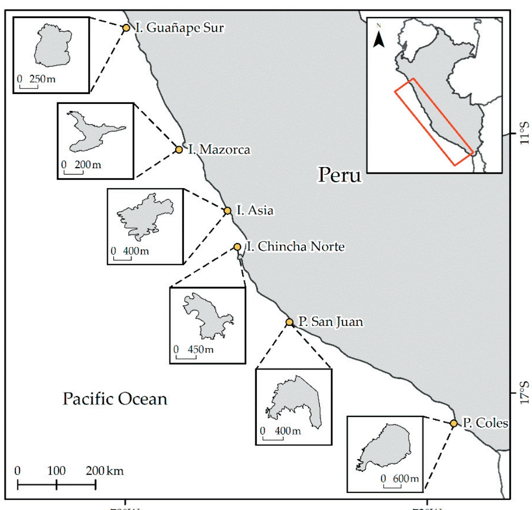

Figure 1. Location of the guano islands and headlands monitored in this study (I=Island, P=headland).

Figura 1. Ubicación de islas y puntas guaneras monitoreadas en este estudio (I=Isla, P=Punta).

2016-SERNANP-RNSIIPG. Most of the study sites were free of breeding guano birds during our visits, and therefore the disturbance was kept minimal. Also, the sites were in the immediate guano harvesting plans of AGRORURAL.

Data collection

It is important to note that the quantity of guano estimated in this study refers to 'raw guano' (i.e., without sieving), which contains the remains of other materials such as feathers, small stones, bird carcasses, etc. The calculation of the total quantity of guano accumulated was based on a sampling of points over the island/headland surface. Before the fieldwork, georeferenced regular-distributed points over most part of the island or headland surface were uploaded to a hand-held GPS. The distance between points varied across locations between 17 and 47 m. The larger the area sampled on each island or headland, the longer the distance between points. In sectors where guano birds were present, these pre-established points were not used to sample; instead, random sampling had to be done in areas outside the visual range of the birds to avoid disturbance. The sampling points were then used to interpolate the total amount of guano on the entire surface of the island/headland. In the field, the following variables were recorded at each sampling point.

Coordinates X and Y. The coordinates were recorded with a Garmin GPSmap 78s GPS in the UTM (Universal Transverse Mercator) coordinate system, zone 17S, 18S or 19S, and datum WGS 1984. The GPS had an average navigation error of at least 3 m. Because of the accuracy limitations of the GPS, we do not attempt to include the altitude records in the analysis.

Slope of the terrain. A clinometer (Redline Professional 800 mm multifunction level with an accuracy of ±1°) mounted on a 1-m flat ruler was placed on the terrain following the direction of the most common slope in the vicinity of the sampling point. The slope angle relative to the horizontal was corrected at all times using a bubble level. The terrain was usually irregular in most of the study sites, so obtaining an accurate measurement of the slope was challenging. To decrease the measurement error, we set the clinometer at three different parallel sites close to sampling point and averaged all these values to obtain one record. The clinometer at all sampling points was always set on the ground following the direction of the slope.

Depth of the guano layer. A 150 cm long t-shaped iron rod was sunk vertically in the guano crust until reaching the deepest point, which was identified by contact with the bedrock. Once the maximum depth was found, the rod was grasped at ground-level and removed from the guano. The length of the portion that had been buried was measured with a measuring tape with an accuracy of ±1 mm. This step was repeated for two additional points around the sampling point within a circle of approximately 1.5 m radius. The final guano depth for that sampling point was the mean of the three measurements.

Guano density. A small portion of the ground at each sampling point was excavated to obtain a surface guano sample. This sample was pulverized *in situ* as much as possible and the excess of feathers and stones was cleaned. The sample was poured and compacted into in an aluminum can with a volume of 10 cm^3. Once the container was tightly packed, the guano sample was weighed on a Valtox® electronic balance with an accuracy of ±1 g. The guano density was then determined as the ratio between the weight of the guano sample and its volume.

Proportion of guano/rock. The guano was not evenly distributed over the surface of the island/headland. There were zones where the deposits of guano were interrupted by rocky areas without guano. We excluded these areas from our calculations of the amount of guano at each location by determining an approximate proportion between guano and rock at each sampling point. These proportions were determined in 0.25 ratio increments from 0 to 1 by direct inspection in a circle of 3-m radius around the sampling point.

Analysis of data

Estimating the quantity of guano using the geostatistical method. Data analysis was performed in a Geographic Information System using ArcGIS 10.5 software (Esri Inc 2016). The flowchart with the procedures and products used in the geostatistical method is depicted in Figure 2. The shapefiles (polygons) of the total area of each island and headland were drawn using both equidistant georeferenced points (spaced at <10 m) taken along the perimeter of each location, and high-quality georeferenced images obtained from Google Earth Pro 7.3 software (Google LLC 2019). The attributes of the sampling points (coordinates XY, slope of the terrain, depth of guano layer, guano density and proportion guano/rock) were entered in an event table in Excel, imported to ArcGIS as shapefiles and projected into the UTM coordinate system (Figure 3a, 3b). Because the sampling points were used to interpolate the quantity of guano over the entire surface of the island or headland, it was necessary to calculate the cell size of the interpolation grid, according to the method. The cell size (length of each side of an individual cell) was determined by calculating the mean of the distances between the closest sampling points using the Average Nearest Neighbor tool in ArcGIS. Once it was defined for each location (Table 2), the quantity of guano (QG) was calculated per sampling point as if it covered an entire cell area according to the equation (1).

$$QG = DG * \cos(SA) * GD * CS^2 * PGR * 10^{-3} \quad (1)$$

where:

QG: quantity of guano (t)

DG: depth of guano (m)

SA: slope angle (sexagesimal degrees)

GD: guano density (kg/m^3)

CS: cell size (m)

PGR: proportion of guano/rock

For the interpolation, a kriging estimation within the ArcGIS Spatial Analyst toolbox was performed. Kriging is an advanced geostatistical procedure that generates a surface estimated from a set of scattered points with z-values; in the case of this study, these z-values corresponded to the quantity of guano inside a cell that had as its epicenter the sampling point (Yao et al. 2013). Unlike the inverse distance weighing (another geostatistical tool), kriging uses the weighed sums of the adjacent sampled points which is less biased. The cell size was calculated as explained above. The method used was ordinary kriging with a spherical semivariogram model because the autocorrelations with the distances between consecutive points were accurately represented. The kriging interpolation

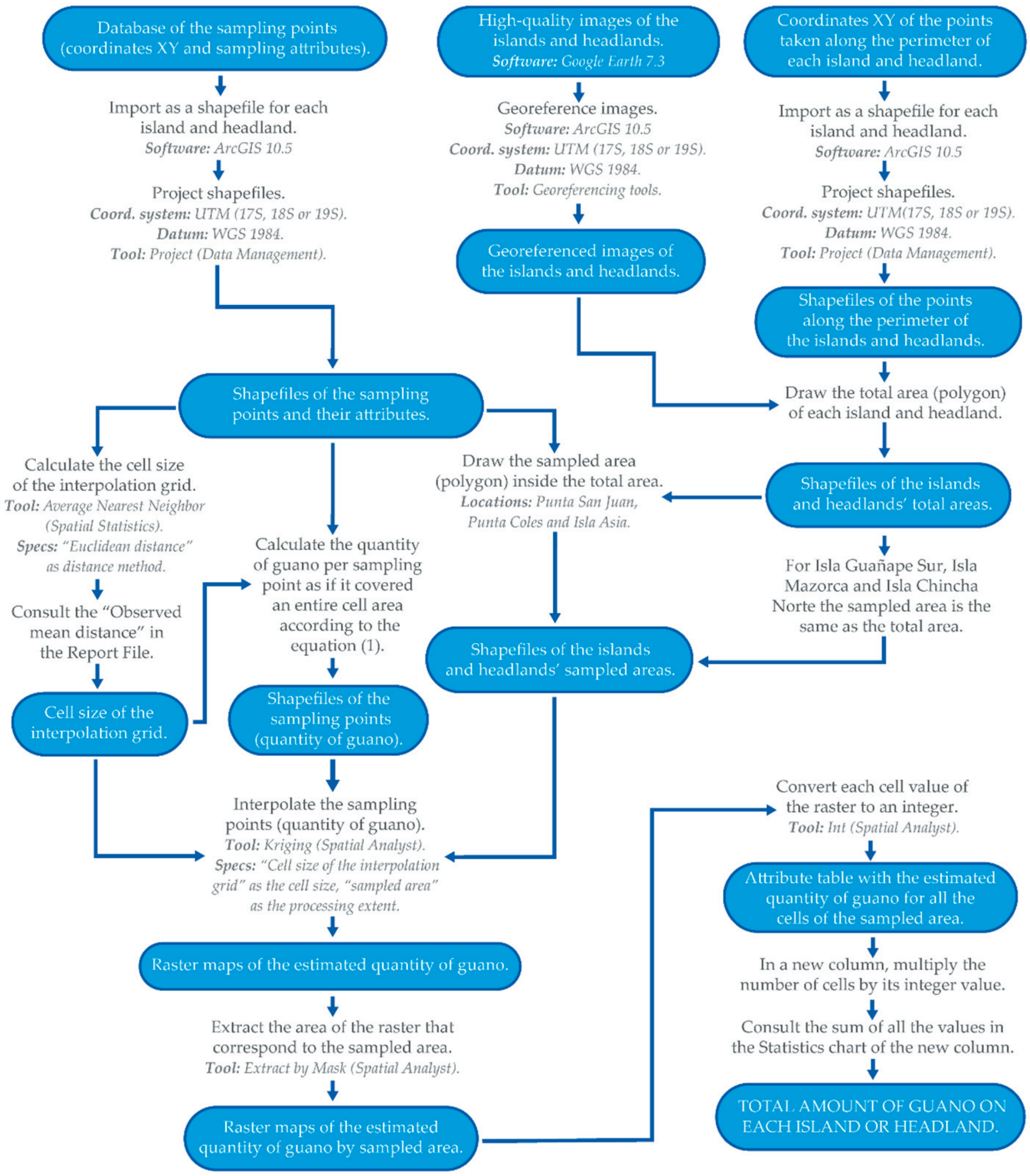

Figure 2. Flowchart for the calculation of the total amount of guano following the geostatistical method in ArcGIS. The boxes indicate the products, whereas the text outside the boxes represents the processes.

Figura 2. Diagrama de flujo para el cálculo de la cantidad total de guano siguiendo el método geoestadístico en ArcGIS. Los recuadros indican los productos, mientras que los textos fuera de los cuadros representan los procesos.

procedure generated raster maps where each interpolated cell on the entire sampling surface of the island and headland contained an estimated quantity of guano (Figure 3c, 3d). Finally, the total amount of guano on each island or headland was calculated by the sum of the values estimated in each cell. The entire sampling dataset for Isla Guañape Sur was collected by the staff of AGRORURAL and provided to the corresponding author to calculate the guano quantities according to the geostatistical survey method.

Raster mapping. For better visualization, the raster maps of the total quantity of guano generated by the kriging model were smoothed using a cell size of 2.3 m for most locations (Figure 3e, 3f; Figure 4).

Quantities of guano harvested. The most reliable validation for the results of the geostatistical method was to contrast them against the quantities of guano harvested immediately after the sampling. In some study sites, the guano was harvested weeks

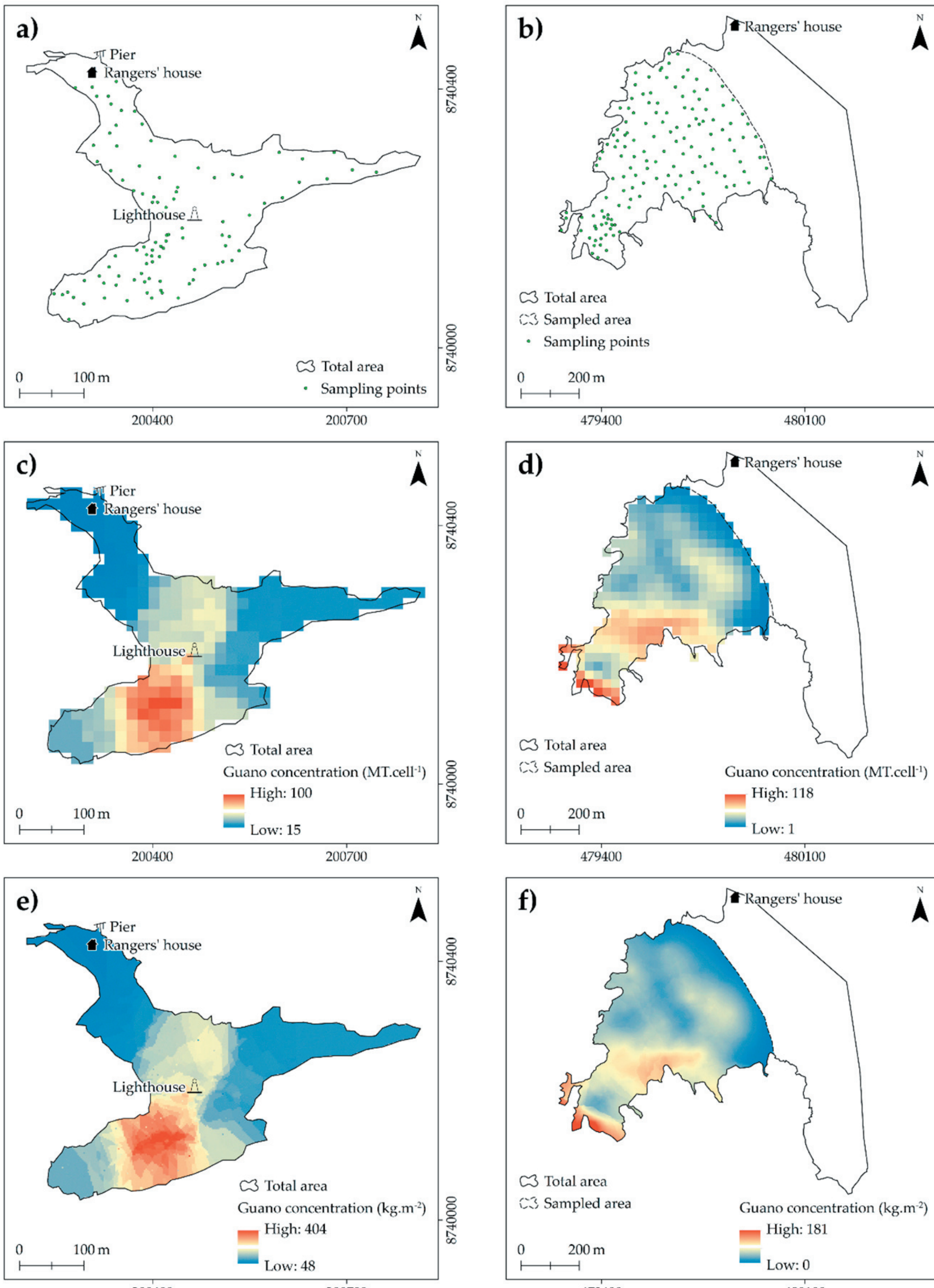

Figure 3. Examples of the spatial distribution of the sampling points, rasterization by kriging interpolation and smoothing of the grid on Isla Mazorca (a, c, e) and Punta San Juan (b, d, f).

Figura 3. Ejemplos de la distribución espacial de puntos de muestreo, rasterización e interpolación de kriging y suavizado de la cuadrícula en Isla Mazorca (a, c, e) y Punta San Juan (b, d, f).

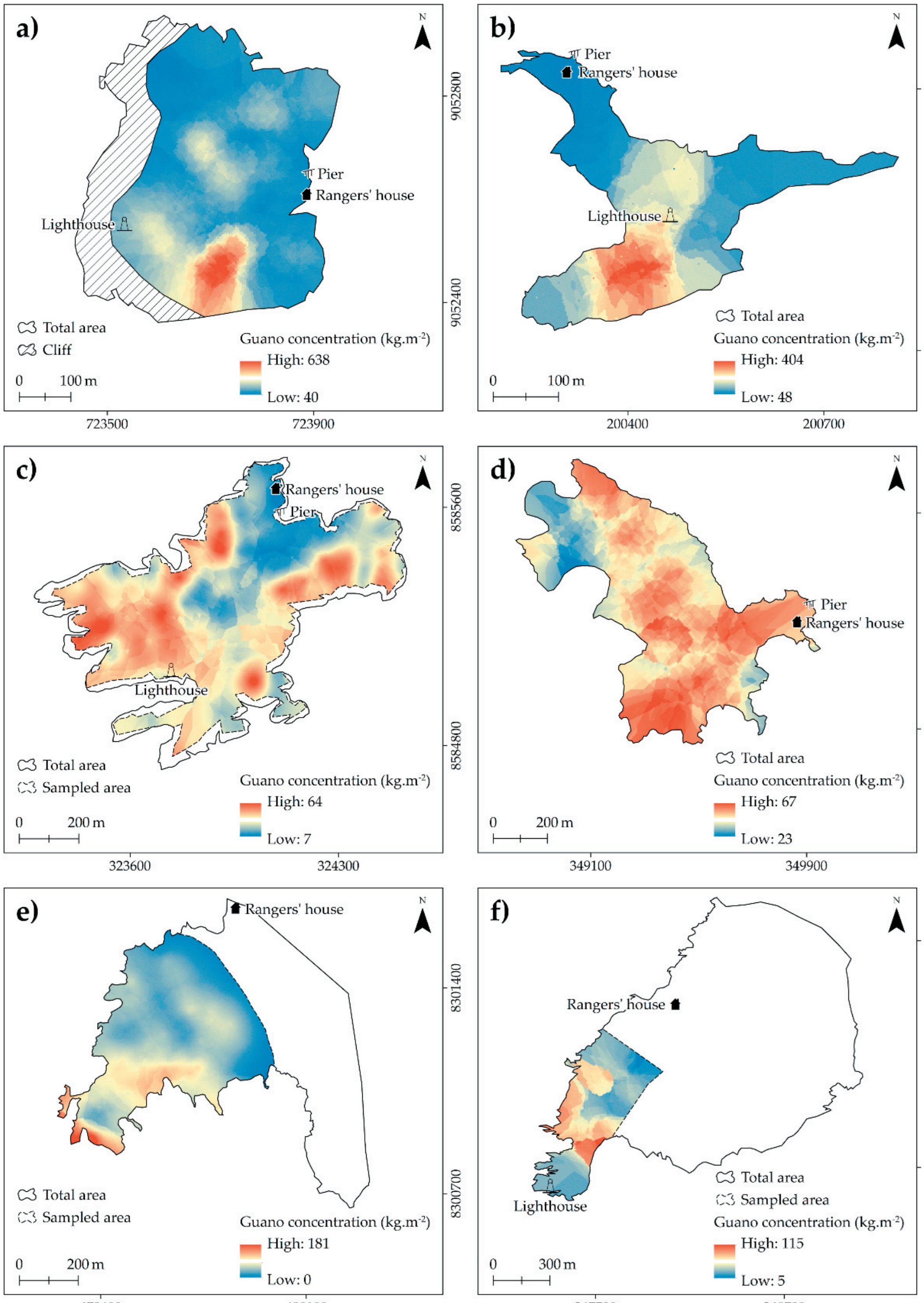

Figure 4. Spatial distribution of guano concentration (expressed in kg/m^2) found in the six locations: a) Isla Guañape Sur, b) Isla Mazorca, c) Isla Asia, d) Isla Chincha Norte, e) Punta San Juan and f) Punta Coles. The striped area indicates cliffs and the white area indicates buffer zones without guano.

Figura 4. Distribución espacial de la concentración de guano (expresada en kg/m^2) encontrada en las seis localidades: a) Isla Guañape Sur, b) Isla Mazorca, c) Isla Asia, d) Isla Chincha Norte, e) Punta San Juan y f) Punta Coles. El área rayada indica acantilados y el área en blanco indica zonas de amortiguamiento sin guano.

or months after data collection, which allowed for comparisons. The harvesting data for each location were obtained from the Annual Management Plans of AGRORURAL (AGRORURAL 2019b).

Statistical analyses. The comparisons of guano density and depth of the guano crust between locations were performed using General Linear Models (GLMs). All tests were performed using the statistical software SAS 9.4 (SAS Institute 2016). Means are expressed as ±1 standard deviation. The differences were considered significant when P<0.05.

Results

Assessment of the total quantity of guano with the geostatistical method

The depth of the guano layer varied significantly between locations (GLM, $F_{6,1027}$=38.9, P<0.0001) with mean values between 0.07 and 0.28 m (Table 2). The guano density was also significantly different between locations (GLM, $F_{6,1027}$=71.53, P<0.0001), ranging from 597 to 747 kg/m^3 (Table 2). According to the geostatistical method, the total quantity of guano estimated by interpolation (cell sizes between 17 and 47 m) (Table 2) varied across the study sites between 10921 t on Isla Mazorca and 26142 t on Isla Guañape Sur (Table 2).

Raster maps and spatial distribution of the guano deposits

The guano at each of the locations was not uniformly distributed; some areas had higher concentrations of guano than others (Figure 4). The empty areas within each location represent buffer zones (Punta San Juan, Punta Coles and Isla Asia) where guano was not found; therefore, sampling was not necessary. The southern zone adjacent to the lighthouse on Isla Guañape Sur contained the largest quantity of guano (Figure 4a). On Isla Mazorca, the largest quantity of guano occurred in the central zone of the island, mainly in the southern area near the lighthouse (Figure 4b). Isla Asia had an almost uniform distribution of guano, except for the central and northeastern part of the island (Figure 4c). On Isla Chincha Norte, the highest concentrations of guano were found in the south and north of the island (Figure 4d). The highest concentrations of guano at Punta San Juan were found in the southwestern zone (Figure 4e), whereas at Punta Coles, the southeastern and, to a lesser extent the northwestern area, had the highest guano concentrations (Figure 4f).

Validation of the geostatistical method

When the quantities of guano estimated by the geostatistical method were compared with those harvested, between 5 and 18% of error were found (Table 3). Unfortunately, the sample size was too small to allow a reliable calculation of any statistical test and the comparisons must be interpreted with caution.

Discussion

This study is a first attempt to estimate the amount of seabird guano deposits in Perú using a geostatistical approach. Previous methods did not incorporate the topography of the terrain nor presented maps of the spatial distribution of the quantity of guano on the islands/headlands. The nature of the data and methods used were easily incorporated into a GIS format, and therefore, mapping and quantitative analysis of the amount of guano on the study sites were possible with an error of 5-18% when contrasted with the

Table 2. Cell size and total quantity of guano according to the geostatistical method for each of the study sites. The mean ± 1 SD of the guano density, depth of the guano layer and guano/rock ratio from the sampling points for each location are also reported.

Tabla 2. Tamaño de celda y cantidad total de guano según el método geoestadístico para cada una de las localidades de estudio. Se muestra también los promedios ± 1 DS de la densidad de guano, profundidad de la corteza de guano y proporción guano/roca a partir de los puntos de muestreo para cada localidad

Study site	Cell size (m)	Geostatistical total quantity of guano (t)	Guano density (kg/m^3)	Depth of guano layer (m)	Proportion of guano/rock
Isla Guañape Sur	20.0	26142	747±62	0.28±0.29	0.78
Isla Mazorca	17.1	10921	704±75	0.28±0.21	0.72±0.21
Isla Asia	46.8	16419	675±270	0.07±0.05	0.58±0.29
Isla Chincha Norte	45.0	24040	597±127	0.09±0.04	0.87±0.21
Punta San Juan	30.1	11048	663±86	0.07±0.07	0.74±0.43
Punta Coles	24.9	11492	707±248	0.07±0.09	0.9±0.28

Table 3. Comparison between the values of the total quantity of raw guano (without sieving) estimated with the geostatistical method (geostatistical quantity) and the quantities of crude guano harvested in the most recent harvesting event. The % error is calculated as (geostatistical quantity-quantity collected)/quantity collected x 100. The date of the last guano harvesting prior to sampling is also shown.

Tabla 3. Comparación entre los valores de la cantidad total de guano bruto (sin tamizar) estimado con el método geoestadístico (cantidad geoestadística) y las cantidades de guano bruto extraídas en la última campaña de extracción. El % de error se calcula como (cantidad geoestadística-cantidad extraída)/cantidad extraída x 100. También se presenta la fecha en que se realizó la última extracción de guano previa al muestreo.

Area of study	Month and year of sampling	Geostatistical total quantity of guano (t)	Date of the onset of the most recent harvesting	Quantity collected in the most recent harvesting (t)	Error (%)
Isla Guañape Sur	June 2014	26142	April 2015	23861	+9.6
Isla Mazorca	May 2016	10921	May 2016	10300	+6.0
Isla Asia	May 2017	16419	May 2017	13911	+18.0
Isla Chincha Norte	February 2018	24040	February 2018	25271*	-4.9

* 1000 t of guano had already been harvested on Isla Chincha Norte when the sampling began (AGRORURAL, personal communication, June 14, 2018), so this quantity has been subtracted from the total amount harvested.
* 1000 t de guano ya habían sido extraídos en Isla Chincha Norte al empezar el muestreo (AGRORURAL, comunicación personal, 14 junio 2018), por lo que esta cantidad ha sido restada del total extraído.

amount of guano harvested. Nevertheless, fieldwork techniques for data collection can be substantially improved for future guano surveys. First, to georeference the sampling points, a conventional GPS navigator with a minimum of 3-m positional error was used. A submetric GPS would significantly reduce this error to centimeters and further provide an accurate measure of the altitude at each sampling point. Thus, 3D surface maps and volume of the guano layers could be created using raster models such as triangular irregular networks (Zhang et al. 2008) or digital elevation models in GIS (Smith et al. 2006). Second, the guano density was measured *in situ* with an electronic balance and a container with a known volume. Windy conditions or a lack of complete horizontally of the balance may influence the accuracy of weighing. To obtain better measurements, samples of guano can be stored and packed for subsequent analysis in a closed, controlled environment. The density also varies along the column of the guano deposit because the guano close to the bedrock has a larger content of water. It is recommended to sample and check the guano properties with a soil probe, particularly in deep layers of guano. If there are differences in color or texture, samples at the bottom and top of the column should be taken and stored for subsequent measurements of guano density. Third, other techniques such as a ground-penetrating radar used in geosciences and agriculture to map depth of glaciers, snow or soils can also be applied to measuring the depth of the guano layer (Collins et al. 1989; Pälli et al. 2002; Sucre et al. 2011) instead of an iron rod. The measurement of the depth does not appear to have major problems when the guano layers are >30 cm, but when the layers are very thin (<2 cm), the measurements became increasingly difficult, particularly when the guano was hard. Fourth, the slope of the terrain can vary greatly between different areas of the island/headland, and slope measurements can be challenging in very irregular terrains, particularly because the guano bird nests are unevenly distributed over the surface leading to a difficult positioning of the clinometer. As recommended above, a finer-scale topographic study (using submetric high resolution GPS or theodolites) could accurately measure elevation and generate 3D maps of all locations in such a way that the slopes would no longer need to be measured at each fixed sampling point. Fifth, the values of rocky areas for each island/headland are fixed and could be excluded from the geostatistical analysis once they can be identified and measured in topographic maps. Thus, it would be unnecessary to estimate a coarse ratio of guano/rock for each sampling point.

There are several factors that would influence the guano quantity estimation error. For instance, the time elapsed between the sampling and the guano harvesting dates would lead to the underestimation of the amount of guano because the guano birds would produce more guano during this interval. Likewise, in some cases the entire potential area of guano cannot be sampled due to the presence of guano birds in some sectors, which would underestimate the amount of guano to be harvested. On the other hand, the guano may not be completely collected from the area that was sampled because of the presence of birds, leading to an overestimation of the quantity of guano. It is recommended to conduct the sampling and measurements only days before the harvesting starts and to make comparisons by sectors within the same locality to properly validate the geostatistical method.

Perú is the only country in the world that harvests significant quantities of seabird guano for commercial use (Cushman 2005), which prevents comparisons with other regions on field methods and geostatistical analyses for the quantification of the volume of guano deposits. There have been some applications of geostatistical approaches in GIS to map and estimate the volume of ice sheets in Antarctica (Lythe et al. 2001) and sediments in India (Nageswara et al. 2008). Mapping the depth of soil to bedrock is frequently used in agricultural sciences, particularly kriging interpolation because of its accuracy when compared to other methods (Liu et al. 2006; Simeoni et al. 2009; Chen et al. 2015). The main advantages of kriging are that it incorporates the spatial correlation of the data and estimates the average concentration in blocks, which will determine which of the areas requires more attention of management (Largueche 2006). These two last criteria were also found in our study, and thus, the use of kriging interpolation for mapping and estimation of guano quantities are not only comparable to other studies, but also suitable for field application of seabird guano harvesting and management in Perú.

The quantification and distribution maps of guano deposits are of crucial importance for the management and conservation of the guano islands and headlands of Perú. These maps not only allow AGRORURAL to plan adequately and optimize harvesting logistics with the appropriate number of workers, materials, transportation, maximum harvesting time interval and budgets, but also directly influence decision-making by SERNANP with regard to the start and end of the harvesting season and better zoning aimed at minimizing the disturbance to local marine fauna. In the latter case, for example, areas with low concentrations of guano, but with a high concentration of threatened species such as Humboldt penguins (*Spheniscus humboldti*) or Peruvian diving petrels (*Pelecanoides garnotii*), could be excluded from harvesting activities. On the other hand, identifying areas with high concentrations of guano could serve to define where guano harvesting activities could begin.

Conclusions

We provided a geostatistical approach using kriging interpolation in GIS to map guano concentrations and to calculate the total amount of guano on the islands and walled-off headlands of Perú with an error of 5-18%. This error may be substantially reduced with the use of more precise instruments for data collection such as submetric GPS, ground-penetrating radars and augers or soil probes, which would provide accurate measurements of sampling location, altitude, depth of guano layers and density. Better estimations of the guano volume on Peruvian seabird colonies is crucial to optimize harvesting and to plan adequate management.

Acknowledgements. This study was carried out through the FONDECYT 2015-152 Project "Implementación de Nuevas Técnicas para el Monitoreo Biológico de las Aves Guaneras en el Perú", funded by the Fondo Nacional de Desarrollo Científico y Tecnológico (FONDECYT) and co-funded by Universidad Científica del Sur, Lima-Perú. The authors gratefully acknowledge AGRORURAL and SERNANP for the permits granted for the realization of this study within the protected natural area RNSIIPG. Many thanks to J. Figueroa and M. Roca for their time in answering several questions., and to C. Burga, R. Quispe, C. Cepeda, C. Irigoin and M. Gonzales for their willingness to help. To P. Medina and R. Moreno for helping in the field work at Punta San Juan, and to M. Cardeña and the members of the Punta San Juan Program - Center for Environmental Sustainability - Universidad Peruana Cayetano Heredia (UPCH), for the kindness and hospitality. To V. Ropón, I. Balbín, J. Ramírez, L. Valdivia, C. Flores, M. García, D. Acosta, D. Gonzales and D. Ardiles for their help with total commitment in the field work at Isla Asia. To V. Adrianzén, M. Díaz and M. Quispe for their support in the field work at Punta Coles. To V. Chávez and M. Llica for their hospitality and help in the field work at Isla Mazorca. Finally, a special thanks to C. Símbala for the design of the flowchart and other figures.

References

AGRORURAL. 2018. Plan Anual de Comercialización 2018 del Programa de Desarrollo Productivo Agrario Rural - AGRORURAL. Resolución Directoral Ejecutiva N° 124-2018-MINAGRI-DVDIAR-AGRO RURAL-DE. Ministerio de Agricultura y Riego, Lima, Perú. URL: tinyurl.com/y6k4enpc.

AGRORURAL. 2019a. Plan Anual de Comercialización de Guano de Isla para el Ejercicio Fiscal 2019 con eficacia anticipada al 2 de enero de 2019, propuesto por la Dirección de Abonos del Programa de Desarrollo Productivo Agrario Rural - AGRORURAL. Resolución Directoral Ejecutiva N° 222-2019-MINAGRI-DVDIAR-AGRO RURAL-DE. Ministerio de Agricultura y Riego, Lima, Perú. URL: tinyurl.com/y4qefops.

AGRORURAL. 2019b. Plan Anual de Extracción para el Ejercicio Fiscal 2019 propuesto por la Dirección de Abonos del Programa de Desarrollo Productivo Agrario Rural – AGRORURAL. Resolución Directoral Ejecutiva N° 099-2019-MINAGRI-DVDIAR-AGRO RURAL-DE. Ministerio de Agricultura y Riego, Lima, Perú. URL: tinyurl.com/y2wgwpaj.

Carrasco, L. D., and M. A. Meza. 2017. Impacto de la Extracción del Guano sobre las Poblaciones de Aves Guaneras en algunas Islas y Puntas Guaneras de la Costa Peruana. Tesis de pregrado. Universidad Nacional Agraria La Molina, Lima, Perú. Pp. 138. URL: tinyurl.com/y2a5j5la.

Chen, Ch., K. Hu, H. Li, A. Yun, and B. Li. 2015. Three-Dimensional Mapping of Soil Organic Carbon by Combining Kriging Method with Profile Depth Function. PLOS ONE **10**(6):e0129038. https://doi.org/10.1371/journal.pone.0129038.

Coker, R. E. 1919. Habits and economic relations of the guano birds of Perú. Proceedings of the US National Museum **56**(2298):449-511. https://doi.org/10.5479/si.00963801.56-2298.449.

Collins, M. E., J. A. Doolittle, and R. V. Rourke. 1989. Mapping Depth to Bedrock on a Glaciated Landscape with Ground-Penetrating Radar. Soil Sci Soc Am J **53**:1806-1812. https://doi.org/10.2136/sssaj1989.03615995005300060032x.

Cushman, G. T. 2005. The Most Valuable Birds in the World: International Conservation Science and the Revival of Perú's Guano Industry, 1909-1965. Environmental History **10**(3):477-509. https://doi.org/10.1093/envhis/10.3.477.

Cushman, G. T. 2013. Guano and the Opening of the Pacific World: A Global Ecological History. First edition. Cambridge University Press, New York, USA. https://doi.org/10.1017/CBO9781139047470.

Esri Inc. 2016. ArcGIS Desktop (version 10.5.0.6491) [Software]. Environmental Systems Research Institute, Redlands, California, USA.

García, M., M. Valverde, and J. Iannacone. 2016. Dinámica Poblacional de las Aves Guaneras en la Campaña de Recolección de Guano de la Isla Guañape Norte, Perú, 2007-2009 y 2014. The Biologist (Lima) **14**(2):307-326.

Google LLC. 2019. Google Earth Pro (version 7.3.2.5776) [Software]. Google LLC, Mountain View, California, USA.

Hutchinson, G. E. 1950. The Biogeochemistry of Vertebrate Excretion. The American Museum of Natural History, New York, USA. https://doi.org/10.1097/00010694-195010000-00010.

Jahncke, J., and C. Rivas. 1998. Recuperación, erosión y retención de otolitos en bolos de Guanay: ¿son los bolos realmente buenos indicadores de la dieta? Boletín Instituto del Mar del Perú **17**(1-2):35-45.

Largueche, F.-Z. B. 2006. Estimating Soil Contamination with Kriging Interpolation Method. American Journal of Applied Sciences **3**(6):1894-1898. https://doi.org/10.3844/ajassp.2006.1894.1898.

Liu, T.-L., K.-W. Juang, and D.-Y Lee. 2006. Interpolating Soil Properties Using Kriging Combined with Categorical Information of Soil Maps. Soil Sci Soc Am J **70**:1200-1209. https://doi.org/10.2136/sssaj2005.0126.

Lythe, M. B., D. G. Vaughan, and the BEDMAP Consortium. 2001. BEDMAP: A new ice thickness and subglacial topographic model of Antarctica. Journal of Geophysical Research **106**(B6):11335-11351. https://doi.org/10.1029/2000JB900449.

Murphy, R. C. 1936. Oceanic birds of South America: a study of species of the related coasts and seas, including the American quadrant of Antarctica, based upon the Brewster-Sanford collection in the American Museum of Natural History. The Macmillan Company / The American Museum of Natural History, New York, USA. https://doi.org/10.5962/bhl.title.11916.

Nageswara Rao, K., Ch. Udaya Bhaskara Rao, and T. Venkateswara Rao. 2008. Estimation of sediment volume through Geophysical and GIS analyses - A case study of the red sand deposit along Visakhapatnam Coast. Journal of Indian Geophysical Union **12**(1):23-30. https://doi.org/10.1007/s11852-009-0042-2.

Pälli, A., J. C. Kohler, E. Isaksson, J. C. Moore, J. F. Pinglot, V. A. Pohjola, and H. Samuelsson. 2002. Spatial and temporal variability of snow accumulation using ground-penetrating radar and ice cores on a Svalbard glacier. Journal of Glaciology **48**(162):417-424. https://doi.org/10.3189/172756502781831205.

Piérola, N. 1854. Informes sobre la existencia de huano en las Islas de Chincha presentados por la Comisión nombrada por el Gobierno Peruano, con los planos levantados por la misma Comisión. El Heraldo, Lima, Perú.

SAS Institute. 2016. SAS: Statistical Analysis System (version 9.4) [Software]. SAS Institute, Cary, North Carolina, USA.

Schneider, D., and D. C. Duffy. 1988. Historical variation in guano production from the Peruvian and Benguela upwelling ecosystems. Climatic Change **13**:309-316. https://doi.org/10.1007/BF00139812.

Simeoni, M. A., P. D. Galloway, A. J. O´Neil, and R. J. Gilkes. 2009. A procedure for mapping the depth to the texture contrast horizon of duplex soils in south-western Australia using ground penetrating radar, GPS and kriging. Australian Journal of Soil Research **47**:613-621. https://doi.org/10.1071/SR08241.

Smith, M. J., J. Rose, and S. Booth. 2006. Geomorphological mapping of glacial landforms from remotely sensed data: An evaluation of the principal data sources and an assessment of their quality. Geomorphology **76**(1-2):148-165. https://doi.org/10.1016/j.geomorph.2005.11.001.

Sucre, E. B., J. W. Tuttle, and T. R. Fox. 2011. The Use of Ground-Penetrating Radar to Accurately Estimate Soil Depth in Rocky Forest Soils. Forest Science **57**(1):59-66.

Villacorta, F. 2003. Antonio Raimondi: Informes y polémicas sobre el guano y el salitre (Perú 1854-1877). Fondo Editorial Universidad Nacional Mayor de San Marcos, Lima, Perú.

Yao, X., B. Fu, Y. Lü, F. Sun, S. Wang, and M. Liu. 2013. Comparison of Four Spatial Interpolation Methods for Estimating Soil Moisture in a Complex Terrain Catchment. PLOS ONE **8**(1):e54660. https://doi.org/10.1371/journal.pone.0054660.

Zhang, Q.-F., L. Wang, and F.-Q. Wu. 2008. GIS-Based Assessment of Soil Erosion at Nihe Gou Catchment. Agricultural Sciences in China **7**(6):746-753. https://doi.org/10.1016/S1671-2927(08)60110-8.