

## MODEL-BASED GEOMORPHOLOGY OF MALPELO ISLAND AND SPATIAL DISTRIBUTION OF BREEDING SEABIRDS

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### ABSTRACT

The spatial distribution of seabird nests present on Malpelo Island, the main characteristics of the island's topography, and the types of substratum available for nesting were addressed using a Digital Elevation Model (DEM). The model is based on data from remote sensors (satellite images, aerial photography and panoramic photography), and from field data processed through a geographical information system. The nests of *Sula granti* prevail on the surfaces of Malpelo Island and neighboring islets, while those of the remaining species (*S. sula*, *Creagrus furcatus*, *Anous stolidus*, *A. minutus* and *Gygis alba*) are spatially restricted to the cliff margins and to crevices or caverns at different heights. The presence of terrestrial predators and predatory birds (*Fregata* spp.) seems to mainly explain the marginal distribution of other breeding species. The cartographic data presented here differ significantly from past and current representations, especially those concerning the island's emerged surface and other geomorphologic features. This new cartographical information will support future studies on the terrestrial fauna and flora of Malpelo Island and its islets.

**KEY WORDS:** Seabirds, Nest distribution, Digital Elevation Model, Malpelo Island, Colombia.

### RESUMEN

**Modelación geomorfológica de la Isla Malpelo y distribución espacial de aves marinas anidantes.** La distribución espacial de nidos de aves marinas en la Isla Malpelo, las principales características del relieve del suelo de la Isla y los tipos de sustratos disponibles para anidación, fueron estudiados utilizando un Modelo Digital de Elevación (MDE). El modelo está basado en datos de sensores remotos (imágenes de satélite, fotografías aéreas y fotografías panorámicas), y en datos de campo procesados mediante un sistema de información geográfico. Los nidos de *Sula granti* prevalecen en las superficies de Malpelo e islotes vecinos, mientras que aquellos de las restantes especies (*S. sula*, *Creagrus furcatus*, *Anous stolidus*, *A. minutus* y *Gygis alba*) están espacialmente restringidos a los márgenes de los acantilados y a grietas o cavernas a distintas alturas. La presencia de depredadores terrestres y aves depredadoras (*Fregata* spp.) parecen ser las

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principales explicaciones de la distribución marginal de esas otras especies anidantes. Los datos cartográficos aquí presentados difieren significativamente de pasadas y actuales representaciones, especialmente en lo que concierne al área emergida de la Isla y a otros aspectos geomorfológicos. Esta nueva información cartográfica pretende apoyar futuros estudios sobre la fauna y flora terrestres de Malpelo y sus islotes.

**PALABRAS CLAVE:** Aves marinas, Distribución de nidos, Modelo Digital de Elevación, Isla Malpelo, Colombia.

## INTRODUCTION

Malpelo Island is the top of a submerged mountain chain (Stead, 1975) and its topography relief is uneven and rough, giving the impression of an inaccessible and inhospitable naked rock (Townsend, 1895; Graham, 1975). Due to its remote location from the Pacific coast of Colombia and difficult access across its uneven and rough surfaces, research work conducted on the island has been relatively scarce, and in consequence, the cartographical information remains incomplete and poor. Up to date, only some bi-dimensional representations, with contour lines, have been made, including cartography regarding the island geomorphology and geology. These representations, on which all existing estimations of Malpelo's surface and its inhabiting fauna are based, were made more than three decades ago by the Smithsonian Institute (Kiestler and Hoffman, 1975).

For the specific case of Malpelo, the traditional two-dimensional mapping methods provide incomplete information on the location, basic area, and contour lines of the island. The lack of information on the surface inhabited by different organisms, and their influence areas, difficult the estimation of their density, total population and biomass. For instance, research on the resident birds of Malpelo demands a reliable cartographical base to support this and any biological study, because the direct estimation of the total number of individuals is not possible due to the uneven topography of the island (López-Victoria and Estela, 2006).

Malpelo is home of the greatest breeding colony of the Nazca Booby (*Sula granti*) in the world and harbors populations of at least other six breeding bird species, the Masked Booby (*Sula dactylatra*), the Red-footed Booby (*Sula sula*), the Swallow-tailed Gull (*Creagrus furcatus*), the Brown Noddy (*Anous stolidus*), the Black Noddy (*Anous minutus*) and the White Tern (*Gygis alba*) (Pitman *et al.*, 1995; Pitman and Jehl, 1998; Álvarez-Rebolledo, 2000; López-Victoria and Estela, unpublished). The ecology of these seven seabird species, as well as of other 50 bird species, including further seabirds and small migratory birds, have been subject of study since the end of the XIX century (Townsend, 1895), and especially during the last 20 years (Pitman *et al.*, 1995; Álvarez-Rebolledo, 2000; López-Victoria and Estela, 2006). However, the housing requirements of resident birds have been poorly studied in terms of nesting space and location, due to the difficulties to conduct field work on the island.

The use of remote sensors and geographical information systems has proved to be a practical tool used in different ornithological studies during the last decades (Gottschalk *et al.*, 2005). Adequate graphical representations can be obtained through a Digital Elevation Model (DEM), defined as a numerical structure of data, representing the spatial distribution of the elevation of the ground surface (Felicísimo-Pérez, 1994). This technique combines the information obtained from remote sensors, the data collected in the field and the existing cartography.

The purpose of this study was to develop a DEM for Malpelo Island and neighboring islets, based on field data and information from remote sensors. An approximated cartographical data base was generated in order to: 1) estimate the resident seabird requirements in terms of nesting spatial distribution and 2) describe the main characteristics of the island's topography and substratum, as a function of the area occupied by nests. This new cartographical data base is also intended to support future studies on the terrestrial fauna and flora of Malpelo Island and neighboring islets.

## MATERIALS AND METHODS

From October 2003 through June 2006 seven visits to Malpelo were made. Location and elevation of relevant spots identified on the island's surface were recorded, using a GPS Garmin Map76S (provided with barometer). The length and width of the eastern, central and southern areas of Malpelo were surveyed, and location [error (x, y) less than 15 m] and elevation [error (z) less than 3 m] of the ground relief were recorded. Additionally, panoramic and detailed photographs were taken from different angles of the islands. High resolution (126 mm format) oblique aerial photographs, taken by the Southwest Fisheries Science Center-SWFSC (Pitman *et al.*, 1995), were also obtained. The general outline and location of the islands were estimated from an image of an Aster satellite (NASA) with a resolution of 15 m (ASTER On-Demand L2 Surface Reflectance).

Data processing and analyses were carried out using the ArcGIS 9.1 software. Field data were loaded to the system of coordinates UTM zone 17N and organized in a same vector map (Shapefile format). The geographical points of GPS taken in the field were used as basis for the geographical reference of the satellite image utilizing the mode for geo-reference of the ArcMap within the system wgs84. A preliminary coastal line was digitalized according to the outline interpreted on the reflectance band. Using the preliminary coastal line as a base line and the positioning data taken in the field, the oblique aerial photos were geo-referenced, giving priority to the coastal line. Based on the finished geo-referenced photography, a photo-mosaic was assembled, covering the majority of the islands (the northern islets and the most remote islet from the eastern coast were excluded from the high resolution aerial-photograph set; Figure 1).

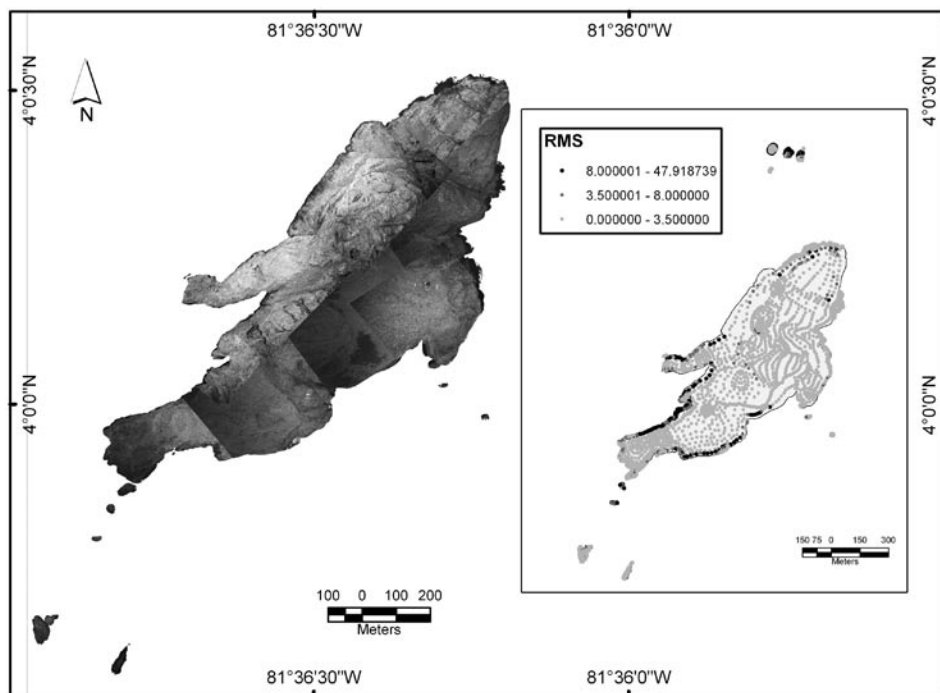


Figure 1. Photo-mosaic of Malpelo Island and neighboring islets. Aerial photographs provided by the Photogrammetry Group of NOAA. On the right side the distribution of the 3228 points used to generate the 3D model with their corresponding RMS value (each value represents the square root of the quadratic difference in each point).

From the aerial photo-mosaic, the coastal line of the islands was re-digitalized with as much detail as possible. Subsequently, the data were standardized and then loaded, including information on position and elevation derived from transects (tracks) made through Malpelo and recorded in the GPS. The data-base obtained using the GPS was complemented using the panoramic photographs taken from boats at different angles and distances from the islands. Using this information, the elevations were established based on the changes of relevant spots of the physiognomy of the islands. These values were calculated by means of linear regression, comparing known elevations to easily identifiable sites of the aerial photography mosaic.

To prevent the edge effect and the deformation of the interpolation due to lack of data on the coastal line, besides estimating the steep slopes of the islands land, a bathymetric file was created using the data of the chart 521 of the Centro de Investigaciones Oceanográficas e Hidrográficas (CIOH).

Once a total of 3228 geographical points were registered, an irregular net was generated using a triangulation of Delaunay (surfaces model type TIN) in order to control the loading of data elevations (Figure 1). Subsequently, a digital elevation model (one

meter of resolution) of the islands was generated, based on the technique of the finite iteration of the difference interpolation. The algorithm “topo to raster” implemented in ArcGIS 9.1 was used to simulate the island’s surface based on the map of geographical points with their estimated elevations, which was the starting point for generating the contour lines (one meter apart). This sequence was used to determine a triangulated surface (TIN) with minor changes, compared to the direct generation of elevation points.

Preliminary maps were used to mark the main geo-morphological characteristics of Malpelo on the field, as a function of the nests’ distribution of the different seabird species (except Masked Booby). Starting from these data and using the geo-referenced mosaic of aerial photography and the contour lines obtained from the estimated surface, the physical limits of zones with homogenous characteristics were digitalized. In addition to field information, the oblique aerial and panoramic photographs were taken into account to establish those limits. Data related to the location vectors of the vegetal coverage, the substratum stability and roughness as a function of the nests presence (four categories), the utilization of the islands by humans (four categories), and the distribution of the nesting sites for six seabirds were loaded (Nazca Booby, Red-footed Booby, Swallow-tailed Gull, Brown Noddy, Black Noddy and White Tern). Through the tool “surface volume” implemented in ArcGIS 9.1 the surface areas (3D) were estimated for each of the attributes of each thematic and a closed analysis was conducted to establish if the error would be acceptable.

Based on the DEM an analysis of slopes was conducted and the surfaces were calculated in two and three dimensions for all the evaluated categories, combining the TIN surface with each of the thematic attributes. Finally, the graphic output for each thematic was generated (maps, views and profiles in 2D and 3D).

## RESULTS

Cartographic data collected for the present study show that Malpelo is an island of elongated form, about 1643 m long and with variable width (maximum width approximately 727 m; Figure 2). The main island is neighbored by 11 to 12 islets, depending on what definition is used for the portions of rock emerging from the sea in the periphery. At least two of the islets are relatively close to the island and one of them is small and low (see farther below). The islets were designated with different names during the last century. We opted to use the names currently given, and widely accepted by divers (Harold Botero. *Embarcaciones Asturias de Buenaventura*, Colombia. Sandra Bessudo and Krupskaya Narváez. *Fundación Malpelo*. Bogotá, Colombia. 2006. Pers. Comm.). The islets distribution and their names are as follows: four islets located 500 m from the northern end of the island, known as Los Mosqueteros; five islets located at different distances from the island’s southern point, known as Tres Reyes, La Gringa, and Escuba; two islets located at the eastern coast of the island, in front of an arch or natural

bridge, known as Vagamares and La Torta. The last islet, located at the western coast of the island, and considered by some people as a shoal, is known as El Mirador. This last islet and the first one of the southern islets (Salomón) are separated from the main island by, maximum, six and two meters, respectively (Figures 2 and 3).

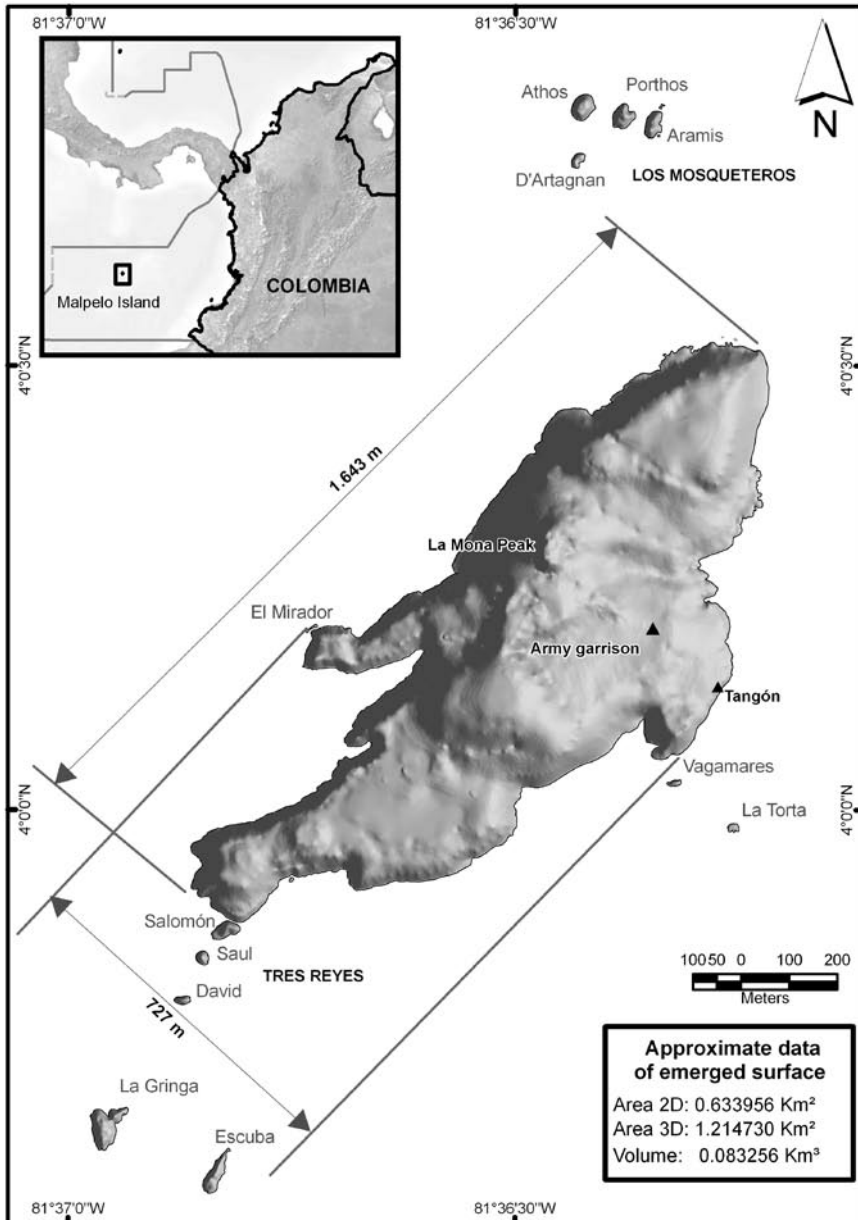


Figure 2. General map of Malpelo Island and neighboring islets.

The flat (cartographical) emerged area of the islands (Malpelo and the islets) is about 0.633 km<sup>2</sup> (ca. 63 Ha). However, their surface area (3D) is about 1.215 km<sup>2</sup> (ca. 121 Ha), i.e. almost twice as large. This large difference results from the uneven ground topography of the islands, and the presence of hills with a maximum height of about 300 m. The northern half of the main island is higher than the southern half and on the top of one of the hills, known as La Mona, a light house was erected (Figures 2 and 3).

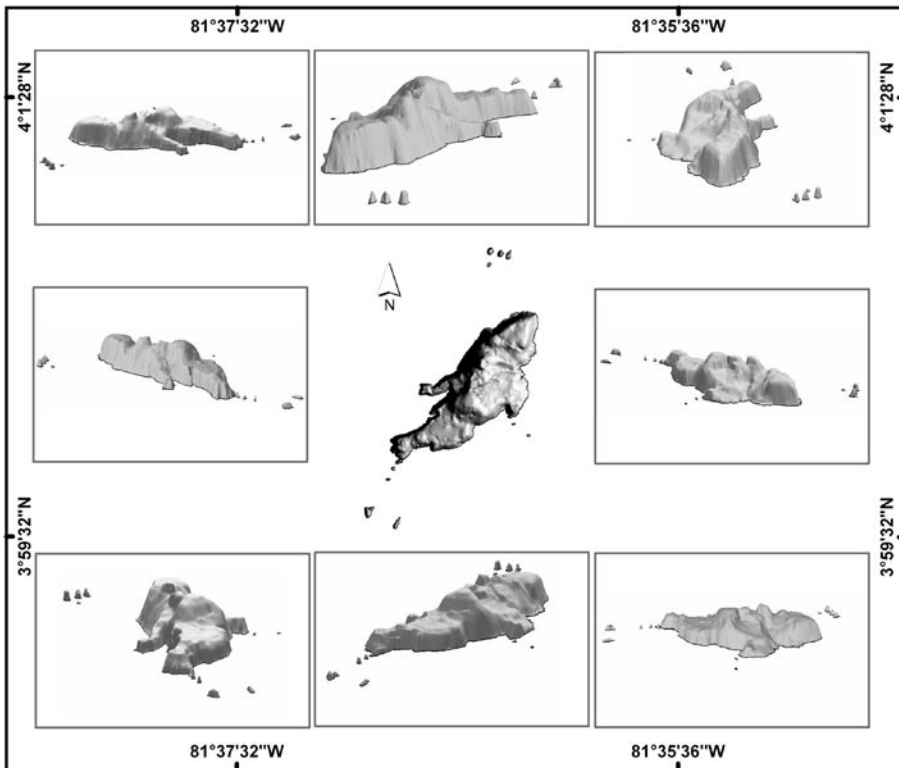


Figure 3. Three-dimensional profiles of Malpelo Island and neighboring islets (viewed from different angles).

The uneven relief of the island's ground presents several steep slopes, which constitute 72% of the islands surfaces. With the exception of some areas of the northeast of the main island, the cliffs extend 20 to 80 m deep under the sea. There are some areas that are almost flat, located on the southern part of the main island, on the eastern coast (where two navy houses were built), on the higher points, and on the highlands of the northern end of the island. With the exception of La Torta and El Mirador, having an emerged flat relief with surfaces completely swept by the swell and the high tides, all the islets are sharp pointed, rise above the sea level more than five meters, and show an uneven ground relief (Figures 4 and 5).

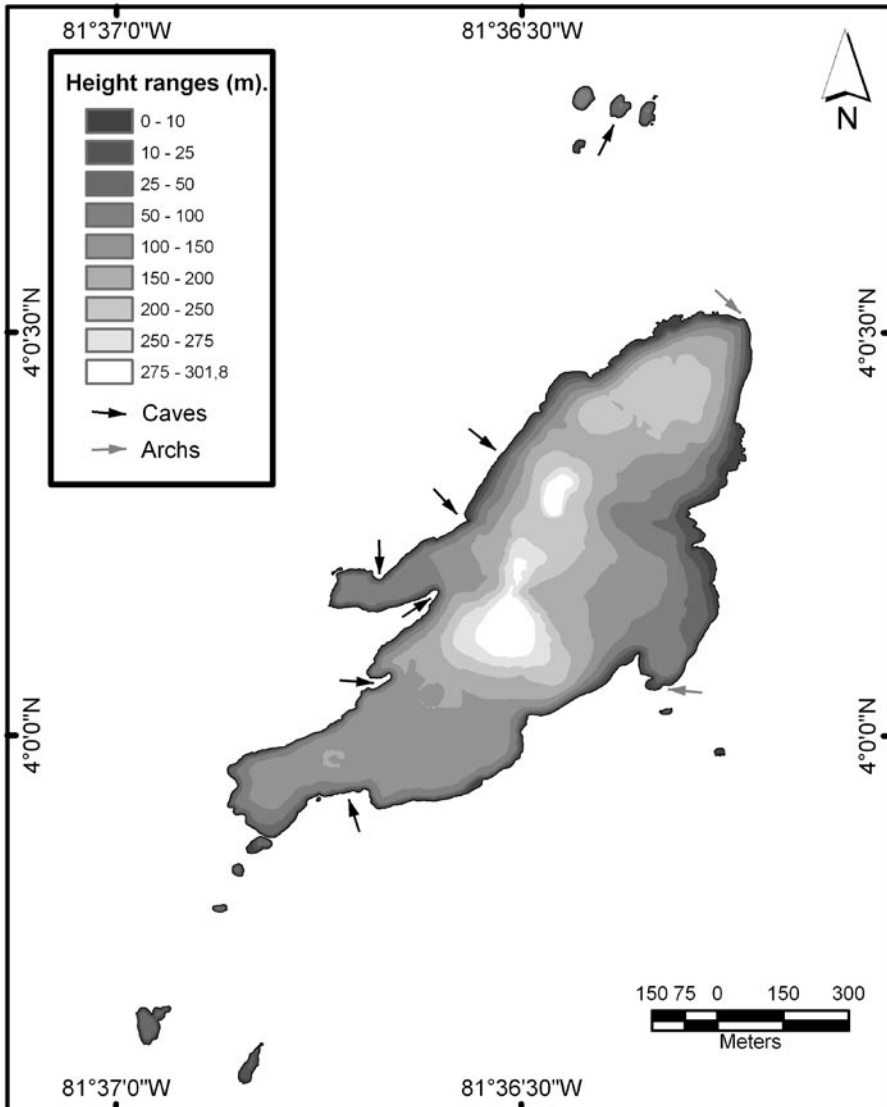


Figure 4. Topographic map of Malpelo Island and neighboring islets showing the approximate location of caves and arches.

Near 72% of the island's ground surface is solid rock of uneven relief; the remaining 28% of the area is plain rock or loose rock of different sizes (Figure 6). In those surfaces where more rock accumulation is found the slopes are smaller, and rocks falling from the hills are piled up there. These areas also correspond to watersheds, which contribute to the flow of water and rocks into the sea. A reduced number or complete absence of nests in these areas was observed.



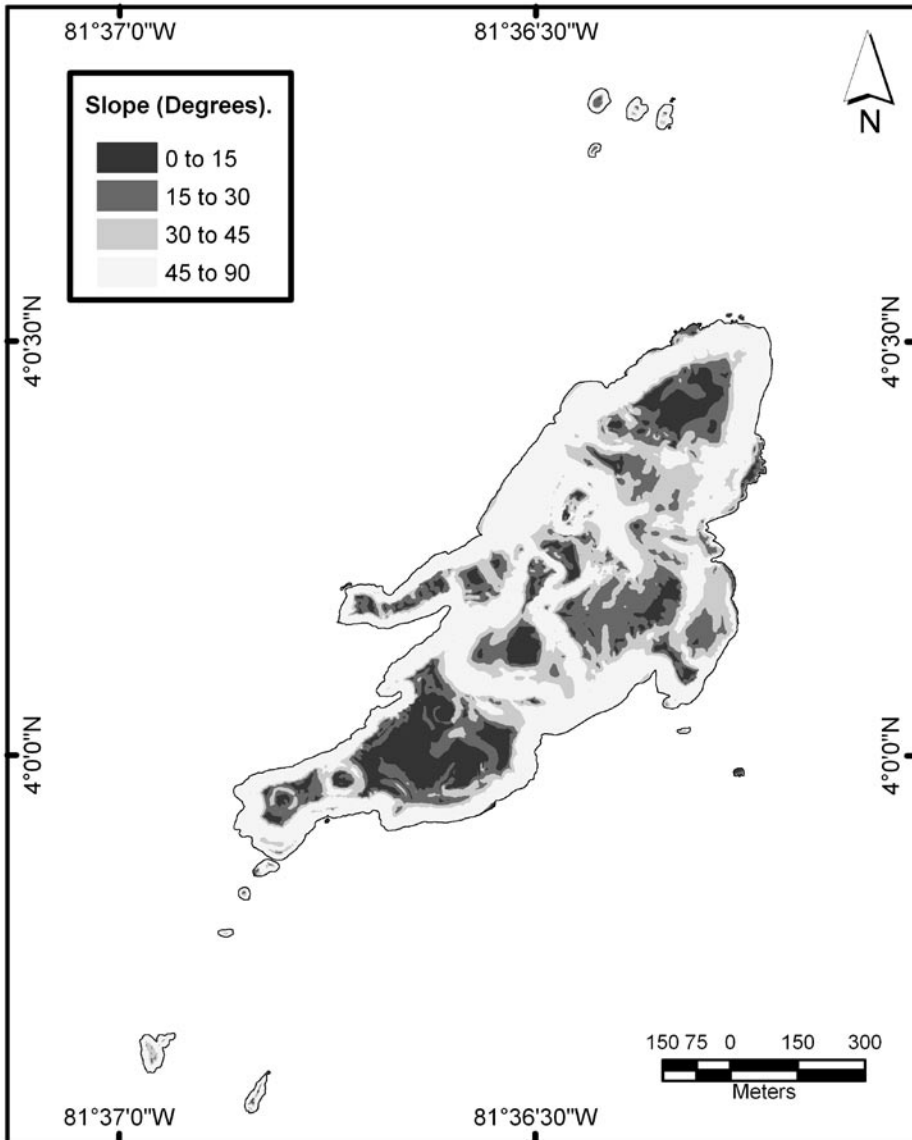


Figure 5. Map of slopes of Malpelo Island and neighboring islets.

Except for some scattered patches of grasses and ferns, not exceeding an area of 0.02 km<sup>2</sup>, the vegetal cover of the islands constitutes micro-algae, mosses and lichens. The largest patch of vegetation (vascular plants), comprising the fern *Pityrogramma dealbata* is located at the center of the main island, towards the western coast, and between 100 and 150 m above the sea level. The grass patches (Poaceae) occur mainly on the top of the islets, and inside crevices and caverns of the hills skirts (Figure 7).

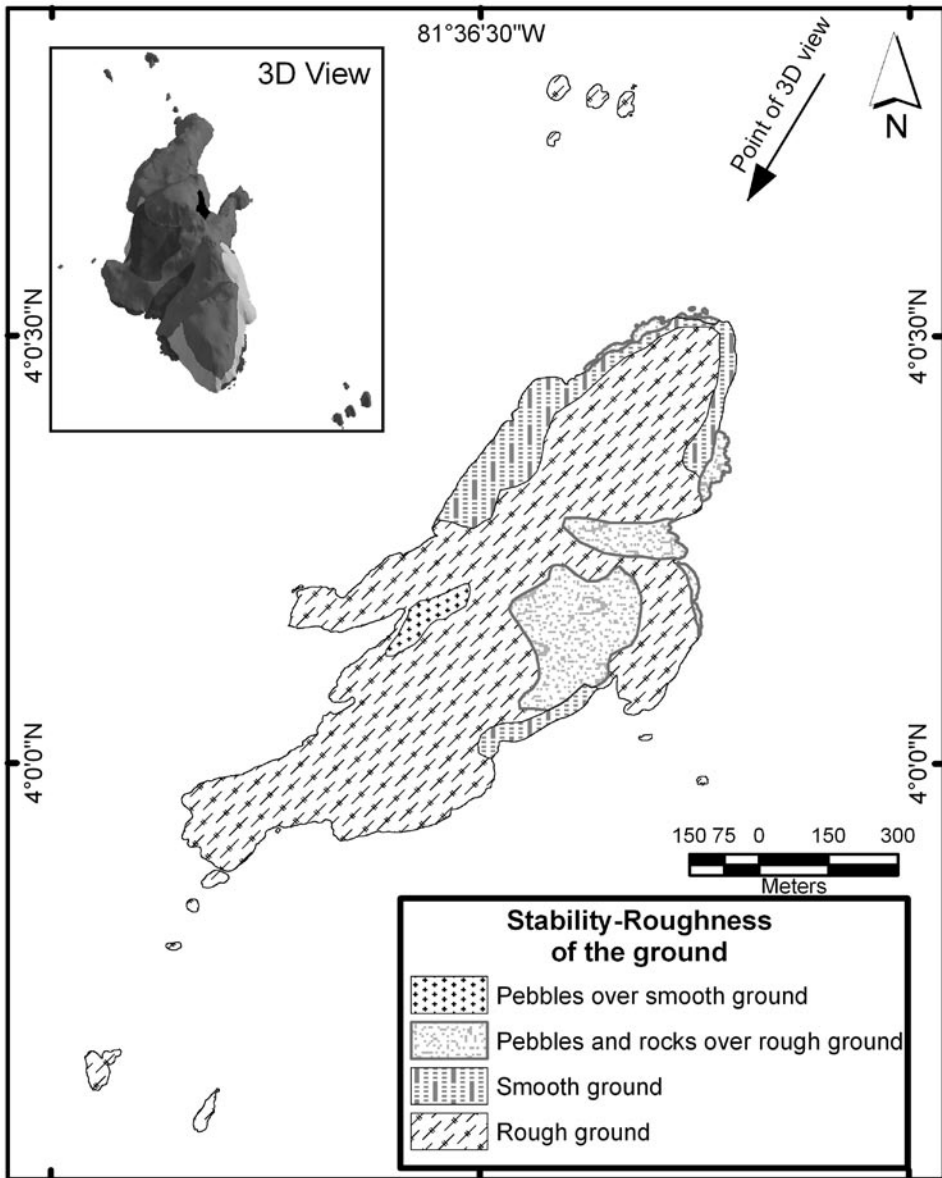


Figure 6. Map of ground's stability-roughness of Malpelo Island and neighboring islets.

Less than 3% of the main island is frequently used by humans and near 90% is sporadically visited. Inhabited areas correspond to those occupied by houses of the Colombian Navy, to the neighboring pathway linking the access dock to the barracks and, occasionally, the pathway to La Mona Hill. Colombian Navy squads or research teams sporadically explore the southern region of the main island and the hills located at the central part.

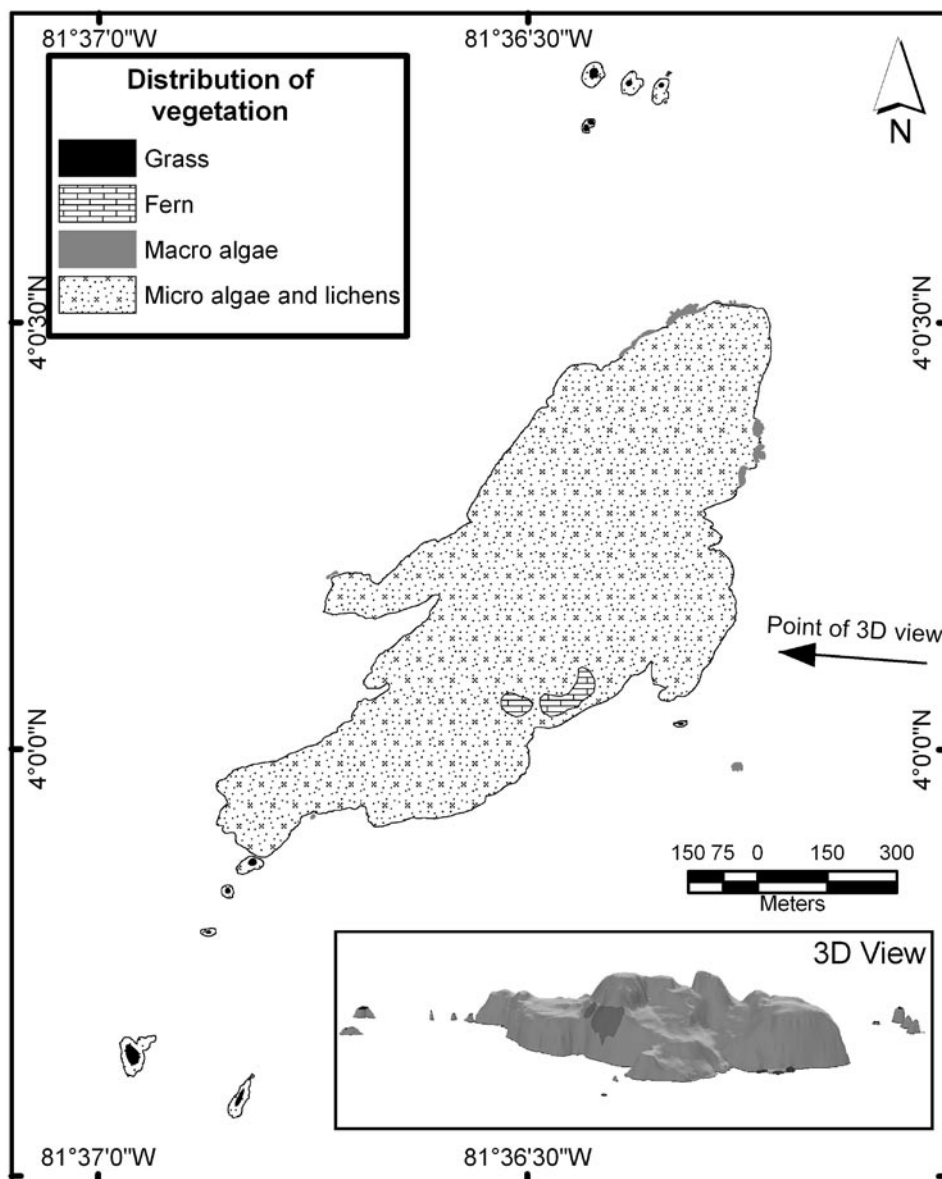


Figure 7. Map of the vegetation cover of Malpelo Island and neighboring islets.

The Nazca Booby is the most abundant species in Malpelo, having nests on almost all islets, with the exception of El Mirador and La Torta (Figure 8). Most nests are found on surfaces with moderate slopes. In those areas with steep slopes the nests are scarce and scattered. Disregarding the general slopes, the micro-relief of the ground where nests occur is flat and made out of solid rock. Nests are made out of pebbles and, in

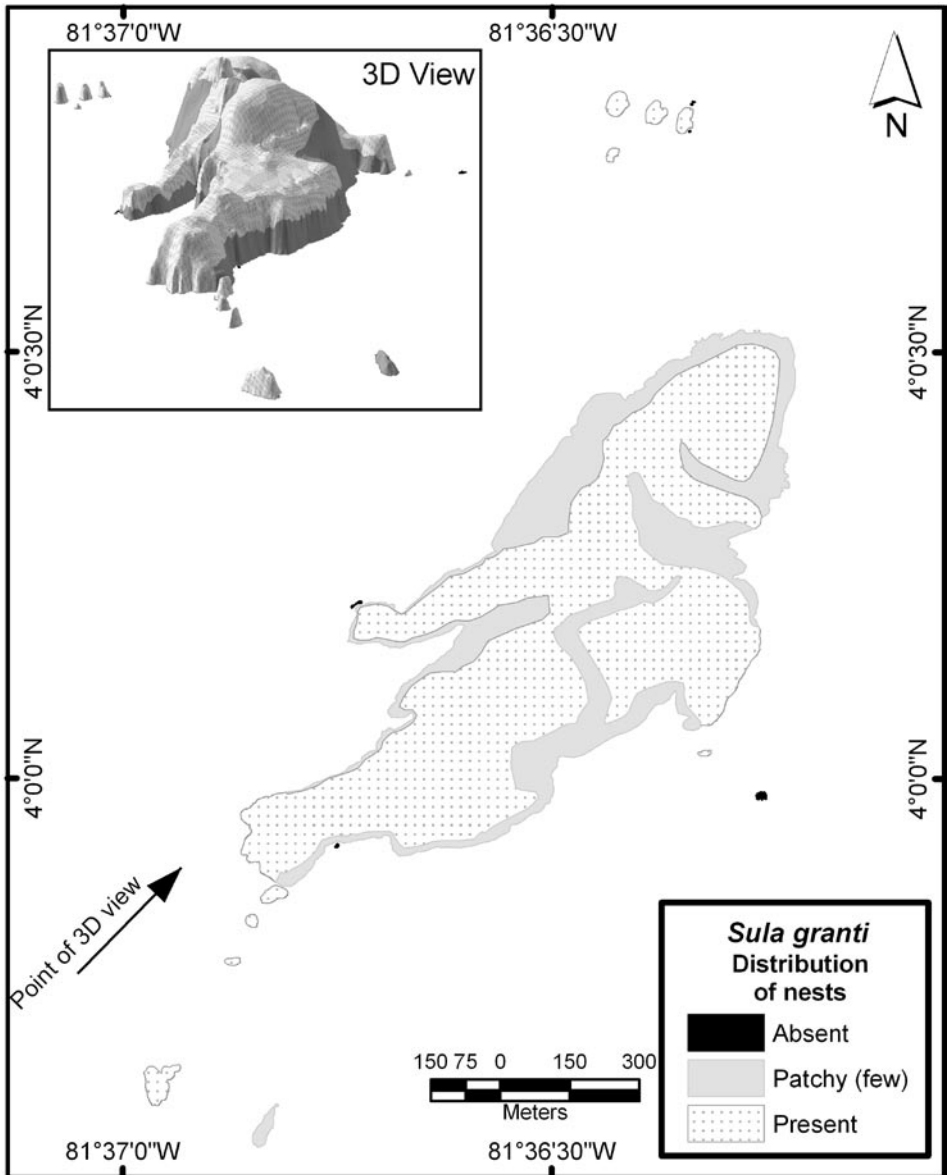


Figure 8. Map of nest distribution of Nazca Booby (*Sula granti*) on Malpelo Island and neighboring islets.

those steep-sloped areas they are located on small terraces or cornices. On the other hand, in those areas where stones or boulders are piled up in great amounts and few places of solid rock are available, nests are scarce and scattered or completely absent.

The Red-footed Booby is present throughout most of the year in the island but is not abundant. In none of the visits a group larger than 60 adult individuals was spotted. All

nests are located on the southern part of the main island, on two low areas comprised by fractures of the rock's surface. There are also some nests inaccessible for humans on the highlands of Athos, the largest northern islet (Figure 9). Nests located on the southern part of the main island are made out of grass, apparently brought by males from the northern

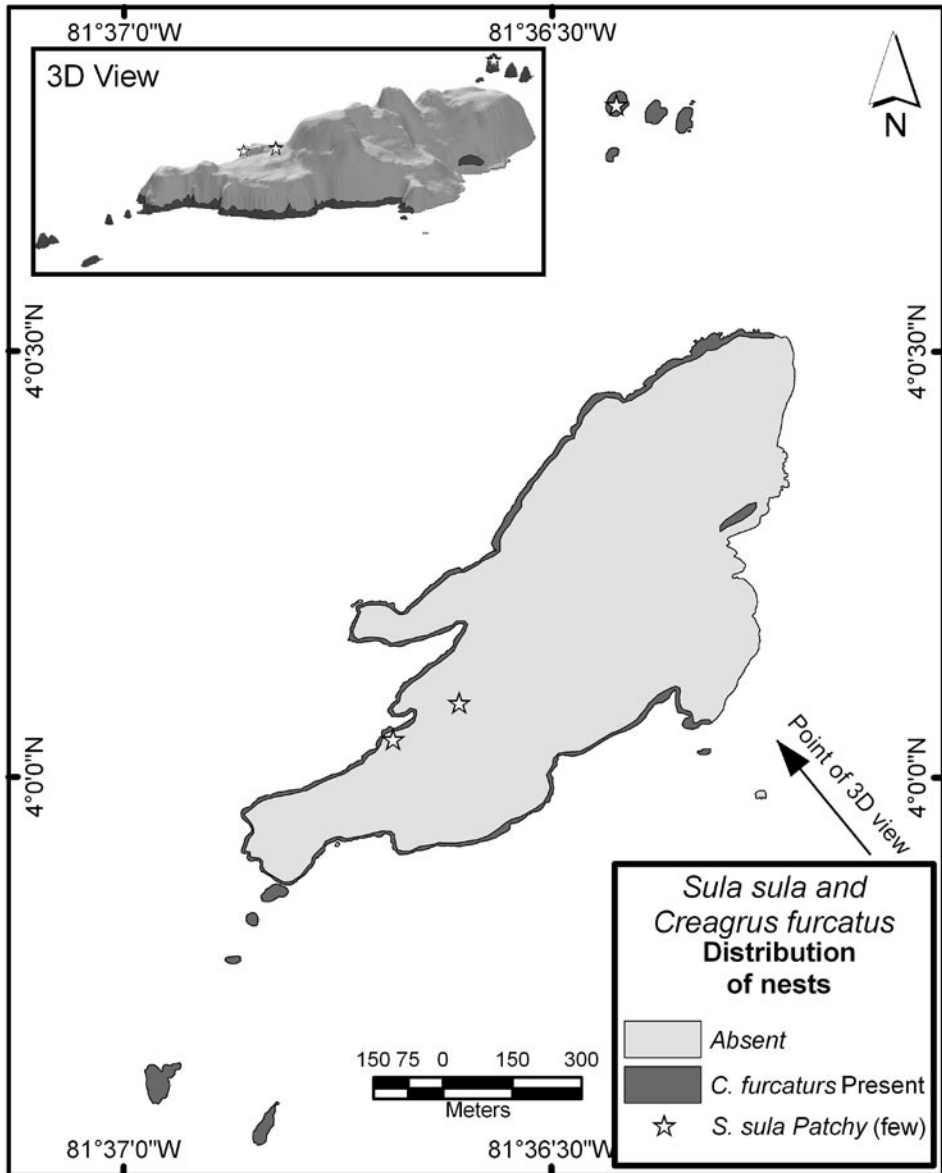


Figure 9. Map of nest distribution of Red-footed Booby (*Sula sula*) and Swallow-tailed Gull (*Creagrus furcatus*) on Malpelo Island and neighboring islets.

and southern islets. These scarce grasses are placed at the top of small rocky, pedestal or pinnacle-shaped promontories, between 30 and 50 cm in diameter, and between 70-100 cm height. Terrestrial crabs (*Gecarcinus malpilenis*) were frequently observed feeding on nest materials of this colony, and no apparent reaction from the birds to counteract the crab's predatory activity was observed. It was not possible to visit the nests located on the northern islet, but observations made with binoculars from the water surface suggest that they are located directly on or at the side of small grass patches.

The nesting distribution of Swallow-tailed Gull is restricted to a distance of 10 to 70 m from the water surface. Nests are scattered and located on small cornices, terraces or crevices of the cliffs, always on solid ground, covered with small stones and small fragments of invertebrates (mostly crabs). In the north-east of Malpelo, in the sector known as Tangón, not a single couple of this species in breeding behavior was observed (Figure 9).

The nesting distribution of Brown Noddy and Black Noddy is sympatric and extends up to the first 5 to 20 m strip of the northern islets, the coast cliffs, and the north-east and mid-east part of the main island (Figure 10). Brown Noddy also builds some scattered nests at the interior of the main island, located at the upper part of the hills and large crevices. As in the case of Swallow-tailed Gull, these two small, tern-like birds use the cliff's terraces, cornices and crevices for nesting. Although Brown Noddy may or may not build nests to lay its egg, most of them were simple structures, several of them had small stones and remains of invertebrates (mostly Grapsidae crabs), and two were built of feathers of the Nazca Booby and plastic remains (in one occasion with a tooth brush). On the other hand, Black Noddy did elaborated nests on all the occasions observed. All nests checked were cup-shaped, and were built with remains of grasses (Poaceae) and synthetic fibers of different kinds (nylon ropes, fishing-mesh, etc.) picked up from the surface of the water, and cemented with excrements. In the Vagamares, La Torta, and El Mirador islets nests were absent.

White Tern nests on the same areas as Noddies do, i.e., on small terraces, cornices and crevices of the cliffs. This bird does not build nests and chooses its nesting places above 7 to 10 m high, up to the hill's peaks (Figure 10). Opposite to the case of the two Noddies species mentioned above, White Tern does not breed colonially. Nesting activities were not observed in La Torta, Vagamares and El Mirador islets.

## DISCUSSION

The most accurate cartography on Malpelo consisted of a nautical chart based on data collected by a US-Navy flight in 1954. This preliminary map was complemented and enhanced during a research cruise carried out by the Smithsonian Institute and the US-Navy in 1972 (Kiester and Hoffman, 1975). Comparison of that cartography with the

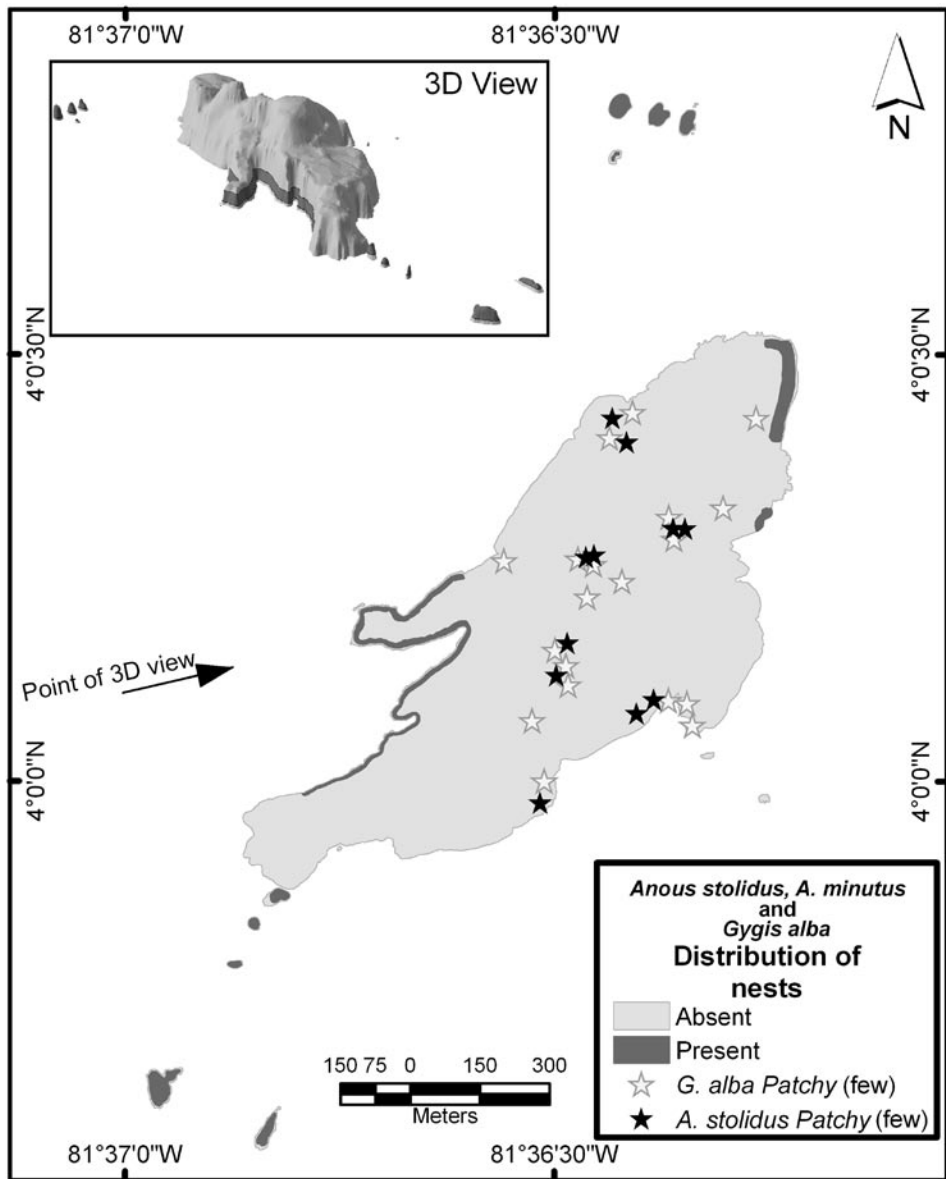


Figure 10. Map of nest distribution of Brown Noddy (*Anous stolidus*), Black Noddy (*A. minutus*) and White Tern (*Gygis alba*) on Malpelo Island and neighboring islets.

information obtained in this study allow shedding light on the following four general, significant differences: a) the southern end of Malpelo is narrower, b) the Tres Reyes and La Gringa islets are lined up between them, c) the shape, location and size of most islets is different, and d) the small peninsula located at the mid west of Malpelo has

a different orientation and is longer (Figure 11). A further difference between results obtained in this study and those from the study carried out by the Smithsonian regards the island's maximum height, reported by this institution as 376 m (some conversions from the original figure in feet result in about 400 m; Pitman *et al.*, 1995), which is, at least, 76 m higher than the 300 m estimated in this study. These differences result from the triangulation method used by the Smithsonian to measure the heights from the ship. Our results agree with the measures of about 300 m reported by Sarmiento (1953), and those obtained by Caiza and Guerrero (2000) using a GPS, in which a figure depicting the hill Cerro La Mona measuring 296 m ( $\pm 10$  m) high, is shown.

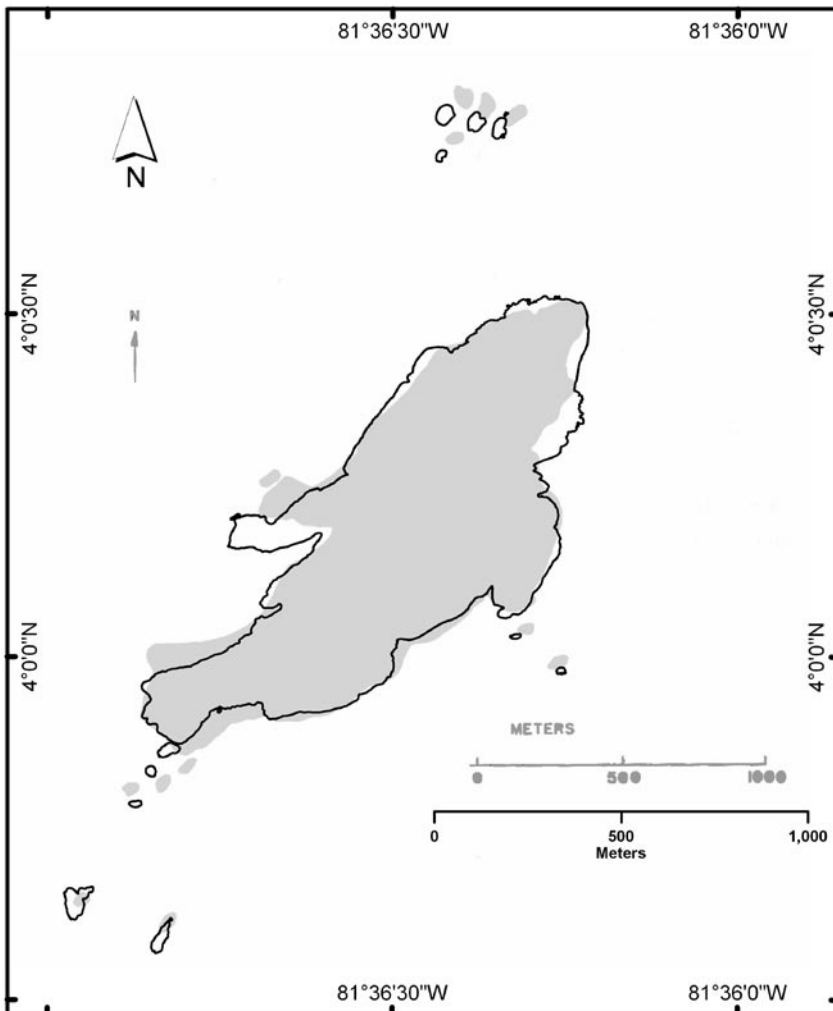


Figure 11. Comparison between the contour line map of Malpelo and neighboring islets published by the Smithsonian Institute in 1975 (gray) and the one obtained in this study (black line).



In a number of studies, the emerged flat area of Malpelo has been reported as varying between 35 and 63 Ha (0.35-0.63 km<sup>2</sup>) (Sarmiento, 1953; Prah, 1990; Brando *et al.*, 1992; Álvarez-Rebolledo, 2000; Caira and Guerrero, 2000; Díaz *et al.*, 2000). Results obtained in this study show values that coincide with the higher previously reported data for the flat area (cartographic), and even double that given surface area (3D= 1.2 km<sup>2</sup>). These differences have important implications when estimating the populations of the different organisms living on the islands, especially, when density values are extrapolated. Despite its small size, walking on the surface of Malpelo makes direct observations difficult or impossible, and therefore it is mandatory to know the surface area value to make biological estimations of the different populations as accurate as possible.

The number of islets neighboring Malpelo has been reported with different values, depending on the selected classification system. For instance, Sarmiento (1953) reported six islets, while in the maps published by Kiester and Hoffman (1975) twelve islets are shown (Figure 11); Prah (1990) mentioned eleven islets while Álvarez-Rebolledo (2000) reported ten. A total of eleven islets, with emerged areas during high tide, and separated from the main island, are currently recognizable. The first southern islet is so close to the main island that, probably, for several researchers, it does not appear as an independent land portion and, hence, the discrepancies found in the literature. In addition, El Mirador is so low that during heavy swell it is completely covered with water and therefore could be excluded as an islet; on the other hand, it is not a shoal either. In some areas several rocks fallen from the main island and separated by a few centimeters from the coast line are observed, though they cannot be classified as islets.

Another confusing aspect regards the distance from Malpelo to the Pacific coast of Colombian mainland. According to the calculations made in this study, the nearest point (to the Pacific coast of Colombia) is the Corregimiento Playa del Caballo, Mosquera municipality, Nariño department, about 380 km from the main island. On the other hand, the distance from the main island to Buenaventura sea port, located almost at the same latitude of Malpelo, is about 497 km (data obtained from the LabSI-INVEMAR; according to the coast line reported by the Instituto Geográfico Agustín Codazzi-IGAC).

Comparison of panoramic photographs taken during the last century with more recent aerial photos reveals an evident change of the largest vegetation patch formed by the fern *Pityrogramma dealbata*. The first researchers did not mention its presence (Slevin, 1928; R. Smith in Bond and Meyer de Schauensee, 1938; Murphy, 1945), although currently it is visible from the ship's anchoring place, close to the eastern coast of the main island. Subsequently, the vegetation is reported in the publication of the Smithsonian Institute, in which the scientific name is recorded for the first time, though without making mention of its coverage (Graham, 1975). Interestingly, in the aerial photographs of 1988 and in some other photographs published in 1990 (Prah, 1990) and 1992 (Brando *et al.*, 1992), the vegetation patch appears larger than the one currently

observed. The time of arrival of this fern is uncertain but it is possible that some spores reached the islands swept by winds from Central America; a further possibility is that the first human visitors that traveled among the eastern tropical Pacific islands, introduced the spores adhered to their clothes or travel gear. The presence of the terrestrial crab (*Gecarcinus malpilensis*) may explain the apparent reduction of the vegetation coverage but this should be confirmed experimentally. On the other hand grass patches growing on the picks of the islets and the presence of algae, lichens and mosses have been mentioned in the literature since early XX century (see Graham, 1975).

The Nazca Booby breeds on the coastal margins of the Galápagos, on areas almost lacking vegetation and close to cliffs (Nelson, 1978; Duffy, 1984; Townsend *et al.*, 2002), apparently due to the need of high and windy places for taking off (Duffy, 1984). In Malpelo, on the other hand, nests are distributed everywhere because the almost complete lack of vegetation and the uneven topography make most of the island's surface available for nesting. Therefore, nest distribution in Malpelo does not seem to be restricted by space, distance to the sea or nest location with respect to the wind; on the contrary, the ground slope and substratum stiffness seem to play an important role in this context.

The Red-footed Booby nests in colonies, almost always on trees or shrubs and, rarely, on grass thickets or even on artificial structures when no other vegetation is available (Schreiber *et al.*, 1996). The Malpelo colony is small and atypical; the building process of nests is very rudimentary and the eggs are laid on the rock ground, because the nest materials are frequently removed and eaten by crabs. The two colonies of this species closest to Malpelo are located on Cocos Island (Costa Rica) and the Galápagos Islands (Schreiber *et al.*, 1996).

The Swallow-tailed Gull nests on the Galápagos Islands under conditions similar to those found in Malpelo (Harris, 1970). The only difference is the maximum height at which nests are located, as that in Malpelo appears to be lower, probably due to the pressure exerted by terrestrial predators (crabs and lizards).

The Brown and Black noddies nest sympatrically in other colonies on cliff cornices as well as on shrubs and trees (Gauger, 1999). The Malpelo colony differs from other colonies because it comprises few dozens of couples; contrastingly, other colonies comprise thousands of couples (Gauger, 1999). The relative low number of couples found in Malpelo may be best explained by the presence of the terrestrial crab and at least one of the lizards (*Diploglossus millepunctatus*), as well as by the pressure exerted by the frigate birds (*Fregata magnificens* and *F. minor*) on the broods of these two species, if nests are located on exposed areas; when nests are protected inside crevices or cornices, it is very difficult for frigatebirds to hunt the broods (Gauger, 1999). Another factor affecting the nest location of the *Anous* species is the wind pattern that predominates in Malpelo during the second half of the year (winds blowing from the south and the south-west). These species are strongly affected by heavy winds and thunders, which kill broods as well as

adult individuals (Chardine and Morris, 1996; Gauger, 1999). These species, as well as the other two Laridae species present in Malpelo, nest mostly on sectors protected from tropical winds and thunders characteristic of this season.

The White Tern shares some nesting sectors with the two noddies species in Malpelo, though not at heights within the cliff area. This may be explained because noddies out-compete White Tern for nesting sites, as observed in the colony of Tern Island (Niethammer and Patrick-Castilaw, 1998). Nevertheless, other observations point out that Black Noddy is not able to successfully compete for nesting areas against White Tern, which frequently takes up its nests (Gauger, 1999). In any case, White Tern is not colonial as are both noddies species (Chardine and Morris, 1996; Niethammer and Patrick-Castilaw, 1998; Gauger, 1999), and hence, several nests of this species are scattered throughout the whole area of Malpelo, including the top of the hills.

In general terms, data on the nesting distribution of the seabirds of Malpelo collected in this study agrees with those reported in the literature (Harris, 1970; Anderson, 1993; Chardine and Morris, 1996; Niethammer and Patrick, 1998; Gauger, 1999). The predominance of Nazca Booby in most of the island's surfaces seems to be explained by the following main factors: a) it is the largest bird, in relation to other birds present in the island, and out-competes other species for nesting space (i.e. Red-footed Booby), b) it appears to be the only species in Malpelo able to counteract a permanent predatory pressure from the terrestrial crab and one of the lizards (*Diploglossus millepunctatus*), and c) it is the best adapted, compared to other birds breeding on the island, as it finds ideal conditions for nesting (i.e., doesn't require vegetation for nesting). In the case of the other species, although there are favorable conditions for nesting on many sectors of the island's surfaces, they appear to be unable to resist the pressure exerted by crabs and lizards. In those areas where these predators have been observed, only nests of Nazca Booby were found; contrastingly, no crabs or lizards were observed in those areas where nests of other species were found. These evidences are circumstantial and should be confirmed experimentally.

Future studies on the population biology of plant and animal species present in Malpelo should consider as a starting point the current surface area of the island and its uneven geomorphology. More accurate approaches to the DEM will be achieved by loading the model with inputs from remote sensors of better resolution (i.e., radar images and/or aerial photography). The northern sector of Malpelo is still poorly explored and requires more detailed cartographic research.

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