Landscape structure in two reefs in La Parguera and the distribution of the *Lytechinus variegatus*

by
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ABSTRACT

Landscape ecology techniques are being used to determine patterns that influence natural processes in terrestrial ecosystems extensively. The purpose of this research was to evaluate the landscape structure of the reefs in La Parguera using remote sensing technology. The overall project has a particular focus on seagrass beds and the *Lytechinus variegatus*, this organism is a common inhabitant of the seagrass meadows. An IKONOS image from 2006 was used; the area of each reef covers approximately 1 km^2 at a spatial resolution of 1 m. Two benthic maps were generated with seven classes using a supervised classification after applying a water column correction. Landscape structure analysis was executed using FRAGSTATS software, to calculate different metrics in combination with field assessments of sea urchin distribution. The metrics were analyzed at two different levels; class level with nine indices selected and landscape level with eleven indices. The abundance of sea urchins in Enrique Reef was 1.32 #urchin/m^2 while in Laurel the abundance was is 0.48 #urchin/m^2. Results show sea urchin aggregation in Enrique Reef and an even distribution in Laurel Reef. These data can be used to assess the condition of seagrass beds for change detection analysis and as a tool for restoration and conservation.

RESUMEN

Las técnicas de ecología del paisaje han sido utilizadas extensamente para estudiar los patrones que influyen los procesos naturales en ecosistemas terrestres. El propósito de este estudio es evaluar la estructura de paisaje de los arrecifes de La Parguera usando técnicas de teledetección. Este proyecto se enfoca particularmente en praderas de hierbas marinas y en *Lytechinus variegatus*, este organismo es un habitante muy común en este ecosistema. Para este estudio se utilizó una imagen IKONOS del 2006; el área que cubre cada arrecife es aproximadamente 1 km^2 con una resolución espacial de 1 m. Se generaron dos mapas bénticos con siete clases, usando clasificaciones supervisadas esto luego de haber completado una corrección de la columna de agua. El análisis de estructura de paisaje se llevo a cabo con el programa FRAGSTATS, para calcular diferentes métricas en combinación con data de distribución del erizo. Las métricas utilizadas fueron analizadas a dos niveles: a nivel de clase se seleccionaron nueve índices y a nivel de paisaje once índices. La abundancia del erizo en Enrique fue 1.32 #erizos/m^2 mientras que en Laurel fue 0.48 #erizos/m^2. Los resultados muestran una tendencia de agregación en la población de Enrique y una distribución uniforme en Laurel. Este tipo de información se puede utilizar para evaluar cambios en la condición de las hierbas marinas y como herramienta para evaluar restauración y conservación de estos ambientes.

A los estudiantes del sistema UPR por su lucha incansable, por exigir una educación accesible, justa y de excelencia

"Es bonito soñar, pero es de idiotas quedarse soñando" Rafael Cancel Miranda

"No estoy hecho para conformarme con la injusticia." Ramón Emeterio Betances

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General Introduction

Landscape ecology is founded on the notion that environmental patterns strongly influence ecological processes (Turner, 1989). These processes can be altered by anthropogenic activities, such as deforestation and uncontrolled development, among other factors. These activities can produce fragmentation of different terrestrial and marine habitats such as seagrasses. Seagrasses are a climax species in coastal Caribbean environments and serve as habitat and feeding areas to many species. Spalding et al. (2003) estimated that the world's total area covered by seagrasses is 177,000 km^2, and Costanza et al. (1997) calculated that the economical value of all ecosystem services provided by seagrasses approaches US$3.8 trillion per year. However due to its localization at shallow coastal areas, this ecosystem is impacted by human activities on a regular basis. Short and Wyllie-Echeverria (2000) estimated that about 12,000 km^2 of seagrass beds have been lost worldwide between 1985 and 1995. The sea urchin *Lytechinus variegatus* (Variegated Urchin) is a common inhabitant of the seagrass meadows and grows up to 5-8 cm in diameter. This sea urchin uses seagrass habitats as refuge and to feed and to protect itself from ultraviolet rays. Species diversity is higher in seagrasses compared with bare sand habitats; based on this premise a loss of seagrass would result in a reduction of species diversity (Boström et al, 2006).

The purpose of this study is to establish a foundation for the study of seagrass landscape structure in La Parguera, southwestern Puerto Rico and its effects on *L .varieg*atus,. For this study remote sensing methods were applied. An IKONOS satellite image of $1m^2$ of resolution was used to develop benthic map of the two study sites: Enrique and Laurel reefs. FRAGSTATS software (McGarigal and Marks 1995) was used to produce landscape structure metrics at class and landscape levels for each reef. Sea urchin distribution measurements were taken at the two sites. The general hypothesis of this study is that if seagrass beds present high fragmentation, the sea urchin distribution will be aggregated but if the seagrasses do not present high fragmentation the sea urchin distribution will be random.

This study is divided in two chapters. The first chapter covers the benthic mapping and corrections applied to the satellite data and the landscape structure analysis of the reefs and its limitations. The second chapter addresses the sea urchin density and distribution in two reefs and the explanation of the pattern found and its relationship to landscape metrics.

Chapter 1. Landscape Structure of Seagrass Beds in La Parguera

1. Introduction

Landscape ecology according to Turner (1989, 2005) emphasizes broad spatial scales and the ecological effects of the spatial patterning of ecosystems and focuses on the reciprocal interactions between spatial pattern and ecological processes. In other words, this science is founded on the notion that environmental patterns strongly influence ecological processes (Turner, 1989). These processes can be altered by anthropogenic activities such as deforestation and uncontrolled development, among other factors. These activities can produce the fragmentation of different terrestrial and marine habitats changing the landscape structure. Landscape structure refers to the spatial relationship among distinctive ecosystems or landscape 'elements'—more specifically, the distribution of energy, materials and species in relation to the size, shapes, numbers, kinds and configurations of the ecosystems (Xu and Wang, 1993 as cited by Li et al., 2001). Quantifying landscape structure is a prerequisite to the study of landscape function and change (Li et al., 2001). Turner (1989) establishes that landscape structure must be identified and quantified in meaningful ways before the interactions between landscape patterns and ecological processes can be understood.

In coastal areas, seagrass meadows may be extensive and continuous, or they may be fragmented into mosaics of discrete patches surrounded by a matrix of unvegetated sediment by forces such as waves and currents, animal foraging, and boating activities (Fonseca and Bell 1998, Fonseca et al., 1982, Robbins et al., 1994). According to Robbins and Bell (1994) seagrass ecosystems possess a suite of ecological characteristics that allow the direct application of terrestrially developed techniques.

Landscape indexes may be useful for exploring not only the “land-based” habitats for which they were developed, but also the extensive marine landscapes from both intertidally and subtidally by patches of biota (flora and/or fauna) within a matrix of either soft sediments or hard substrates (Robbins et al., 1994.). Seagrasses form temporally dynamic and fragmented subtidal landscapes in which both large- and small-scale habitat structures may influence faunal survival and abundance (Hovel and Lipcius, 2002). In fragmented landscapes, patch size, shape and dispersion, and proximity to the patch edge may influence interactions among species that influence population dynamics, community structure, and species diversity (Andrén, 1994; Forman and Godron, 1981; Forman and Godron, 1986; Paton, 1994). Changing landscape structure can alter species interactions, which could affect species distributions (Schmiegelow and Mönkkönen, 2002). For example, according to Irlandi (1997) predators in aquatic systems do alter their foraging behavior in response to the spatial pattern of habitats (patch shape and size) and not to any changes in characteristics of the vegetation. Remote sensing can characterize benthic features in marine ecosystems, but it requires extensive image processing (Arce, 2005). Hansen et al. (2001) made a related terrestrial study of habitat suitability models derived from Landsat Multispectral Scanner (MSS) imagery for 1975 and Thematic Mapper (TM) imagery for 1997 to represent the landscape for early winter caribou habitat in British Columbia, Canada. Based on a comparative analysis of selected spatial landscape metrics calculated for each time period, changes in the composition and spatial configuration of early winter habitat were quantified. Another study made by Jorge et al. (1997), measured the fragmentation of forest formations in Southeastern Brazil using a Landsat-5 TM image and concluded that the distribution of the savannah patches within the forest were aggregated while patches of natural vegetation as a whole were randomly dispersed in the landscape. Vogelmann (1995) used spatial patterns and rates of forest fragmentation to asses a region in southern New England using Landsat data and found that with increases of human population the forest increases its fragmentation. Fragmentation and landscape heterogeneity may have synergistic effects on physical, chemical and biotic fluxes that can affect the species distributions in complex ways (Hobbs, 2001). In order to develop plans for habitat reconstruction in a region, it is necessary to understand the landscape determinants of species distributions (Westphal et al., 2003). Landscape ecology studies in seagrasses are few but recently this science has been increasing for marine systems. An example of this is Cunha et al. (2005) where emphasizes the importance of the landscape approach and the historical perspective when studying seagrass changes and the importance of taking into consideration long-term changes in seagrass landscapes. Also some studies discuss the increase in patch fragmentation and the major implications for fauna dependent on seagrass habitats (Connolly, 1994; Irlandi, 1997; Hovel and Lipcius, 2001; Pittman et al., 2004). However there is no information on fragmentation in seagrasses in Puerto Rico and therefore studies related to its effects on organisms are also lacking. This study quantifies seagrasses landscape structure to monitor benthic habitats in southwestern Puerto Rico, considering the gradient in depth in a typical reef (Fig.1).

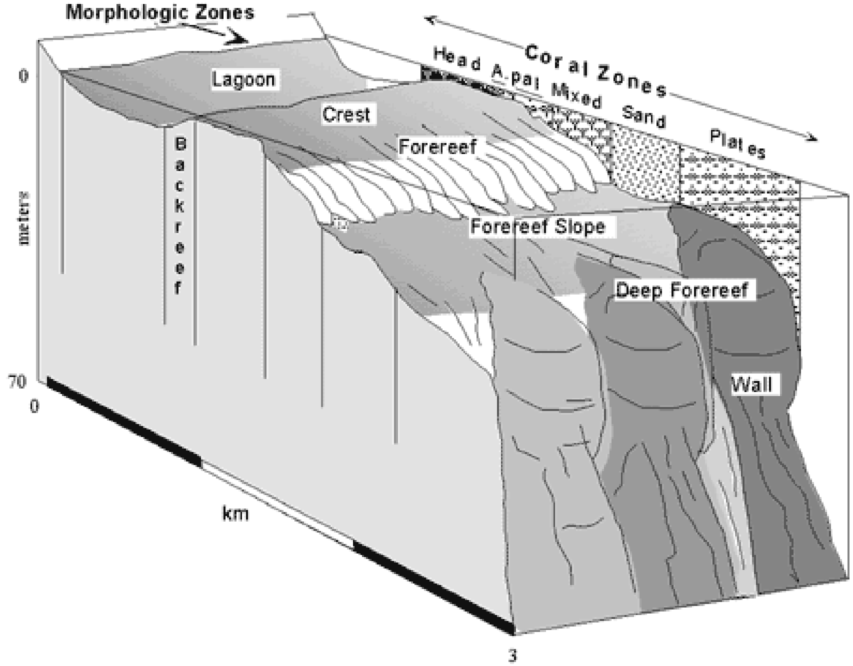


Figure 1. A profile across a "typical" Caribbean reef (Goreau and Land, 1974)

1.1 Hypotheses

1. There is a significant difference in landscape structure between Enrique and Laurel reefs in La Parguera.

1.2 Objectives

The main goal of this study was to quantify landscape structure in two seagrass communities at La Parguera, Puerto Rico.

Specifics objectives are to:

(i) Generate a detailed, accurate benthic map of Enrique and Laurel reefs in La Parguera.

(ii) Compare landscape structure patterns at Enrique and Laurel reefs while taking into consideration differences in depth

2. Methods and Materials

2.1 Study Sites

The study areas are Enrique and Laurel reefs located in southwestern Puerto Rico at the natural reserve of La Parguera (Fig. 2). These sites form part of a reef system that serve as natural barriers, fish nurseries, nursery sites for migratory birds, posses diverse fauna and are used as recreational areas. Both reefs have various habitats such as sand lagoons, coral patches, reef zones and seagrass beds. Enrique and Laurel reefs are approximately 0.5 km in width and 1km in length and can be easily differentiated using satellite remote sensing. The distance from Laurel reef to the coast is approximately 3.55 km and 1.81 km from Enrique reef.

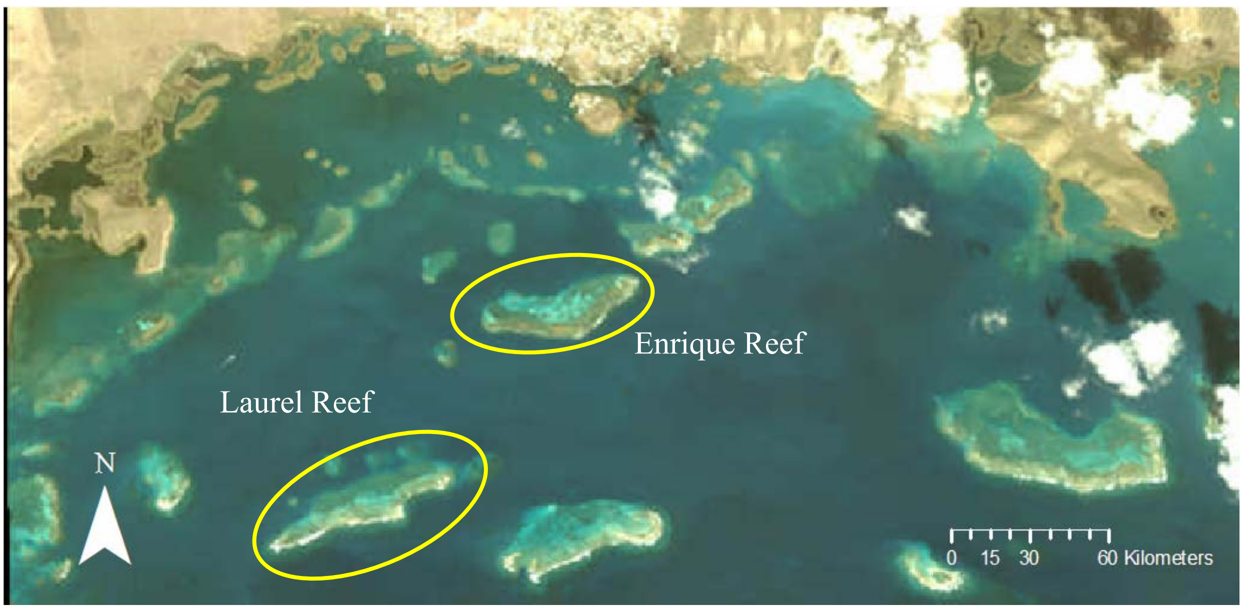


Figure 2. The study sites in La Parguera, Puerto Rico

2.2 Water column corrections

The characteristics of the IKONOS images used are summarized in Table 1. Figures 5-7 present each band in gray scale for Enrique Reef and Figures 11-13 for Laurel Reef. A water column correction procedure was first performed on the 2006 IKONOS images of Enrique and Laurel reefs before doing the benthic maps. Lyzenga (1978, 1981) developed a simple image-based approach to compensate for the effect of variable depth when mapping bottom features. This method produces a depth invariant bottom index from each pair of spectral bands. This technique is only recommended where water clarity is good such as in the study area. To make the correction, a dark pixel subtraction was performed to remove scattering in the atmosphere and external reflection from the water surface. The relationship between depth and radiance was linearized using the natural logarithm of each band pixel value and a calculation of the ratio of attenuation coefficients for the band pair used. A depth invariant index of bottom type is calculated according to:

$$\text{Depth –invariant index} = \mathrm{Ln}(L_i\text{-}L_{\text{dark pixel}})\text{- }[(k_i/k_j)\ \mathrm{Ln}(L_j\text{-}L_{\text{ dark pixel}})]$$

Table 1. IKONOS sensor characteristics

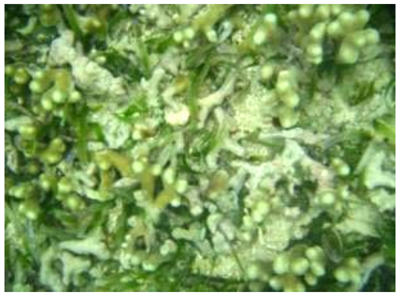
Scene ID	2000030917601 THC
Date	19/2/2006
Radiometric digitization	11 bits

Spectral Bands	Wavelength (µm)	Resolution
1 (blue)	0.40-0.52	4 m
2 (green)	0.52-0.60	4 m
3 (red)	0.63-0.69	4 m
4 (NIR)	0.76-0.90	4 m
Panchromatic	0.45-0.90	1 m

2.3 Benthic Map

IKONOS satellite images and *in situ* measurements were combined to assemble a benthic map of the study areas. The images were processed using the ENVI 4.4 image processing software. After the water column correction of Lyzenga, a supervised classification was performed pixel by pixel. The pixels were validated in the field. The *in situ* data collected for the map was for the type of habitat: sand, soft coral, reef, mangrove and three different types of seagrass densities (Fig. 3) and the location of the position using a sub-meter Trimble Pro XR Global Positioning Systems (GPS). At mixed habitats, the nearest homogenous habitat, its extension as well as the dominant habitat in the general area was considered to classify the map due to the relatively coarse image resolution of IKONOS when compared to the field characterization. The field observations of habitat type were secondarily used to assess the accuracy of the benthic classification. An error matrix was performed to asses the benthic map.

Sand



Sparse seagrass

Dense seagrass

Very dense seagrass

Figure 3. Seagrass density categories used to classifythe benthic map

2.4 Landscape Structure

Based on the classification map created, quantification of landscape structure were analyzed using FRAGSTATS 3.3 software (McGarigal and Marks, 1995) which calculates landscape indexes for the different levels of patch (basic elements of the mosaic), class (each particular patch type), and landscape (mosaic of patches as a complete unit) (Teixidó et al., 2002). According to Riitters et al. (1995) the use of few metrics is a simplification which ignores some potential gain of precision, but at the same time, it avoids both the difficulty of interpreting linear combinations of many metrics, and the need to calculate them all for each map. The current study proposes to choose the simple metrics to have an overview of the landscape structure. The metrics were analyzed at two different levels: class and landscape level. Nine indexes were selected to analyze landscape structure at class level: class area (CA), percent of landscape (PLAND), number of patches (NP), mean patch size (AREA_MN), area-weighted mean shape index (SHAPE_AM) , area-weighted mean patch fractal dimension (FRAC_AM), Euclidean mean nearest neighbor distance (ENN_MN), mean proximity index (PROX_MN), interspersion and juxtaposition index (IJI). Eleven indexes were selected to analyze landscape structure at landscape level: total landscape area (TA), largest patch index (LPI), number of patches (NP), mean patch size (AREA_MN), area-weighted mean shape index (SHAPE_AM), area-weighted mean patch fractal dimension (FRAC_AM), Euclidean mean nearest neighbor distance (ENN_MN), mean proximity index (PROX_MN), patch richness (PR), interspersion and juxtaposition index (IJI), contagion index (CONTAG). For information on how these indexes were calculated see Appendix A (from McGarigal and Marks, 1995). The ASCII version of FRAGSTATS was used in our analysis to calculate the indexes. Some considerations in the calculations were taken as the grid resolution was 1m and the search distance used in the calculation of proximity index was 200 m. This proximity index distance was selected based on a study by Li et al. (2001) where the image used had a grid resolution of 250 m and the search distance used in the calculation of proximity index was 50,000 m; the same proportion is used in this study. This takes into consideration the size of the study area of 1 km. Figure 4 present a summary of the methodology used for this chapter.

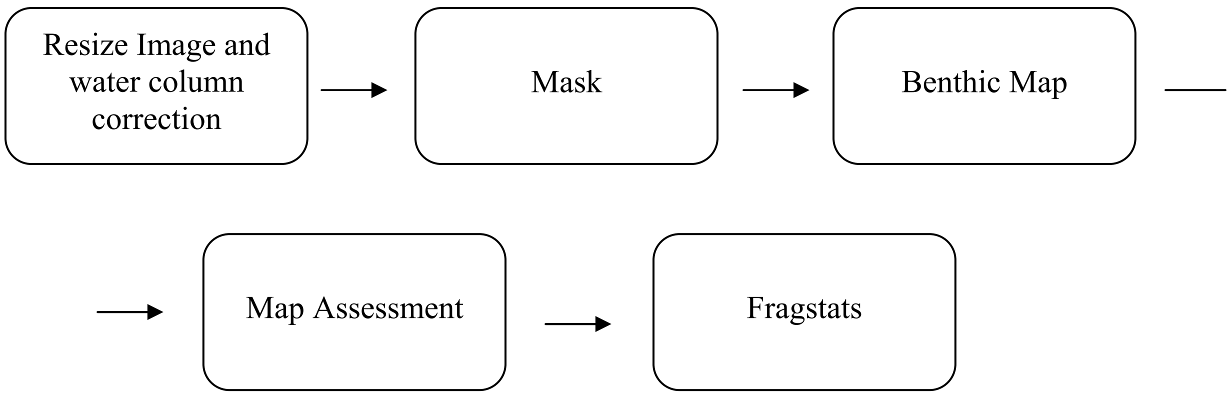


Figure 4. Methods Summary

3. Results

3.1 Water Column Correction

A Lyzenga's water column correction was performed to remove the influence of the water depth in the bottom features prior to benthic mapping. A dark pixel ($L_{dark\ pixel}$) subtraction was performed to remove scattering in the atmosphere and external reflection from the water surface. The dark pixel was obtained subtracting the average and standard deviation of a group of pixels to account for noise in the image. Based on *in situ* data acquired in December 2005 during an AVIRIS Mission at La Parguera, the attenuation coefficients were calculated (see table 2 for Enrique Reef). Figures 8-10 present the depth-invariant products for Enrique Reef. The best depth-invariant band combination for Enrique Reef is the ratio between bands green and red

(Figure 10). This algorithm was used because the contrast of the bottom features is high and the noise signal is low. The algorithm used for Enrique Reef water column correction was:

$$\text{Depth –invariant index} = \mathrm{Ln}(L_{green}-23.24)- [(.125/.53)\ \mathrm{Ln}(L_{red}-13.30)]$$

Table 2. Summary of parameters for Lyzenga's water column for Enrique Reef.

Band	**Attenuation Coefficient**	**Mean**	**Standard Deviation**	**$L_{dark\ pixel}$ = Mean – std deviation**
B1 Red	.53	74.06	60.76	13.30
B2 Green	.125	101.58	78.34	23.24
B3 Blue	.11	100.22	68.38	31.84

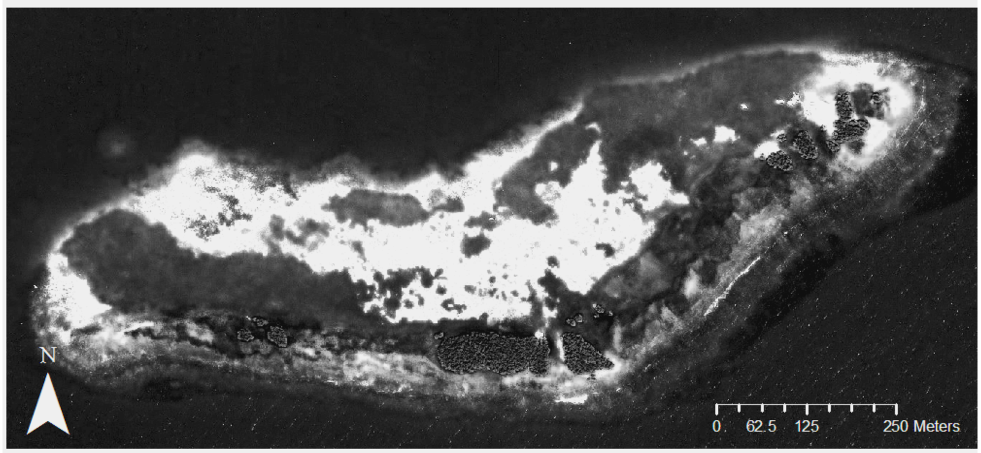


Figure 5. Blue band in gray scale for Enrique Reef

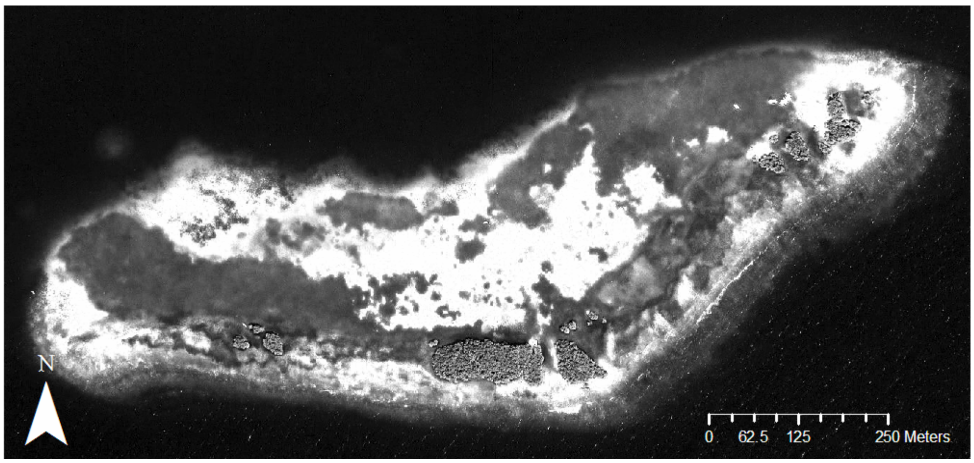


Figure 6. Green band in gray scale for Enrique Reef

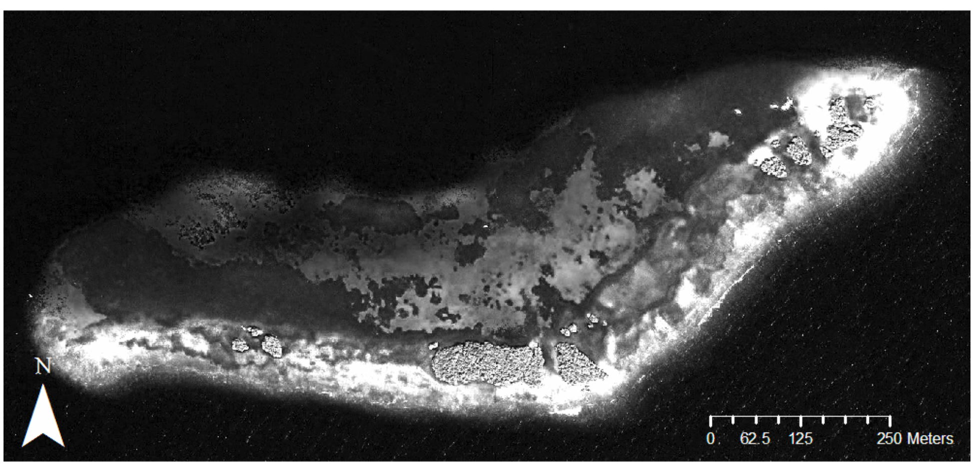


Figure 7. Red band in gray scale for Enrique Reef

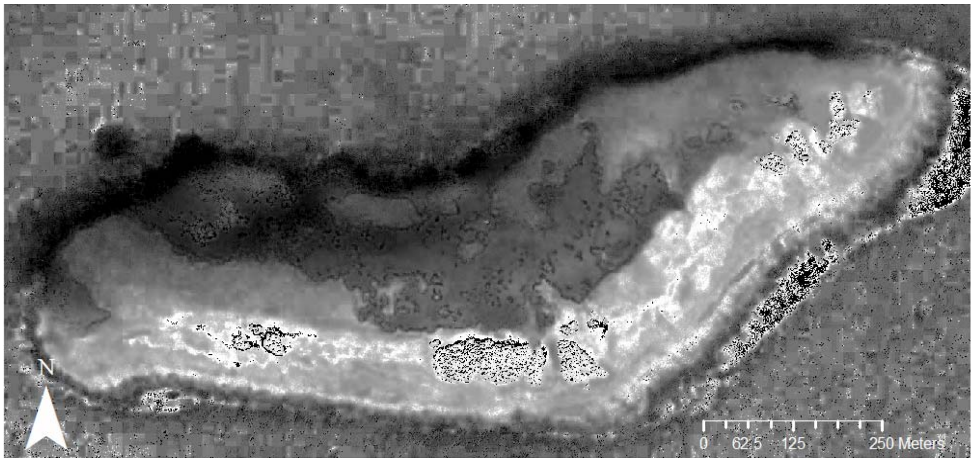


Figure 8. Lyzenga's red/blue band ratio product for Enrique Reef

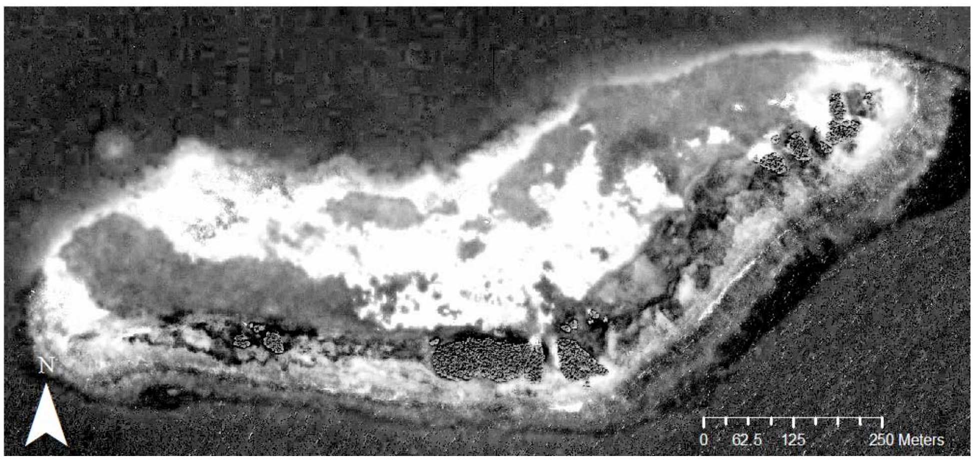


Figure 9. Lyzenga's green/blue band ratio product for Enrique Reef

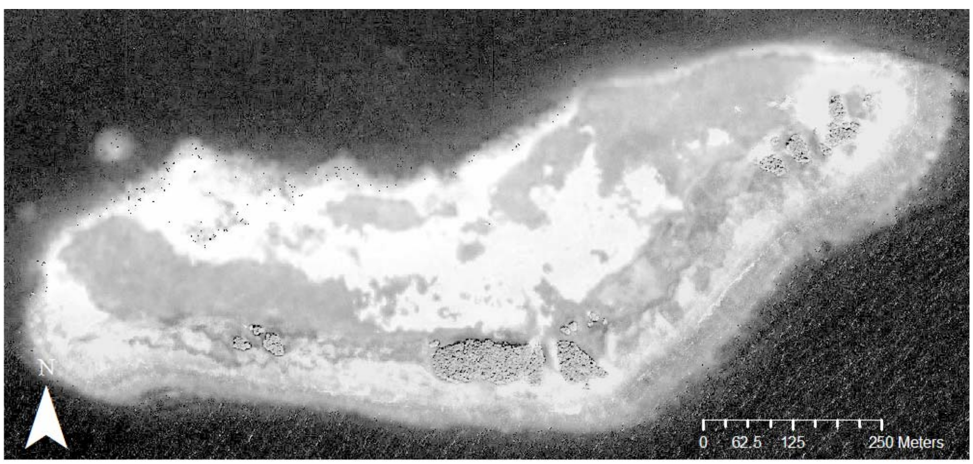


Figure 10. Lyzenga's red/green band ratio product for Enrique Reef

For Laurel, the same attenuation coefficients were applied based on *in situ* data used for the water column correction algorithm (see table 3). The same attenuation coefficients were applied due to the similarity in optical properties between sites according to the observations during the 2005 AVIRIS Mission. Figures 14-16 present the depth-invariant products for Laurel Reef. The best algorithm for Laurel Reef used a ratio between the blue and red bands (Figure 16). This algorithm was used because the contrast of the bottom features is high and the noise signal is low. The algorithm used for Laurel Reef water column correction was:

$$\text{Depth –invariant index} = \text{Ln}(L_{blue}-35.14) - [(.11/.53)\ \text{Ln}(L_{red}-14.90)]$$

Table 3. Summary of parameters for Lyzenga's water column for Laurel Reef

Band	**Attenuation Coefficient**	**Mean**	**Standard Deviation**	**$L_{dark\ pixel}$ = Mean – (2) (std deviation)**
B1 Red	.53	25.92	5.50	14.90
B2 Green	.125	25.85	5.50	14.84
B3 Blue	.11	46.57	5.71	35.14

Figure 11. Blue band in gray scale for Laurel Reef

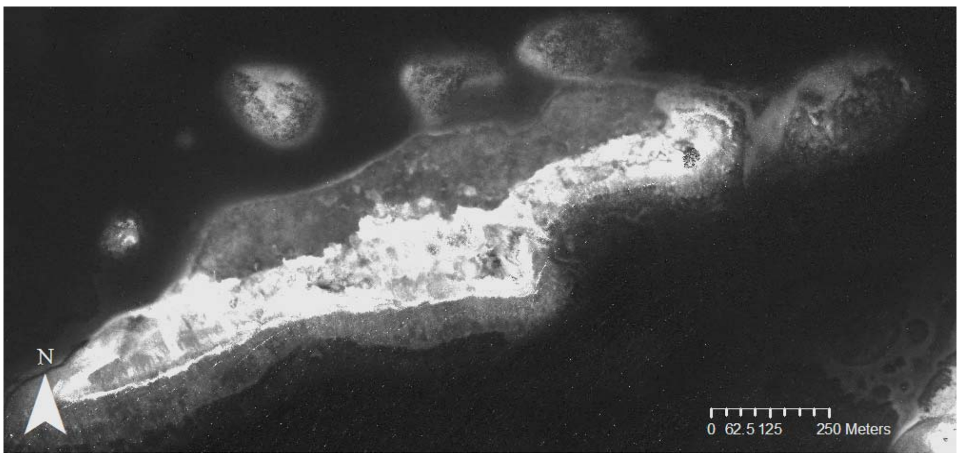


Figure 12. Green band in gray scale for Laurel Reef

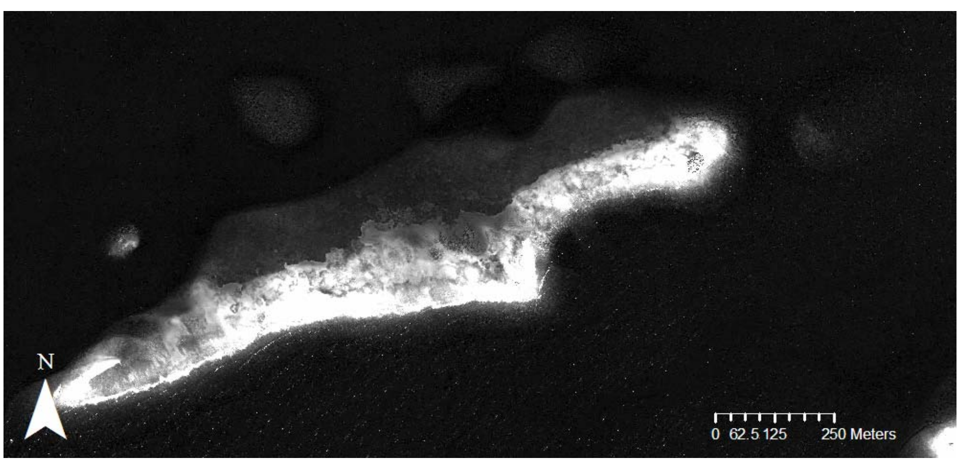


Figure 13. Red band in gray scale for Laurel Reef

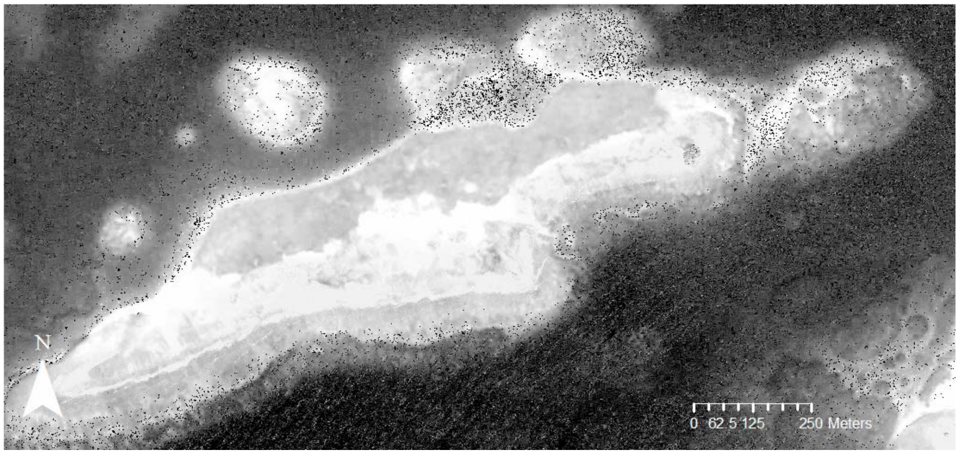


Figure 14. Lyzenga's green/red band ratio product for Laurel Reef

Figure 15. Lyzenga's blue/green band ratio product for Laurel Reef

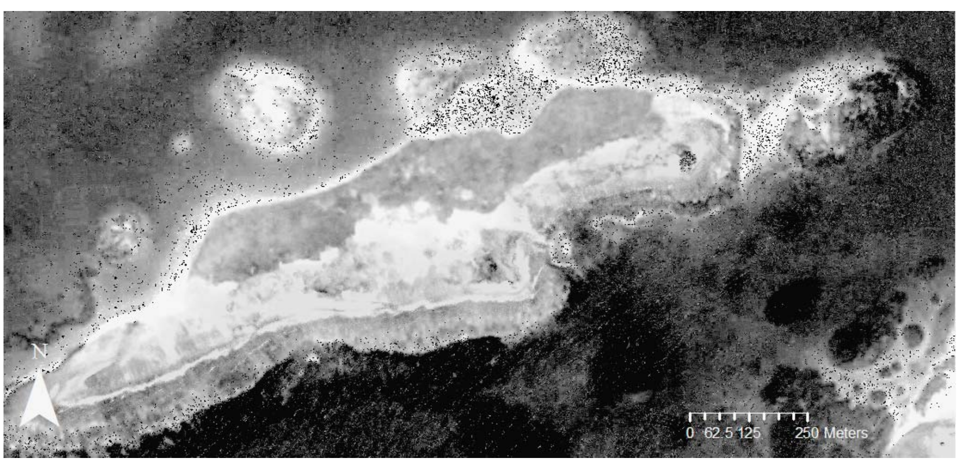


Figure 16. Lyzenga's blue/red band ratio product for Laurel Reef

3.2 Benthic Map

IKONOS images have three broad bands in the red, blue and green region of the spectrum (Table1). Therefore, its spectral resolution is not optimum for differentiating some spectrally-similar bottom features such as deep sand and seagrasses. However, its spatial resolution at 1 m^2 is more than adequate for the requirements of this study. After the water column correction, the first supervised classification resulted in mixed seagrass with corals, soft corals and sand because of the sensor's spectral resolution limitation. For this reason a pixel by pixel classification was made in combination with *in situ* data. A mask was built to eliminate deep water from further analyses. A total of seven classes were obtained for Enrique and Laurel reefs maps. These classes include mangroves, soft coral, fore reef, sand and the three categories of seagrass based on the seagrass densities (sparse, dense, and very dense seagrass, see Table 4). It is important to point out that fore reef is a class and the variation or patches within this category were not evaluated. Sand includes sand, rubble and dead coral. Although these are ecologically different habitats the image does not differentiate between them spectrally therefore they were group in one class. Table 4 presents the depth from a LIDAR 4 m resolution image from December 2007 (Fig. 17) and the zone within the reef for each class.

Table 4. Definition of classes use for benthic map and their depth

Class	Definition	Morphologic Zone	Depth Enrique (m)	Depth Laurel (m)
Sand	Includes sand, rubble and dead coral.	Through all zones	0-5.13	0-9.04
Soft coral	Includes several species of soft corals and patches of soft corals in the lagoon.	Lagoon	0.49-3.70	2.18-8.68
Mangroves	Include two types of mangroves *Rhizophora mangle*, *Laguncularia racemosa* and some vegetation present at the sites.	Crest	0-0.72	0
Fore Reef	Includes area from the reef crest (where the waves break to base at the end of the fore reef). This includes both living and dead hard corals, gorgonians, sponges and other reef components.	Crest and Fore reef	0.34-3.55	0-12.09
Seagrass (three different classes)	Based on the seagrass densities (sparse seagrass, dense seagrass and very dense seagrass) observed through the IKONOS image and *in situ* data.	Crest and Lagoon	Sp 0-4.48 D 0-2.77 VD 0.25-2.77	Sp 0-4.96 D 0-6.12 VD 0.02-3.80

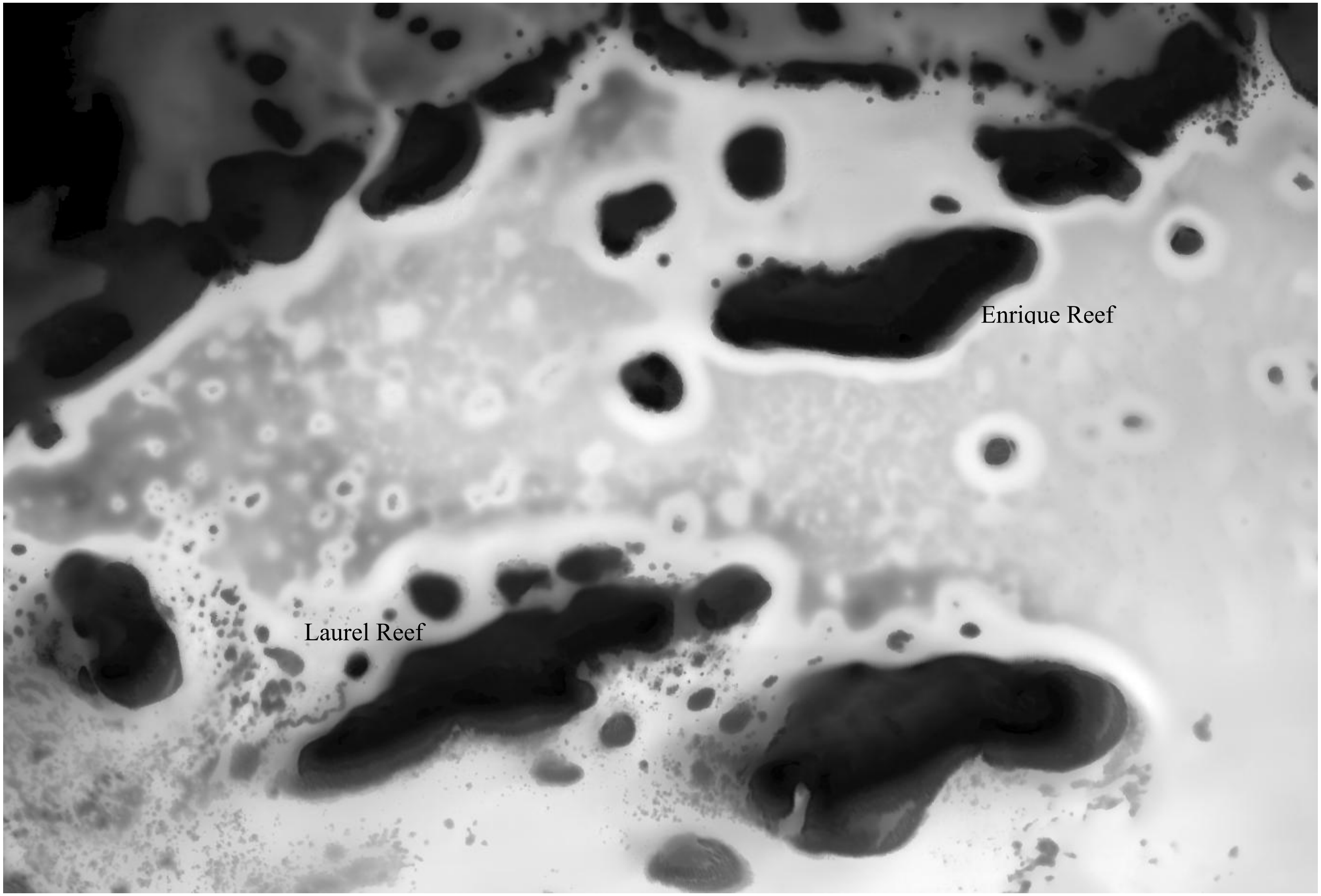


Figure 17. LIDAR bathymetry image subset of 4m resolution from December 2007

Figure 18 and 19 illustrate the benthic maps obtained for Enrique and Laurel Reefs, respectively. To verify the accuracy of the benthic map an error matrix was made to ensure the reliability of the results; this matrix provides a kappa coefficient. In Enrique Reef a kappa coefficient of 55.30% was achieved, this means that 55.3% more pixels were classified correctly than expected by random classification. A total of 154 random points were taken to asses the benthic map, this technique was employed to give equal opportunity to every pixel to be represented in the assessment. According to the error matrix of Enrique Reef (Table 5) the main source of error was the seagrass densities; dense seagrass was confused with sparse and very dense seagrass and sparse seagrass was confused with sand. In Laurel Reef the kappa coefficient obtained was 66.62 %, a total of 229 random points were taken and the same problem in the error matrix (Table 6) was observed where the dense seagrass was confused with sparse and very dense seagrass as did sparse seagrass with sand.

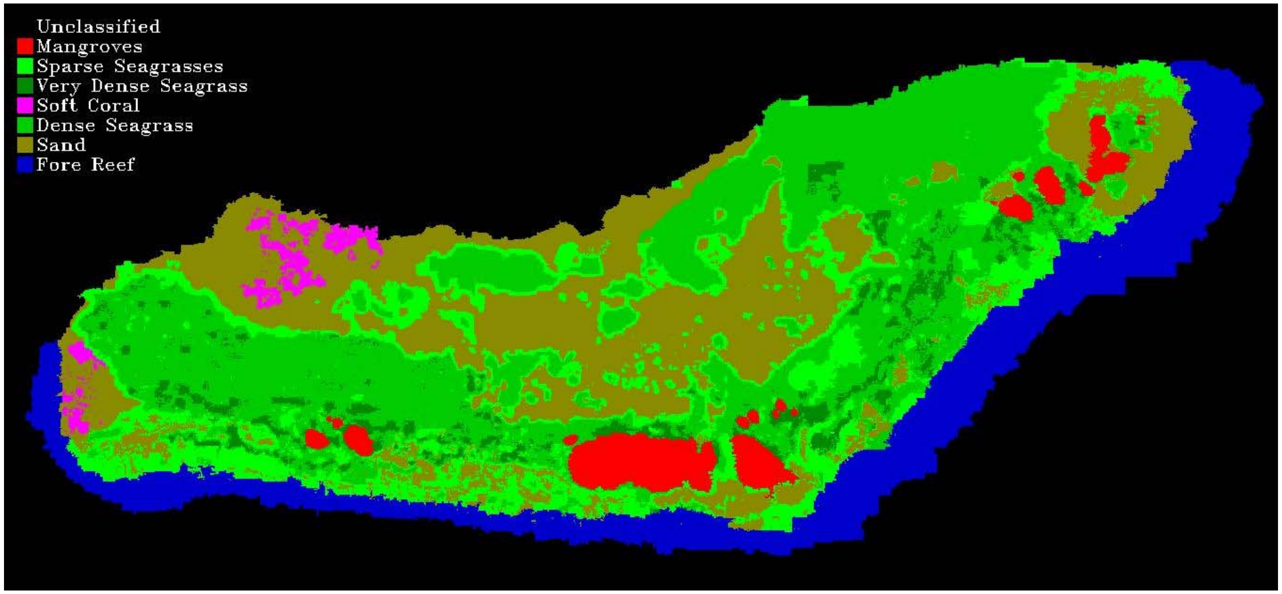


Figure 18. Product of Enrique Reef benthic map

Table 5. Enrique Reef error matrix, Kappa coefficient 55.3

	Mangrove	Sparse Seagrass	Very Dense Seagrass	Soft coral	Dense seagrass	Sand	Fore reef
Mangrove	4	0	0	0	0	0	0
Sparse Seagrass	0	12	0	0	5	4	3
Very Dense Seagrass	1	1	5	0	3	0	0
Soft coral	0	0	0	16	0	0	0
Dense seagrass	1	10	11	0	30	3	0
Sand	0	8	1	2	3	7	0
Fore reef	0	0	0	0	0	0	24

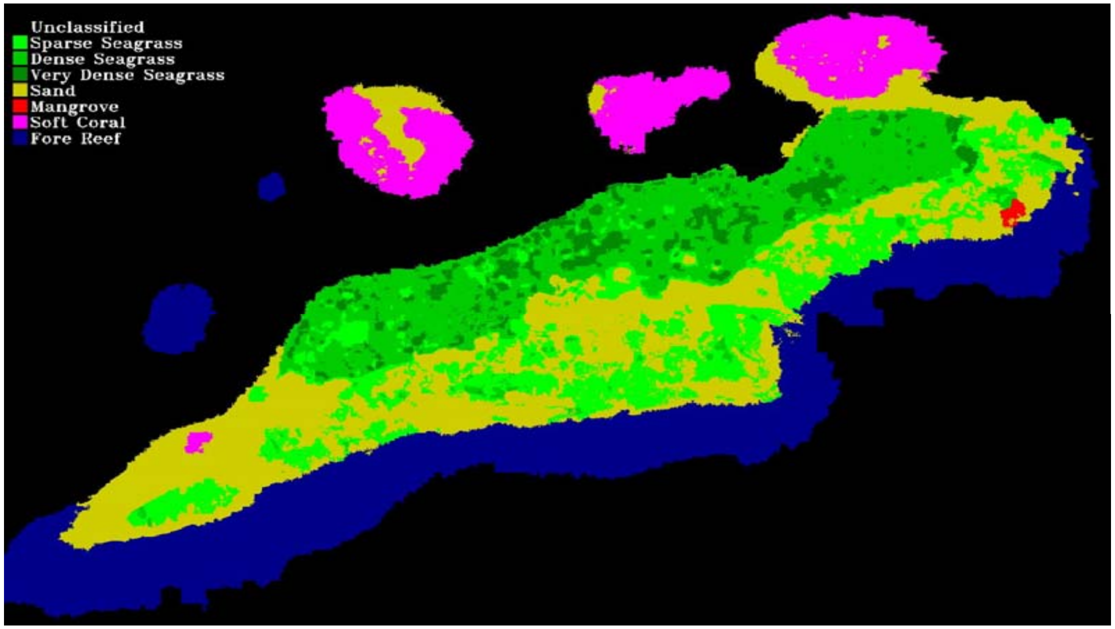


Figure 19. Product of Laurel Reef benthic map

Table 6. Laurel error matrix, Kappa coefficient 64.64 %

	Mangrove	Sparse Seagrass	Very Dense Seagrass	Soft coral	Dense Seagrass	Sand	Fore reef
Mangrove	1	0	0	0	1	0	0
Sparse Seagrass	0	22	0	0	5	9	17
Very Dense Seagrass	0	5	1	0	2	0	0
Soft coral	0	1	0	28	0	1	0
Dense Seagrass	0	27	3	0	16	2	0
Sand	0	19	0	7	8	35	19
Fore reef	0	0	0	4	0	6	78

3.3 Landscape Structure

3.3.1 Landscape Structure at Class Level for Enrique Reef

In Enrique Reef the main patch types are sand, dense seagrass and sparse seagrass, which account approximately for 75% of the total landscape area (Table 7). Among these three types of patches, dense seagrass present coarse grain size and a large mean shape index, suggesting that the natures of these patches are irregular. The highest coarse grain size of the entire map was fore reef. The sparse seagrass class presents a high fractal dimension index which indicates high complexity, a high number of patches, the lowest proximity index and the smaller grain size which confirm more fragmented and isolated patches than sand and dense seagrass. The lowest interspersion and juxtaposition index obtained for these three types of patches is for sand, which indicates that the patches are more unevenly distributed than dense and sparse seagrass. Some other types of patches such as soft coral had the lowest interspersion and juxtaposition index of all and mangroves occupied only a small percent of the total area and were dispersed among the major patch types. It is important to notice that very dense seagrass occupy a small area and has a high number of patches and the lowest proximity index of all classes that indicates large distance between the same types of patches and hence more fragmented and isolated patches than the other class types.

3.3.2 Landscape Structure at Class Level for Laurel Reef

The three classes that predominate in Laurel Reef are sand, fore reef and dense seagrass occupying 20.6%, 16.1% and 12.7%, respectively, of the total landscape area (Table 7). Sand and dense seagrass have a small fractal dimension and high proximity index within these three classes suggesting high continuity and dense clusters. Sand has a large number of small patches with a high complexity. Fore reef present coarse grain size and a small shape index, therefore the nature of these patches become less circular in shape. Sparse seagrass occupy less area than sand, dense seagrass and fore reef but it have a high number of patches and a low proximity index compared to them, suggesting more patches but less contiguous hence high fragmentation. A significant observation is that very dense seagrass occupy a small area, has a high number of patches and the lowest proximity index of all classes in Laurel Reef and show more distance between these types of patches and hence more fragmented and isolated patches than the entire map classes.

Table 7. Class level results for Enrique and Laurel Reef. Class area (CA), Percent of landscape (PLAND), Number of patches (NP), Mean patch size (AREA_MN), Area-weighted mean shape index (SHAPE_AM), Area-weighted mean patch fractal dimension (FRAC_AM), Euclidean mean nearest neighbor distance (ENN_MN), Mean proximity index (PROX_MN), Interspersion and juxtaposition index (IJI)

TYPE	CA (ha)	PLAND Image	PLAND in Site	NP	AREA_MN	SHAPE_AM	FRAC_AM	PROX_MN	ENN_MN	IJI
					Enrique Reef					
Sparse Seagrass	6.70	7.92	16.28	741	0.01	8.65	1.47	487.05	3.35	55.75
Dense Seagrass	13.27	15.69	32.24	280	0.05	11.97	1.44	5173.60	3.50	56.03
Fore reef	6.56	7.75	15.93	4	1.64	6.01	1.32	12291.69	2.00	53.82
Sand	10.73	12.69	26.07	491	0.02	8.06	1.40	1407.95	3.57	43.88
Mangrove	1.62	1.92	3.94	16	0.10	1.79	1.14	91.64	7.15	70.67
Very Dense Seagrass	1.72	2.04	4.18	430	0.00	2.80	1.36	25.58	3.35	23.74
Soft Coral	0.56	0.66	1.36	67	0.01	3.14	1.34	51.95	3.13	5.81
					Laurel Reef					
Sparse Seagrass	8.47	5.38	13.88	550	0.02	6.72	1.41	601.89	4.09	39.65
Dense Seagrass	10.47	6.65	17.16	190	0.06	15.47	1.47	7488.75	5.12	49.10
Fore reef	17.45	11.09	28.61	6	2.91	4.98	1.26	11332.31	29.16	25.92
Sand	16.20	10.29	26.56	560	0.03	10.33	1.42	4953.88	3.31	47.21
Mangrove	0.10	0.06	0.16	2	0.05	2.35	1.25	119.63	2.00	41.07
Very Dense Seagrass	2.52	1.60	4.13	307	0.01	2.45	1.27	37.87	4.57	8.69
Soft Coral	5.79	3.68	9.50	5	1.16	3.28	1.24	1134.58	140.50	0.00

3.3.3 Landscape Structure at Landscape Level

At the landscape level, Enrique Reef was found to have a larger number of patches in less area, smaller patches, more disconnected patches and slightly more complex patches than Laurel Reef, as demonstrated by a higher fractal dimension index and shape index (Table 8). Nonetheless in Laurel we found lower number of patches with stronger continuity but lower interspersion. According to Wickham et al. (1997), contagion measures the degree to which the landscape is composed of a few large or several small patches. High values of contagion indicate that the landscape is clumped into a few, large patches. The contagion values are 50.09% for Enrique and 52.32% for Laurel indicates that Laurel patches are to some extent more aggregated than Enrique. This is confirmed when the interspersion and juxtaposition index prove to be higher for Enrique Reef indicating more interspersed patches. The patch richness for both sites is seven, as expected, because of its previously determined seven classes.

Table 8. Landscape level results for Enrique and Laurel Reef. Total landscape area (TA), largest patch index (LPI), number of patches (NP), mean patch size (AREA_MN), area-weighted mean shape index (SHAPE_AM), area-weighted mean patch fractal dimension (FRAC_AM), Euclidean mean nearest neighbor distance (ENN_MN), Mean proximity index (PROX_MN), Patch richness (PR), Interspersion and juxtaposition index (IJI), Contagion index (CONTAG).

Site	TA (ha)	NP	LPI	AREA_MN	SHAPE_AM	FRAC_AM	PROX_MN	ENN_MN	CONTAG	IJI	PR
Enrique	84.5625	2029	8.59	0.02	8.55	1.40	1264.17	3.44	50.09	57.20	7
Laurel	157.3915	1620	10.47	0.04	8.17	1.36	2853.28	4.54	52.32	50.46	7

3.3.4 Landscape Structure at Class Level for Enrique Reef by Zone

Taking into consideration the gradient of depth and zonation within each reef, the reef was separated into zones. The zones chosen were the lagoon with a depth range of 0.49-3.70 m in Enrique reef and 2.18-8.68 m in Laurel reef and the crest of the reef 0-0.72 m in Enrique reef and 0 in Laurel reef according to the LIDAR image. For the purposes of this study the crest zone is composed by the reef flat and the reef crest and does not include the reef slope or fore reef (Figure 1). Figure 20 is an outline of the different subdivisions that were created and analyzed for each reef.

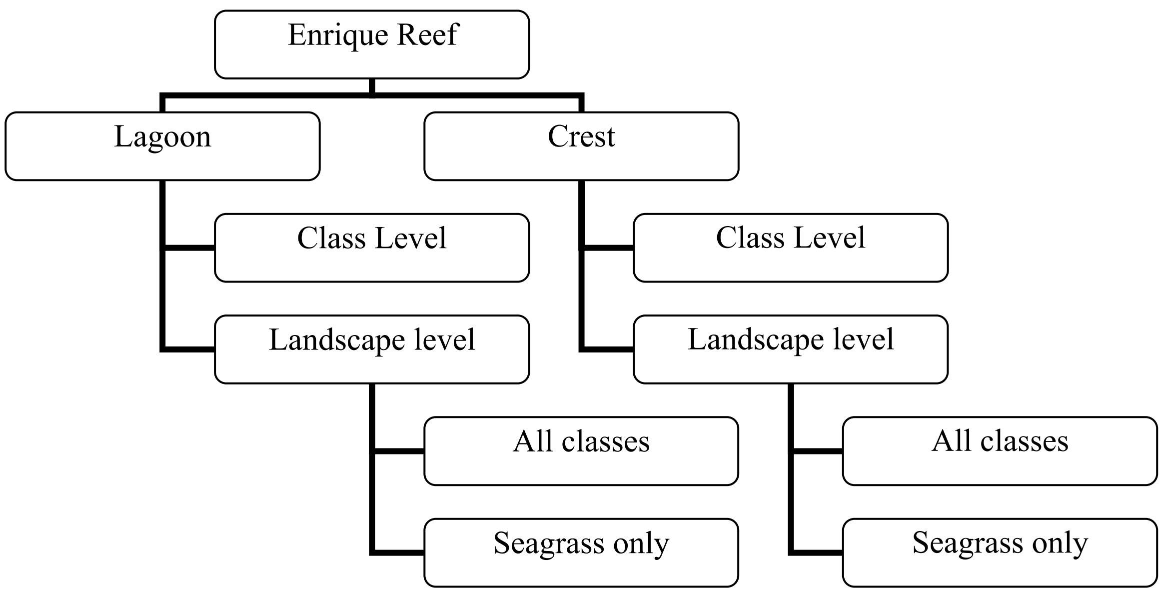


Figure 20. Outline of the different zones used to analyze Enrique landscape structure. These zones were analyzed at two different levels in Fragstats 3.3 (class and landscape). At the landscape level two subdivisions (all classes included in the zone and seagrasses present in the zone) were analyzed.

3.3.4.1 Landscape Structure at Class Level for Enrique Reef in the Lagoon

In the lagoon of Enrique Reef (Fig. 21) the Fragstats results (Table 9) showed that dense seagrass covered most of the area at 11.28 ha. Sparse seagrass and very dense seagrass were the classes with more number of patches covering less area. The patches with a large coarse grain size were dense seagrass with a mean size of 0.08 m^2. The dense seagrass patches together with sand patches have a high shape index and high proximity index 5987.11 for dense seagrass 4036.67 for sand indicating an irregular shape, and that the patches are close within the same class. In the lagoon the class with the highest interspersion and juxtaposition index was soft coral.

3.3.4.2 Landscape Structure at Class Level for Enrique Reef in the Crest

The classes that occupy the larger area in the crest of Enrique (Fig. 22) were sparse seagrass and sand occupying 3.22 ha and 2.50 ha, respectively. Sand has the highest number of patches and mangrove the fewer, while the larger patches are at the crest (Table 10). In this zone the complex patches were dense seagrass with a shape index of 8.82. The patches that demonstrated to be near each other were sparse seagrass where the nearest neighbor had an average distance of 2.7 m. The highest interspersion and juxtaposition index was for mangrove with a 92.78%, indicating that they were dispersed among the other classes.

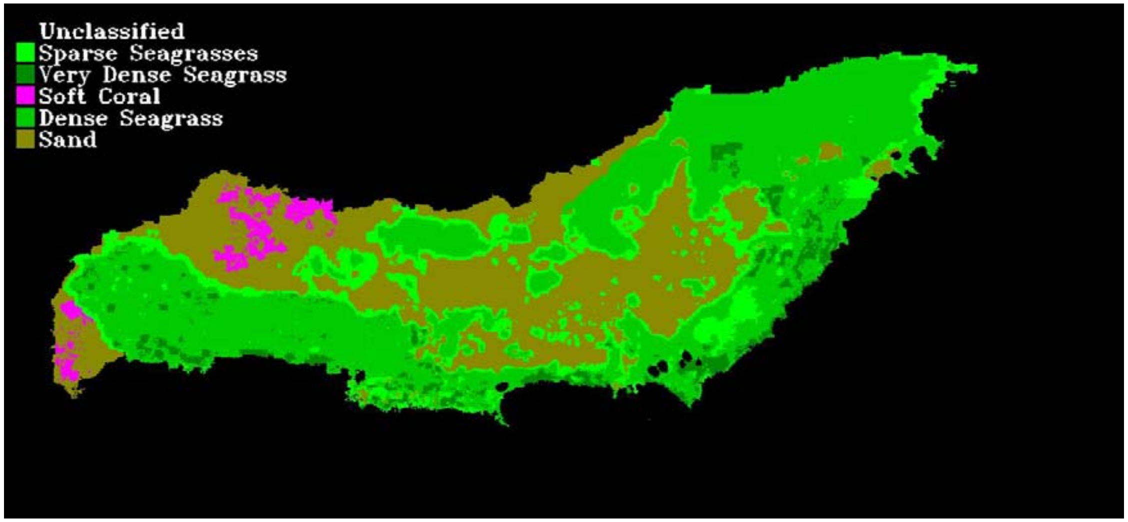


Figure 21. Product of the lagoon of Enrique Reef

Table 9. Class level results of the lagoon in Enrique Reef. Class area (CA), Percent of landscape (PLAND), Number of patches (NP), Mean patch size (AREA_MN), Area-weighted mean shape index (SHAPE_AM) , Area-weighted mean patch fractal dimension (FRAC_AM), Euclidean mean nearest neighbor distance (ENN_MN), Mean proximity index (PROX_MN), Interspersion and juxtaposition index (IJI)

TYPE	CA(ha)	PLAND	NP	AREA_MN	SHAPE_AM	FRAC_AM	PROX_MN	ENN_MN	IJI
Sparse seagrass	3.55	4.19	405	0.01	6.89	1.45	115.48	3.99	56.06
Dense seagrass	11.28	13.34	134	0.08	9.09	1.40	5987.11	3.89	57.52
Sand	8.28	9.79	155	0.05	9.02	1.40	4036.67	4.53	50.56
Very Dense Seagrass	1.17	1.39	308	0.00	2.90	1.36	24.45	3.55	12.52
Soft coral	0.56	0.66	67	0.01	3.14	1.34	51.95	3.13	6.20

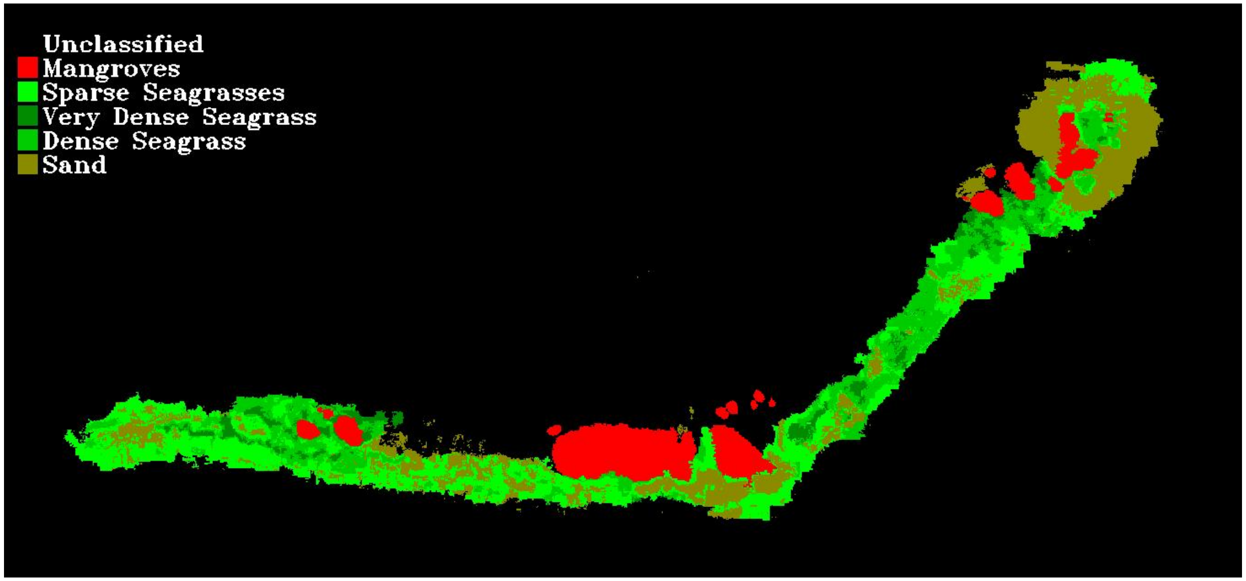


Figure 22. Product of the crest of Enrique Reef

Table 10. Class level results of the crest in Enrique Reef. Class area (CA), Percent of landscape (PLAND), Number of patches (NP), Mean patch size (AREA_MN), Area-weighted mean shape index (SHAPE_AM) , Area-weighted mean patch fractal dimension (FRAC_AM), Euclidean mean nearest neighbor distance (ENN_MN), Mean proximity index (PROX_MN), Interspersion and juxtaposition index (IJI)

TYPE	CA	PLAND	NP	AREA_MN	SHAPE_AM	FRAC_AM	PROX_MN	ENN_MN	IJI
Sparse Seagrass	3.22	3.81	369	0.01	7.47	1.46	455.41	2.77	63.47
Dense Seagrass	1.95	2.30	167	0.01	8.82	1.49	352.82	3.28	77.02
Sand	2.50	2.96	395	0.01	4.90	1.40	178.01	3.60	28.90
Mangrove	1.62	1.92	16	0.10	1.79	1.14	91.64	7.15	92.79
Very Dense Seagrass	0.54	0.64	123	0.00	2.55	1.36	23.22	3.10	40.59

3.3.5 Landscape Structure at Class Level for Laurel Reef by Zone

3.3.5.1 Lagoon

According to Table 11 sand and dense seagrass covered most of the lagoon at 10.94 ha and 10.34 ha, respectively. Sand represents the class with the highest number of patches and soft coral with the lowest number of patches but with the larger patches. The class with the most complex and irregular patches was dense seagrass, indicated by the shape index at 15.64 and the patch fractal dimension index at 1.48. Also this class presents the highest proximity index and an average distance between these patches of 5.23 m as demonstrated by the Euclidean mean nearest neighbor. It is important to point out that this class presents the highest interspersion and juxtaposition index.

3.3.5.2 Crest

In the crest zone of Laurel reef (Fig. 24) only four classes were present: mangrove, sand, sparse and dense seagrass. Sand occupies the most area at 5.31 ha with the highest number of patches, the highest proximity index and an average distance of the patches of 4.67 m (Table 12). Sand is followed by sparse seagrass covering 3.06 ha with a high mean patch size of 0.03 m^2 and more complex patches. Dense seagrass are the patches with the highest interspersion and juxtaposition index and the lager patches are for mangrove with an average size of 0.05 m^2.

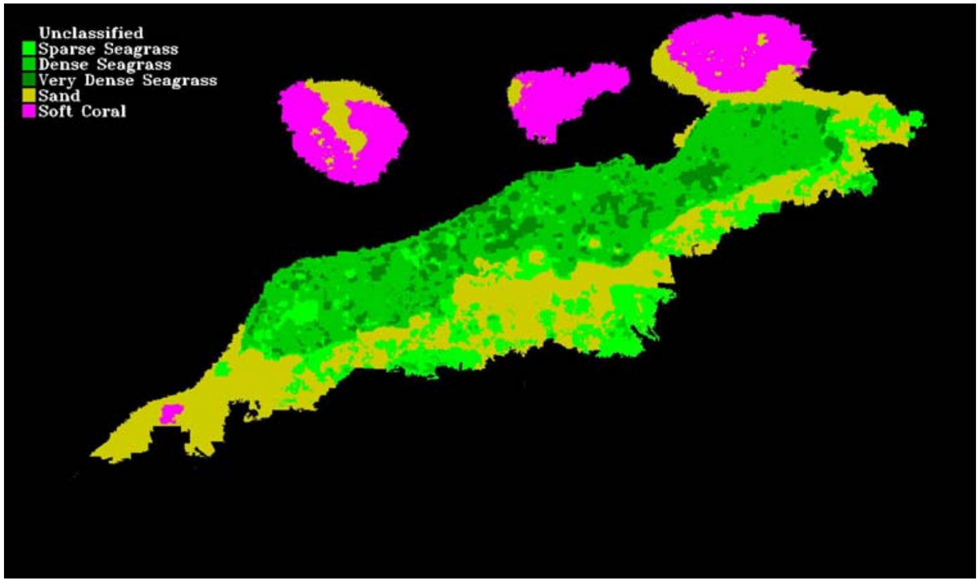


Figure 23. Product of the lagoon of Laurel Reef

Table 11. Class level results of the lagoon in Laurel Reef. Class area (CA), Percent of landscape (PLAND), Number of patches (NP), Mean patch size (AREA_MN), Area-weighted mean shape index (SHAPE_AM) , Area-weighted mean patch fractal dimension (FRAC_AM), Euclidean mean nearest neighbor distance (ENN_MN), Mean proximity index (PROX_MN), Interspersion and juxtaposition index (IJI)

TYPE	CA	PLAND	NP	AREA_MN	SHAPE_AM	FRAC_AM	PROX_MN	ENN_MN	IJI
Sparse Seagrass	5.34	3.39	473	0.01	4.61	1.37	211.51	4.34	53.22
Dense Seagrass	10.34	6.57	153	0.07	15.64	1.48	9295.24	5.23	60.10
Sand	10.94	6.95	310	0.04	7.59	1.38	2414.29	3.81	49.92
Very Dense Seagrass	2.52	1.60	307	0.01	2.45	1.27	37.87	4.57	11.23
Soft coral	5.79	3.68	5	1.16	3.28	1.24	1134.58	140.50	0.00

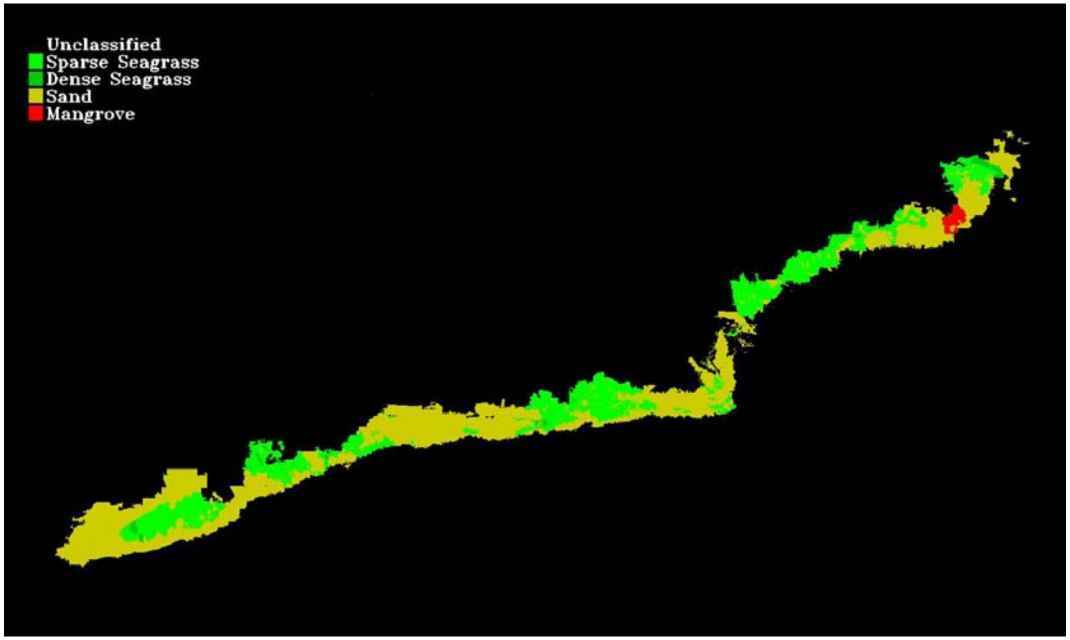


Figure 24. Product of the crest of Laurel Reef

Table 12. Class level results of the crest in Laurel Reef. Class area (CA), Percent of landscape (PLAND), Number of patches (NP), Mean patch size (AREA_MN), Area-weighted mean shape index (SHAPE_AM) , Area-weighted mean patch fractal dimension (FRAC_AM), Euclidean mean nearest neighbor distance (ENN_MN), Mean proximity index (PROX_MN), Interspersion and juxtaposition index (IJI)

TYPE	CA	PLAND	NP	AREA_MN	SHAPE_AM	FRAC_AM	PROX_MN	ENN_MN	IJI
Sparse Seagrass	3.06	1.95	95	0.03	5.62	1.40	513.23	3.15	31.19
Dense Seagrass	0.13	0.08	33	0.00	2.32	1.33	7.75	8.00	40.42
Sand	5.31	3.38	314	0.02	4.74	1.34	537.39	4.67	21.56
Mangrove	0.10	0.06	2	0.05	2.35	1.25	119.63	2	12.04

3.3.6 Landscape Structure at landscape level by zone

3.3.6.1 Lagoon

3.3.6.1.1 All classes

The lagoon in Laurel has a higher number of patches and bigger patches. The shape index is similar in both sites at this level, 8.33 for Enrique reef and 8.43 for Laurel reef (Table 13). According to the proximity index the lower the number, the fewer the neighbors the patch has of the same patch type. Table 13 shows that Laurel has a higher proximity index and a higher average distance between patches at 4.92 m. However, the contagion index suggests that the patches of Enrique reef are more aggregated at 53.05% than Laurel reef at 45.89%. The number of classes at both sites was the same at five classes. Shannon's evenness index (range 0-1), for Enrique was 0.77 and 0.93 for Laurel. At this value approach 1, the distribution of area among patch types is perfectly even.

3.3.6.1.2 Seagrass

When considering only the seagrass classes (sparse, dense and very dense seagrass) in the lagoon (Fig. 25 and 26), the same tendency is found. Laurel has a higher proximity index and a higher average distance between patches of 4.56 m while Enrique presents a higher contagion index of 53.23% and Laurel reef at 45.37% demonstrating that the patches of Enrique Reef are more aggregated (Table 14). Laurel presents a larger number of patches; however the average patch size is the same for both sites at 0.02 m^2. In this case the shape index of Laurel indicates irregular patches although the fractal dimension index is the same for both reefs at 1.41.

Table 13. Landscape level results of the lagoon considering all classes in this zone. Total landscape area (TA), largest patch index (LPI), number of patches (NP), mean patch size (AREA_MN), area-weighted mean shape index (SHAPE_AM), area-weighted mean patch fractal dimension (FRAC_AM), Euclidean mean nearest neighbor distance (ENN_MN), Mean proximity index (PROX_MN), Patch richness (PR), Interspersion and juxtaposition index (IJI), Contagion index (CONTAG), Shannon's Diversity index (SHDI), Shannon's Evenness index (SHEI)

Site	TA	NP	LPI	AREA_MN	SHAPE_AM	FRAC_AM	PROX_MN	ENN_MN	CONTAG	IJI	PR	SHDI	SHEI
Enrique	84.56	1069	8.55	0.02	8.33	1.40	1389.84	3.88	53.05	61.70	5	1.23	0.77
Laurel	157.39	1248	6.32	0.03	8.43	1.38	1833.29	4.92	45.89	61.32	5	1.50	0.93

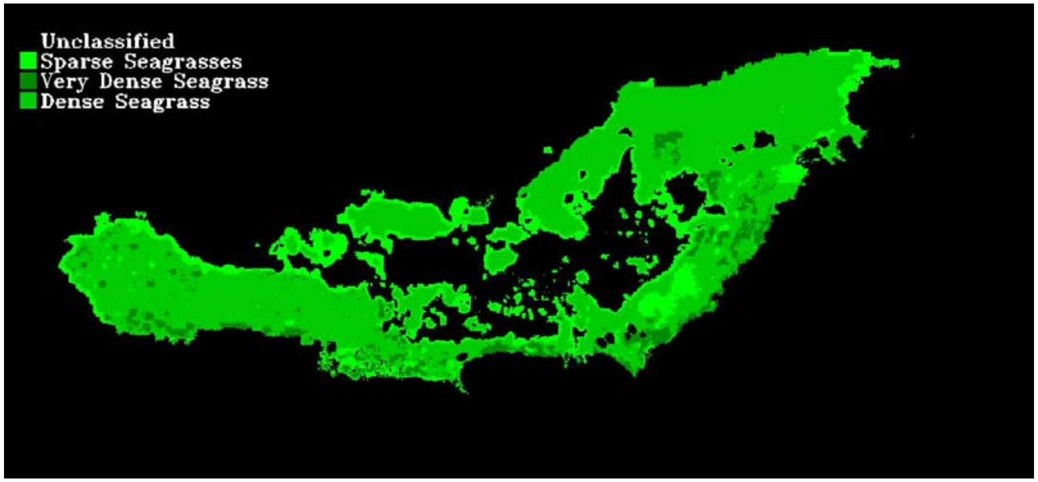


Figure 25. Product of the seagrasses in the lagoon of Enrique Reef

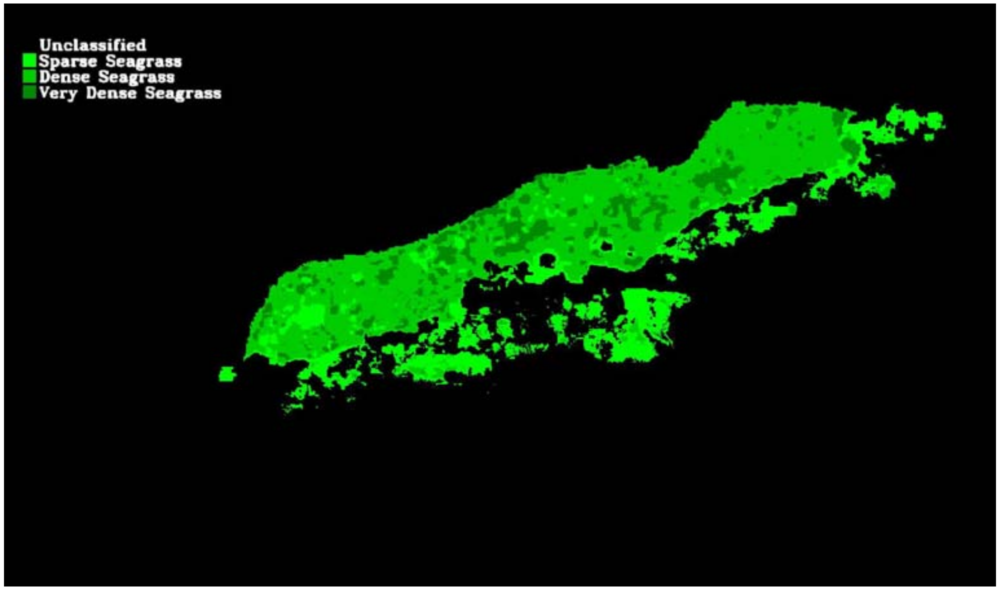


Figure 26. Product of the seagrasses in the lagoon of Laurel Reef

Table 14. Landscape level results of the lagoon considering only seagrasses in this zone. Total landscape area (TA), largest patch index (LPI), number of patches (NP), mean patch size (AREA_MN), area-weighted mean shape index (SHAPE_AM), area-weighted mean patch fractal dimension (FRAC_AM), Euclidean mean nearest neighbor distance (ENN_MN), Mean proximity index (PROX_MN), Patch richness (PR), Interspersion and juxtaposition index (IJI), Contagion index (CONTAG), Shannon's Diversity index (SHDI), Shannon's Evenness index (SHEI).

Site	TA	NP	LPI	AREA_MN	SHAPE_AM	FRAC_AM	PROX_MN	ENN_MN	CONTAG	IJI	PR	SHDI	SHEI
Enrique	84.56	849	7.35	0.02	8.14	1.41	951.99	3.82	53.23	69.30	3	0.77	0.70
Laurel	157.39	948	6.32	0.02	10.57	1.41	1623.56	4.56	45.37	68.14	3	0.96	0.87

3.3.6.2 Crest

3.3.6.2.1 All classes

When taking into consideration all classes included in the crest (Figs. 22 and 24), at the landscape level Enrique crest present a greater number of patches but smaller patches than in Laurel crest (Table 15). The coarse grain size of Laurel patches is larger and these patches are clumped as demonstrated by a higher proximity (490.97) and contagion index (64.17%). On the other hand, Enrique presents more complex and diverse patches. This diversity is due to the lower number of classes in Laurel crest where only sand, sparse seagrass, dense seagrass and mangrove are present.

3.3.6.2.2 Seagrass

When considering only the crest seagrasses (Figs. 27 and 28) the same tendency is observed where Enrique crest present a greater number of patches but are smaller and more irregular than Laurel crest patches. Higher proximity (494.70) and contagion indexes (84.54%) is found in Laurel (Table 16). However, Enrique has more diverse patches that are distributed more evenly within the crest as demonstrated by the Shannon's evenness index at 0.83.

Table 15. Landscape level results of the crest considering all classes in this zone Total landscape area (TA), largest patch index (LPI), number of patches (NP), mean patch size (AREA_MN), area-weighted mean shape index (SHAPE_AM), area-weighted mean patch fractal dimension (FRAC_AM), Euclidean mean nearest neighbor distance (ENN_MN), Mean proximity index (PROX_MN), Patch richness (PR), Interspersion and juxtaposition index (IJI), Contagion index (CONTAG), Shannon's Diversity index (SHDI), Shannon's Evenness index (SHEI).

Site	TA	NP	LPI	AREA_MN	SHAPE_AM	FRAC_AM	PROX_MN	ENN_MN	CONTAG	IJI	PR	SHDI	SHEI
Enrique	84.56	1070	1.25	0.01	5.88	1.39	281.87	3.26	39.77	65.22	5	1.49	0.93
Laurel	157.39	444	1.12	0.02	4.99	1.36	490.97	4.58	64.17	30.41	4	0.78	0.56

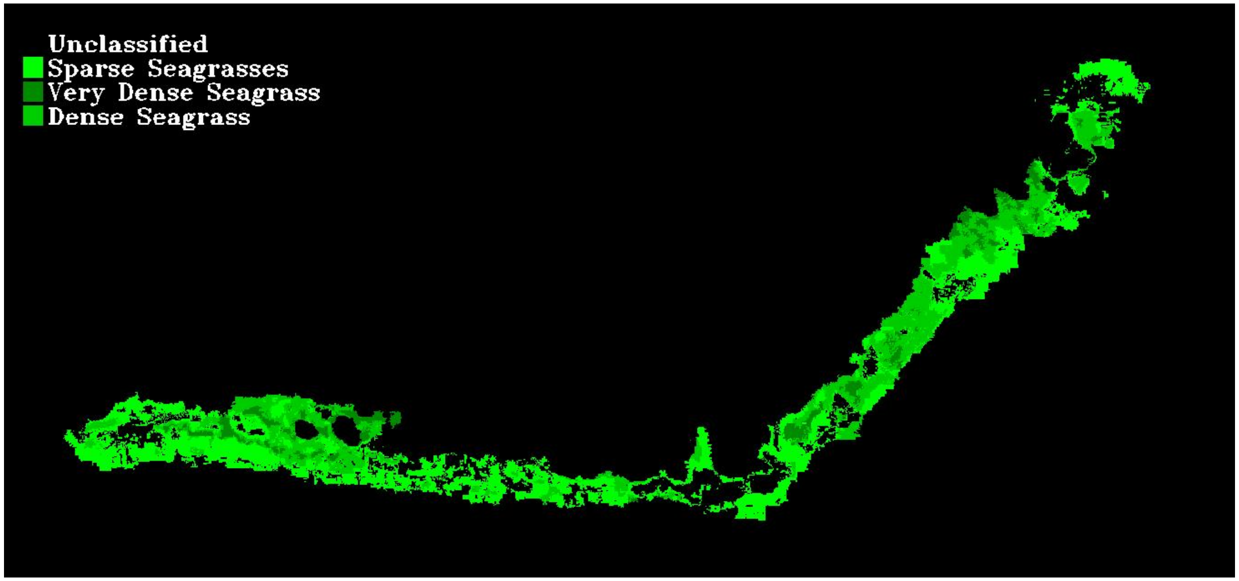


Figure 27. Product of the seagrasses in the crest of Enrique Reef

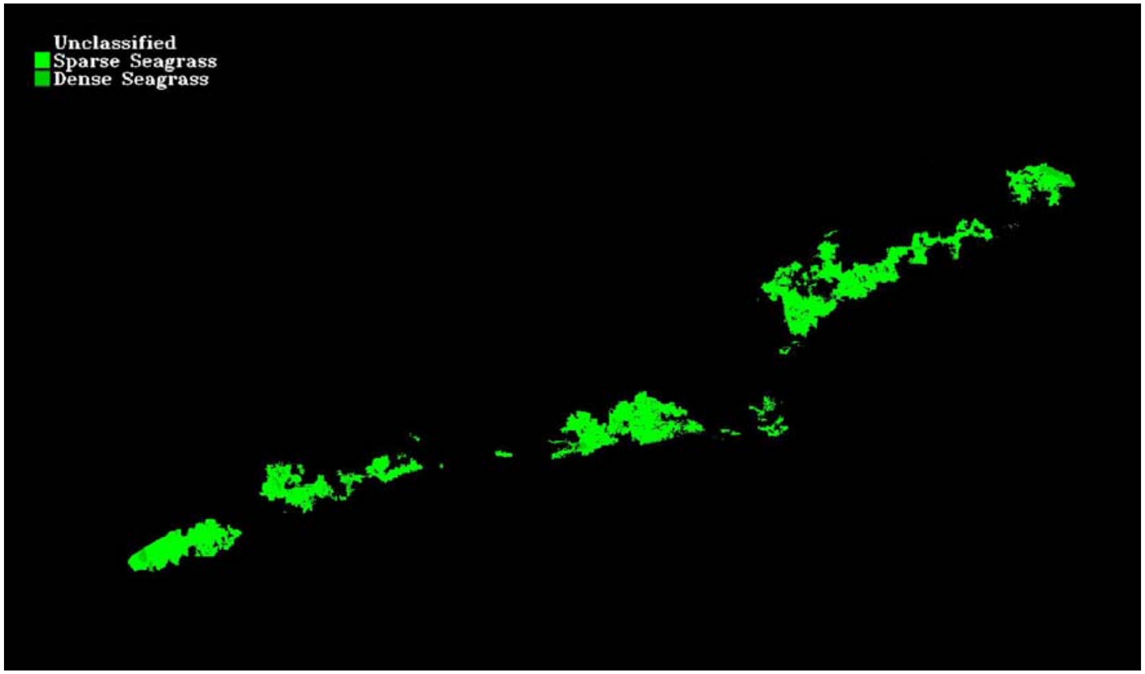


Figure 28. Product of the seagrasses in the crest of Laurel Reef

Table 16. Landscape level results of the crest considering seagrasses only in this zone. Total landscape area (TA), largest patch index (LPI), number of patches (NP), mean patch size (AREA_MN), area-weighted mean shape index (SHAPE_AM), area-weighted mean patch fractal dimension (FRAC_AM), Euclidean mean nearest neighbor distance (ENN_MN), Mean proximity index (PROX_MN), Patch richness (PR), Interspersion and juxtaposition index (IJI), Contagion index (CONTAG), Shannon's Diversity index (SHDI), Shannon's Evenness index (SHEI).

Site	TA	NP	LPI	AREA_MN	SHAPE_AM	FRAC_AM	PROX_MN	ENN_MN	CONTAG	IJI	PR	SHDI	SHEI
Enrique	84.56	659	1.25	0.01	7.47	1.46	348.75	2.96	42.64	74.78	3	0.91	0.83
Laurel	157.39	141	0.73	0.02	6.13	1.41	494.70	5.06	84.54	N/A	2	0.16	0.23

4. Discussion and Conclusions

The results from this study in the Natural Reserve of La Parguera can have implications for the management of these resources and the use of these reefs as recreational areas. Enrique and Laurel reefs presented various habitats such as sand, corals, mangroves and seagrasses that were easily differentiated from satellite images. To study the landscape structure of these ecosystems the IKONOS satellite image was corrected for sunglint and water column attenuation and then mapped. The best Lyzenga band combination was a ratio between the green and red bands, for Enrique reef and the blue red bands for Laurel reef. Landscape metrics were calculated using FRAGSTATS with seven classes for both reefs. These classes include mangroves, soft coral, fore reef, sand and three categories of seagrasses. To validate the accuracy of the benthic map an error matrix was completed to verify the results; a kappa coefficient of 55.30 % was achieved for Enrique reef and 66.62 % for Laurel reef. Fleiss, 1981 stated that a map that has a kappa coefficient between 0-45% is considered poor, 45-75% is considered good and a 75-100% is considered excellent. Taking this into consideration both benthic maps are good for the purpose of this study. It needs to be noted that the main source of error was the seagrass densities where dense seagrass was confused with sparse seagrass and very dense seagrass or sparse seagrass were confused with sand. This confirms that the spectral resolution of the IKONOS image is not adequate for discrimination between spectrally similar bottom types. However, the spatial resolution of IKONOS at 1 m was more than adequate for mapping most of the patch sizes encountered in this study.

A study made by Andréfouët et al. (2003) concluded that Landsat and IKONOS overall accuracies of the classifications showed decreasing accuracy with increasing habitat complexity.

Also they established that for IKONOS, overall accuracy was 77% for 4–5 classes, 71% for 7–8 classes, 65% in 9–11 classes, and 53% for more than 13 classes. If we had considered depth when the water column correction was completed the accuracy of the maps could have improved.

The FRAGSTATS results indicate that the characteristics of the landscape structure are similar between sites. At the class level, sand and dense seagrass dominates both sites although the third type that dominates Enrique reef is sparse seagrass and fore reef in Laurel reef. Fractal dimension and shape at both sites is greater for dense seagrass revealing high complexity of the patch shapes with some continuity. The mean patch size is very low for very dense seagrass and very high for fore reef at both sites, but it needs to be considered that seagrass is divided into three categories and fore reef is only one. If seagrass was considered as one class, soft coral or sand at the class level could account for the lower mean patch size. The lowest interspersion and juxtaposition index is for soft coral at both sites reflecting that this type of patch is adjacent to few types of patches such as sand. It is important to recognize that for both sites very dense seagrass occupy a small area, has a high number of patches and the lowest proximity index of all classes which indicates isolated patches compared to the other classes. In contrast, the other characteristics of the landscape structure at the class level are different. At the landscape level in Enrique reef there were more patches in less area with smaller, more disconnected and slightly more complex patches. On the other hand, Laurel reef has larger and more aggregated patches. This can indicate smaller, fragmented and easily disturbed classes in Enrique reef.

Considering the gradient of depth within each reef, the reef was separate in zones. The zones chosen were the lagoon and the crest of the reef. Analyzing the results at different levels (class and landscape level) the same tendency at each zone was observed. At the class level for the lagoon zone the dense seagrass and sand dominated both sites; these classes show the highest shape and proximity index telling us that the patches are continuous and complex. Also in this zone sparse seagrass and very dense seagrass covered a small area and presented high number of patches indicating fragmentation of this classes.

At the crest zone the main patch types are sparse seagrass and sand in both sites with the higher proximity indexes. Dense seagrass show high complexity in Enrique crest while at Laurel this class covers less area.

At the landscape level for the lagoon zone Enrique show more aggregated patches than Laurel while considering both all classes and only segrasses. Although at the landscape level for the crest, Enrique reveals smaller patches and less clumped patches than Laurel. In other words, the patches in Enrique lagoon are aggregated although the patches in Enrique crest do not demonstrated this pattern. This explains the similarity of the contagion index when the depth gradient was not considered.

A difference in landscape structure between Enrique and Laurel reefs was found when considering the zonation of the reef. However, if this is not considered the sites are mostly the same. Although we cannot determine which factors affect the landscape structure at these sites we can assume it is the proximity to the coast for Enrique reef and its habitual use for recreational purposes.

FRAGSTATS software provides a variation of landscape metrics but scale is one problem. If we change the scale, the results will change because some metrics are sensitive to scale. McGarigal et al. (1994) emphasize that many of the FRAGSTATS statistics are sensitive to the resolution of the map analyzed. Raines et al. (2002) exemplifies the large scaling difference between the two measures of fractal dimensions and shape index due to the differences in scales. Li et al. (2001) analyzed the landscape structure of a basin in a broad scale, with a resolution of 250 m and states that a change in scale and resolution affects the metrics calculated from FRAGSTATS. In this study landscape structure was examined in a fine resolution of 1m, which considers every polygon in the map. Therefore, new metrics that are sensitive to variations in spatial resolution should be developed (Frohn, 1998).

Chapter 2. Distribution and Density of *Lythechinus variegatus* in La Parguera

1. Introduction

Seagrasses are marine angiosperms that constitute the basis for highly diverse and productive coastal ecosystems (Green and Short, 2003). The sea urchin *Lytechinus variegatus* Lamarck (Fig. 29) is a common inhabitant of the seagrass beds of South Florida and the Caribbean (Montague et al., 1995) and it is distributed from the east coast of the United States to Brazil (Hendler et al., 1995). *Tripneustes ventricosus* and *L. variegatus* are permanent residents of the meadows where they feed on seagrasses (Zieman et al., 1984). Rivera (1978) considered it a keystone species in *Thalassia* due to its direct effect on the seagrass meadow and its secondary effects on associated flora and fauna in Jobos Bay, Puerto Rico. This sea urchin species is abundant in La Parguera seagrass beds because of the extensive fields found in this reef system and the lack of predators in the area.

Figure 29. Lytechinus variegatus

The current study aims to measure the density and distribution pattern of *L. variegatus* at two sites in La Parguera. Camp et al. (1973) found urchin densities in Florida from 3 to 636 indv/m^2 and Gómez (2000) from 10.8- 31.4 indv/m^2 in Venezuela. It has been established that urchin densities can fluctuate due to food and protection availability. However, Beddingfield et al. (2000) studied *L. variegatus* in Florida where they found that the densities fluctuated seasonally and were higher in seagrass beds comprised of *Thalassia testudinum* than in *Syringodium filiforme* or on sand flats.

Moreover, in studies of sea urchin distribution Moore et al. (1963) concluded that urchins show a marked tendency to cluster together in groups, which is attributed to spawning (from February to March). However, the aggregation may be taken as a characteristic of the species. Studies completed by Montague et al. (1995) and Beddingfield et al. (2000) determined that urchins tended toward random dispersions within the seagrass meadows and never varied during seasons on the sand flat.

It is expected that the species distributions (Westphal et al., 2003) are affected by changes in the landscape structure due to the alteration of species interactions (Schmiegelow and Monkkonen, 2002). Fragmentation and landscape heterogeneity may have synergistic effects on physical, chemical and biotic fluxes that can affect the species distributions in complex ways (Hobbs, 2001). An example of this is that the predators in aquatic systems do alter their foraging behavior in response to the spatial pattern of habitats (patch shape and size) and not to any changes in vegetation characteristics according to Irlandi (1997). The causes of the distribution patterns have been studied for some organisms. According to Pisut (2004) facultative omnivorous species such as *L. variegatus* may greatly alter the abundances of other invertebrates in seagrass communities by preying on juvenile and adult bivalves as well as gastropod egg masses. These potential food resources, however, are patchily distributed within seagrass beds.

In a study made by Hovel and Lipcius (2002) taking into consideration landscape heterogeneity, the survival of blue crabs was higher in the two connected fragmentation types (continuous patches and small patches) than where seagrass patches were isolated (large patches and very small patches) and the seagrass density was higher in the interior of large patches than at the edge. Westphal (2003) studied various bird species in an Australian reserve and found that many of the woodland birds were in small fragments, so this may be indicative of insensitivity by many species to small patch size and a greater importance on the number of patches in the landscape. Even within the same species the effect of fragmentation has been shown to vary across regions with different proportions of habitat cover most of the species responding positively to area-independent fragmentation (Westphal et al., 2003).

Landscape structure of seagrass beds was determined in chapter one of this thesis. The results of that chapter show that sand and dense seagrass dominates both sites and high complexity with some continuity was found. In Laurel Reef the patches were larger and aggregated although in Enrique Reef they were disconnected and complex.

1.1 Hypothesis

There is a significant difference in density and distribution patterns of *Lytechinus variegatus* between Enrique and Laurel Reefs due to differences in landscape structure between sites.

1. If the patches are together (aggregated) the distribution patterns of the sea urchins should be random within the patches.
2. If the patches are distant the distribution patterns of the sea urchins should be aggregated within the patches due to food and refuge availability.

1.2 Objectives

The main goal of this study is to determine the distribution of *L. variegatus* at two sites at La Parguera.

Specific objectives are:

1. Determine and compare *L. variegatus* density and distribution patterns in Enrique and Laurel Reefs.
2. Determine if landscape structure affects the distribution of *L. variegatus.*

2. Methods

2.1 Study Sites

The study areas are Enrique and Laurel Reefs located in southwestern Puerto Rico at La Parguera (Figure 30). Enrique and Laurel Reefs present extensive seagrass beds and various habitats such as sand flats, corals and mangroves. Both are approximately 0.5 km in width and 1km in length. These sites are part of the La Parguera Marine Reserve and serve as natural barriers, fish nurseries, rest for migratory birds, possess diverse fauna and are used for recreational purposes. The distance from Laurel and Enrique reefs to the coast is approximately 3.55 km and 1.81 km, respectively.

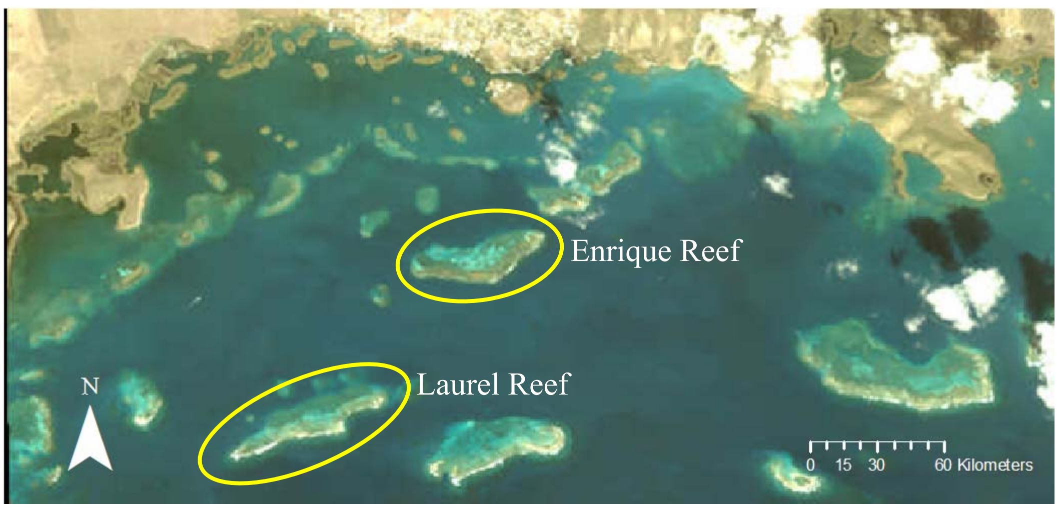


Figure 30. Study sites in La Parguera, Puerto Rico

2.2 Density and Distribution measurements

The distribution of *L. variegatus* was measured from August to November 2008 during the afternoon when the sea urchin migrates from the substrate to the *Thalassia* blades, using a 1x1 m quadrat to quantify the number of individuals per unit area. This quadrat was placed randomly throughout the seagrass beds of the study areas. A total of approximately twenty 1 m^2 quadrats were measured for each site every sampling date. The position within the quadrat was recorded using a Trimble ProXR GPS with UTM NAD83 as the coordinate system and the density of the seagrass was taken into account: sparse, dense and very dense seagrass. SigmaPlot 9.0 was used for statistical analysis of the data. The distribution of the *L. variegatus* was determined with Hill's aggregation index (Hill, 1973). This analysis is quick and easy to use with raw data. Initially a variance/mean ratio was used but this is not a good index of the intensity of the patterns. Hill's index of patchiness (H_i) states:

$$H_i = \frac{s^2 - \bar{x}}{\bar{x}^2}$$

where s^2 is the variance, $\bar{x}$ is the mean and $\bar{x}^2$ is the mean square. If Hill's index of patchiness is equal to 0 the pattern is random, if < 0 the pattern is even and if is > 0 the pattern is aggregated.

3. Results

3.1 Density measurements

Nineteen visits were conducted to the sites; ten for Enrique Reef and nine for Laurel Reef. A total of 339 sea urchins were counted in Enrique and 136 in Laurel. The sea urchin density for Enrique Reef was 1.23 urchins/m^2 and 0.48 urchins/m^2 for Laurel Reef. Table 17 summarizes these results.

Table 17. Summary of sea urchin density measurements.

Sites	Enrique	Laurel
Number of visits	10	9
Total number of organisms	339	136
Total number of quadrats	276	286
Average (#urchins/quadrat)	1.23	0.48

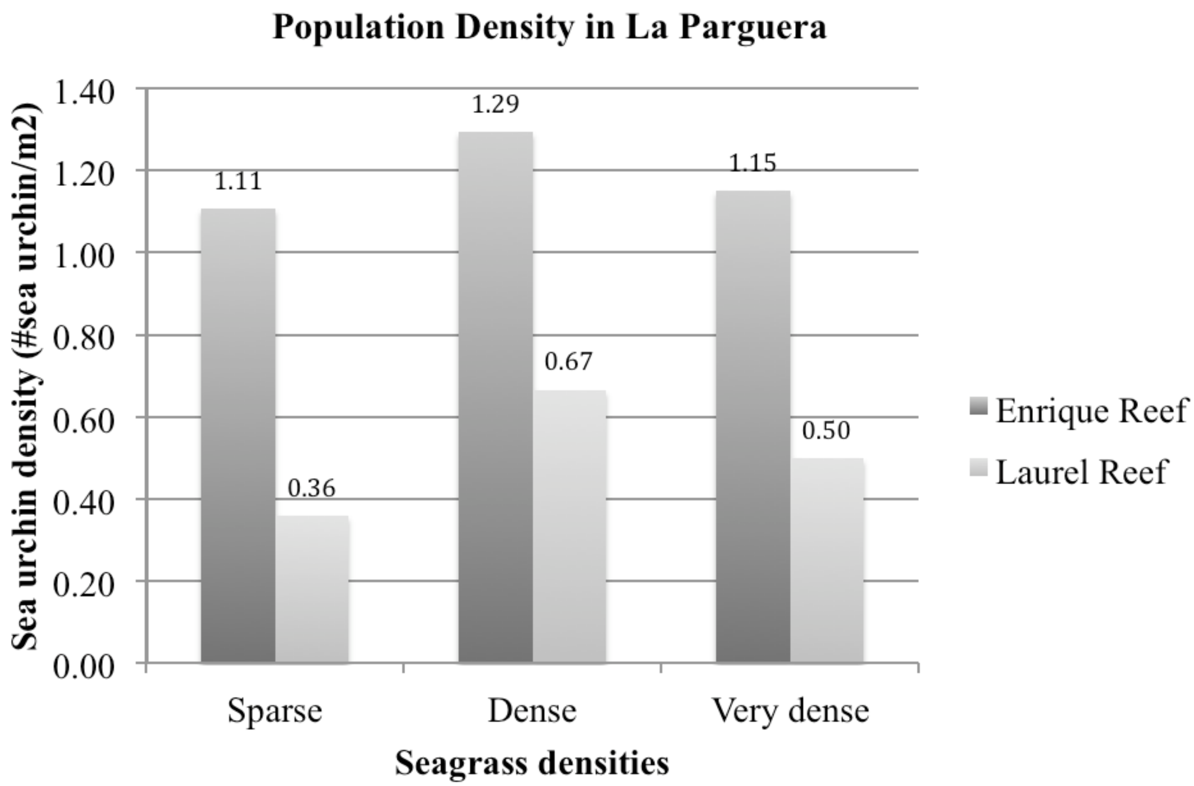


Figure 31. Comparison of sea urchin density among sites between seagrass density

A two way ANOVA was performed on these data (Table 18). The difference in the mean values between the study sites was greater than would be expected by chance alone after allowing for effects of differences in the seagrass density. This indicates that although there were no statistical differences within the sites in the seagrass density, significant differences between sites were found. Hence, seagrass density has no effect on urchin density. This test assumes equal sample size but the numbers of visits to the sites and the numbers of quadrants are not the same.

Table 18. Two way ANOVA results for sea urchin density

Source of variation	DF	SS	MS	F	P
Site	1	19.764	19.764	11.795	<0.001*
Segrass density	2	7.422	3.711	2.215	0.110
Site x Segrass density	2	0.455	0.228	0.136	0.873
Residual	556	931.653	1.676		
Total	561	1019.532	1.817		

A t-test was performed to look for differences in sea urchin density among sites between seagrass density. A significant difference in sea urchin density was observed among sites between seagrass density as sparse and dense seagrass (P = 0.00 and P = 0.00) (Table 19). This table shows that there may be a significant reef density interaction due to the very dense seagrass. This result contradicts results of Table 18 above. This contradiction may be caused by unequal variances, which is a violation of ANOVA assumptions.

Table 19. T tests results of population density between sites

	Enrique Sea Urchin Density	Laurel Sea Urchin Density	t	p	df
Sparse Seagrass	1.11	0.36	4.7	0.00	254
Dense Seagrass	1.29	0.67	3.8	0.00	276
Very Dense Seagrass	1.15	0.5	0.9	0.4	26

3.2 Distribution measurements

The distribution of the *L. variegatus* in Enrique and Laurel Reefs was determined with Hill's Aggregation Index (Tables 22 and 23). The blank spaces in Tables 6 and 7 results from no quadrats measured that day for either sparse or very dense seagrass, since the quadrats were placed randomly through the seagrass beds.

Table 20. Hill's Patchiness Index results for Enrique Reef

Date	Sparse Seagrass	Dense Seagrass	Very Dense Seagrass
8/12/2008	0.00	0.77	2.00
8/26/2008	1.15	1.95	-0.36
8/28/2008	-1.71	0.33	-3.10
9/9/2008	0.81	1.44	4.12
9/16/2008	12.61	1.84	
9/25/2008	5.87	0.28	
10/8/2008	-1.50	-3.80	
10/16/2008	12.61	1.84	
10/27/2008	0.91	-0.26	
11/18/2008	-1.18	-7.88	

Table 21. Hill's Patchiness Index results for Laurel Reef

Date	Sparse Seagrass	Dense Seagrass	Very Dense Seagrass
8/12/2008	-0.20	0.34	
8/14/2008	-3.27	0.05	-0.17
8/27/2008	-4.12	-1.81	-2.67
9/2/2008	-13.93	-2.30	
9/5/2008	-2.59	-0.72	
9/10/2008	-3.87	0.00	
9/18/2008	-0.33	-4.77	
10/9/2008	-1.32	-1.30	
10/20/2008		-1.5	

A Two Way ANOVA for Hill's Patchiness Index was performed between sites (Table 24). The difference in the mean values among the different sites is greater than would be expected by chance alone after allowing for effects of differences in seagrass density. There is a statistically significant difference ($P = 0.026$). But the difference in the mean values among the seagrass densities is not significantly different ($P = 0.926$) and hence seagrass density does not affect the Hill's Index. The mean for Hill's Patchiness Index for Enrique Reef is 1.09 and -2.15 for Laurel Reef hence in Enrique the sea urchin population is aggregated but evenly distributed in Laurel.

Table 22. Two way ANOVA results for Hill's Aggregation Index

Source of variation	DF	SS	MS	F	P
Site	1	79.74	79.74	5.36	0.03
Segrass density	2	2.28	1.14	0.08	0.93
Site x Segrass density	2	77.00	38.50	2.59	0.09
Residual	37	550.75	14.88		
Total	42	765.09	18.21		

Table 23. Quantity of quadrats per seagrass density in Enrique

Date	sparse	dense	very dense
12-Aug-08	2	14	4
26-Aug-08	13	25	2
28-Aug-08	8	22	10
9-Sep-08	14	23	3
16-Sep-08	10	29	1
25-Sep-08	9	14	
8-Oct-08	2	16	
16-Oct-08	7	11	
27-Oct-08	6	11	
18-Nov-08	12	8	

Table 24. Quantity of quadrats per seagrass density in Laurel

Date	sparse	dense	very dense
12-Aug-08	6	13	1
14-Aug-08	18	19	3
27-Aug-08	22	15	3
2-Sep-08	15	11	
5-Sep-08	28	12	
10-Sep-08	37	3	
18-Sep-08	24	16	
9-Oct-08	17	6	
20-Oct-08	6	10	1

4. Discussion and Conclusions

4.1 Sea urchin density

The sea urchin density found for Enrique Reef was 1.23 urchins/m^2 and 0.48 urchins/m^2 for Laurel Reef. The two way ANOVA indicates significant differences in the sea urchin densities values among the sites but no differences within the sites in the seagrass densities. However, the causal mechanisms (dispersal, predation, etc.) are unknown. Differences in sea urchin densities among sites can be due to differences in substrate, currents, larval settlement, habitat preference, food availability and/or length of the seagrass blades.

A possibility for higher densities at Enrique than Laurel is due to an overall decrease in *Lytechinus* abundances from inshore to offshore habitats as demonstrated in a study made by Rivera (1978) in Jobos Bay.

A study made by Gomez (2000) in Venezuela found sea urchin density averages between 10.8-31.4 sea urchins/m^2, suggesting that this disparity in densities between sites were due to consolidated substrates with more rocks and soft corals. This is the case for Laurel Reef; the substrate in this area is composed mostly by dead coral patches due to its location as a mid shelf reef.

A study by Bell and Westoby (1986) of habitat preference in Australia found that seagrass macrofauna (crabs, finfish, and shrimp) preferred dense to sparse seagrass even when predators were removed from plots. Apparently this is not the case for *L. variegatus* in La Parguera because the two way ANOVA indicates no significant difference between sea urchin densities within sites in the different seagrass densities.

Beddingfield et al. (2000) studied *L. variegatus* in Florida and found that the densities fluctuated seasonally and were higher in seagrass beds comprised of *T. testudinum* than *S. filiforme* or on sand flat. This study was carried out in seagrass beds comprised mostly for *T. testudinum*. The sea urchins in La Parguera preferred sites with *Thalassia* and *Thalassia/Syringodium* where most sea urchins were found. According to Beddingfield and McClintock (1998) the five major food resources utilized by *L. variegatus* in Florida include the seagrasses *T. testudinum* and *S. filiforme* epibionts growing on the seagrasses, the green algae *Enteromorpha compressa* (Greville), and decaying seagrass blades.

Another cause for the difference in population density can be the currents in La Parguera, which are predominantly towards the west-northwest as stated in Appeldoorn et al. (1994) and Williams et al. (2009). Enrique Reef is located further east than Laurel (Figure 30), hence the currents pass through this reef first facilitating the arrival of new larvae. However, larval settlement studies of *L. variegatus* are lacking in this area. Studies made for the sea urchin *Diadema antillarum* suggest that settlement (Bak, 1985) and recruitment of small juveniles (Hunte and Younglao, 1988) in the Eastern Caribbean have a positive correspondence of these early life stages with adult density. On the other hand a study by Miller et al. (2003) showed lack of correspondence between adult density and settlement for the same species.

4.2 Sea urchin distribution

The distribution of the *L. variegatus* in Enrique and Laurel reefs was determined with Hill's Aggregation Index. A Two Way ANOVA without replication for Hill's Patchiness Index was performed between sites, concluding that the difference in Hill's Index is due to the site and not to seagrass densities. According to this index the sea urchin population in Enrique Reef is aggregated and in Laurel is even. There is much debate about reproduction seasonality for *Lytechinus*. Some studies attributed aggregation to spawning, which according to Moore et al. (1963) is from February to March but these data were taken from August to November. Although some sea urchin studies suggest that spawning is generally seasonal depending on the geographic areas and type of the environment (Beddingfield and McClintock, 2000), reports of the timing and duration of spawning vary widely (Moore et al., 1963; Brookban, 1968; Ernest and Blake, 1981; Lessios, 1985). Studies by Montague et al. (1995) and Beddingfield et al. (2000) determined that urchins tended toward random dispersions within the meadows. Beddingfield et al. (2000) observed aggregations of adult sea urchins on sand flats associated with patchy distributions of plant food resources rather than reproductive, which may be the case for Enrique. However, the large variation in Hill's index within seagrass densities (e.g. sparse) argues against this explanation and no significant difference was found in the Hill's Index between seagrass density among sites.

4.3 Sea urchin and landscape structure

The population dynamics of species with limited dispersal ability are likely affected by the distribution of suitable habitat patches (McGarigal and Marks, 1995). Experiments performed by Pisut (2004) demonstrated the ability of *L. variegatus* to detect and orient to chemicals emanating from potential food resources over a distance of 1 m. Also, population dynamics are influenced by the distance between patches and the spatial arrangement of the patches (Kareiva 1990, Lamberson et al., 1992, McKelvey et al., 1992). As we already know the results show that the distribution of sea urchins in Enrique is aggregated and even in Laurel according to Hill's Aggregation Index. The FRAGSTATS results in chapter one indicate that at the landscape level, patches in Enrique were disconnected and complex, while larger and aggregated in Laurel. We can assume that the sea urchin distribution is affected by landscape structure due to the proximity of the patches. This is stated by the mean proximity indexes: 1264 for Enrique and 2853 for Laurel and the Interspersion and Juxtaposition index (IJI). If the proximity index is 0 the patch has no neighbors of the same patch type within the specific search radius (Appendix A). A difference in density and distribution patterns of *L. variegatus* between Enrique and Laurel Reefs was found but it cannot be attributed to differences in landscape structure between sites. However, the patches are together (aggregated) in Laurel and the distribution pattern of sea urchins was even within the patches. In Enrique the patches are distant and the distribution patterns of sea urchins were found to be aggregated within the patches, but the cause for this pattern cannot be determined.

In a study by Westphal et al. (2003) where 12 species of birds were found, they may be adversely affected by landscapes with high patch isolation and highly linear patches. Most of the species had models indicating that landscape pattern alone can explain their distribution reasonably well. These results do not agree with the work of McGarigal and McComb (1995) for different bird species where the difference in abundances was explained mainly by changes in habitat area and to less extent due to habitat configuration. A study by Hovel et al. (2002) did not find a relationship between landscape structure and fishes and decapods density but they only considered two indices (percent cover and total linear edge). We must take into account that seagrasses regions cover approximately the same area in both reefs. Species may respond to landscape patterns in different ways depending on their habitat needs (Gergel and Turner, 2002), which can explain the distribution of the sea urchins in La Parguera but is not the only factor that could affect the distribution. Other factors (seagrass biomass, blade structure, etc.) should be studied for a more complete analysis. More sea urchin data should be taken such as sea urchin size and the zone (crest, lagoon) within the reef as well as the shoot biomass of the seagrasses.

The studies made by Beddingfield et al. (2000) and Moore et al. (1963) determined the spatial patterns of urchins considering only their biology. Further research studies of the urchin home range as well as larger temporal and spatial scales studies are needed. From observations of the geolocation data within each reef the sea urchin seems to prefer the edges of the patches, although we cannot conclude this with the available data.

In order to develop plans for habitat reconstruction in a region, it is necessary to understand the landscape determinants of species distributions (Westphal et al., 2003). Hovel et al. (2002) point out the importance of the forecasting relationships between faunal abundance and aspects of seagrass habitat for habitat restoration efforts to replenish nursery habitat for exploited species. In La Parguera landscape structure and configuration should be considered for management because the reduction of a habitat results in smaller and more patches with high complexity and more distance between patches.

General Conclusions

This study provided baseline information for seagrass landscapes studies in La Parguera. In the long-term, this can help us understand the dynamic of species in benthic habitats. More studies are necessary to provide answers to benthic habitat fragmentation to discern which fragments are critical for species restoration and conservation. The high conservation value of fragments is associated with high irreplaceability.

Seagrass landscapes have been studied approximately since the 80's, but not enough consideration has been taken to study the responses of benthic organisms. Boström et al (2006) examined seagrass landscape studies from 1994-2004 and states the difficulty in linking effects of seagrass landscape pattern to faunal structure. The response of *L. variegatus* in La Parguera can vary with local patch characteristics such as shoot density and above-ground biomass than to changes at the landscape-scale as discussed in other studies.

In Enrique Reef the patches are smaller, more disconnected and slightly more complex than in Laurel Reef where larger and more aggregated patches were found. If we take into consideration the characteristics of each reef zone, the seagrass patches in Enrique Reef were clumped in the lagoon but not in the crest. On the other hand, Laurel Reef presented seagrass patches that were more aggregated in the crest compared to Enrique and more disconnected patches in the lagoon. Considering the crest as a shallower and high-energy environment, this zone is a patchier landscape where the factors that produce this pattern are currents, waves, sedimentation and wind. Hence a difference in landscape structure was found between reefs. Additionally, Enrique had higher density of sea urchins perhaps due to being closer to shore than Laurel. The distribution pattern of sea urchins was different at each site: aggregated in Enrique Reef and evenly distributed in Laurel Reef. Although a relationship between landscape structure and sea urchin distribution was not done a transformation of the data can help to discern this. Measuring shoot density and above-ground biomass should be made to examine the relationship between density and distribution of the sea urchin, as well use metrics at patch level should bring more information for the sea urchins distribution. To improve the kappa coefficient of the benthic maps the combination of the three seagrass densities classes in to one should increase this coefficient. In a future work a hyperspectral image with high spatial resolution must be considered to complete the benthic maps because it provides high spectral resolution which helps differentiate the classes in a more effective way.

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APPENDIX A: Landscape structure metrics

Metrics at Class level

Class metrics are computed for every patch type or class in the landscape; the resulting class output file contains a row (observation vector) for every class, where the columns (fields) represent the individual metrics.

There are two basic types of metrics at the class level: (1) indices of the amount and spatial configuration of the class, and (2) distribution statistics that provide first- and second-order statistical summaries of the patch metrics for the focal class. The latter are used to summarize the mean, area-weighted mean, median, range, standard deviation, and coefficient of variation in the patch attributes across all patches in the focal class. Because the distribution statistics are computed similarly for all class metrics, they are described in common below:

Class Distribution Statistics.--Class metrics measure the aggregate properties of the patches belonging to a single class or patch type. Some class metrics go about this by characterizing the aggregate properties without distinction among the separate patches that comprise the class. These metrics are defined elsewhere. Another way to quantify the configuration of patches at the class level is to summarize the aggregate distribution of the patch metrics for all patches of the corresponding patch type. In other words, since the class represents an aggregation of patches of the same type, we can characterize the class by summarizing the patch metrics for the patches that comprise each class. There are many possible first- and second-order statistics that can be used to summarize the patch distribution. FRAGSTATS computes the following: (1) mean (MN), (2) area-weighted mean (AM), (3) median (MD), (4) range (RA), (5) standard deviation (SD), and (6) coefficient of variation (CV). FRAGSTATS computes these distribution statistics for all patch metrics at the class level. In the class output file, these metrics are labeled by concatenating the metric acronym with an underscore and the distribution statistic acronym. For example, patch area (AREA) is summarized at the class level by each of the distribution statistics and reported in the class output file as follows: mean patch area (AREA_MN), area-weighted mean patch area (AREA_AM), median patch area (AREA_MD), range in patch area (AREA_RA), standard deviation in patch area (AREA_SD), and coefficient of variation in patch area (AREA_CV).

$$MN = \frac{\sum_{j=1}^{n} x_{ij}}{n_i}$$

MN (Mean) equals the sum, across all patches of the corresponding patch type, of the corresponding patch metric values, divided by the number of patches of the same type. MN is given in the same units as the corresponding patch metric.

$$AM = \sum_{j=1}^{n} \left[x_{ij} \left(\frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}} \right) \right]$$

AM (area-weighted mean) equals the sum, across all patches of the corresponding patch type, of the corresponding patch metric value multiplied by the proportional abundance of the patch [i.e., patch area (m^2) divided by the sum of patch areas].

Metrics of area, density and edge

Total (Class) Area (CA)

$$CA = \sum_{j=1}^{n} a_{ij} \left(\frac{1}{10{,}000} \right)$$

aij = area (m^2) of patch ij.

Description CA equals the sum of the areas (m^2) of all patches of the corresponding patch type, divided by 10,000 (to convert to hectares); that is, total class area.

Units Hectares

Range CA > 0, without limit.

CA approaches 0 as the patch type becomes increasing rare in the landscape. CA = TA when the entire landscape consists of a single patch type; that is, when the entire image is comprised of a single patch.

Comments Class area is a measure of landscape composition; specifically, how much of the landscape is comprised of a particular patch type. In addition to its direct interpretive value, class area is used in the computations for many of the class and landscape metrics.

Area (AREA_MN)

$$AREA = a_{ij} \left(\frac{1}{10{,}000} \right)$$

aij = area (m^2) of patch ij.

Description AREA equals the area (m^2) of the patch, divided by 10,000 (to convert to hectares).

Units Hectares

Range AREA > 0, without limit.

The range in AREA is limited by the grain and extent of the image; in a particular application, AREA may be further limited by the specification of a minimum patch size that is larger than the grain.

Comments The area of each patch comprising a landscape mosaic is perhaps the single most important and useful piece of information contained in the landscape. Not only is this information the basis for many of the patch, class, and landscape indices, but patch area has a great deal of ecological utility in its own right. Note that the choice of the 4-neighbor or 8-neighbor rule for delineating patches will have an impact on this metric.

Percentage of Landscape (PLAND)

$$PLAND = P_i = \frac{\sum_{j=1}^{n} a_{ij}}{A}(100)$$

Pi = proportion of the landscape occupied by patch type (class) i.
aij = area (m^2) of patch ij.
A = total landscape area (m^2).

Description PLAND equals the sum of the areas (m^2) of all patches of the corresponding patch type, divided by total landscape area (m^2), multiplied by 100 (to convert to a percentage); in other words, PLAND equals the percentage the landscape comprised of the corresponding patch type. Note, total landscape area (A) includes any internal background present.

Units Percent

Range $0 < PLAND \leq 100$

PLAND approaches 0 when the corresponding patch type (class) becomes increasingly rare in the landscape. PLAND = 100 when the entire landscape consists of a single patch type; that is, when the entire image is comprised of a single patch.

Comments Percentage of landscape quantifies the proportional abundance of each patch type in the landscape. Like total class area, it is a measure of landscape composition important in many ecological applications. However, because PLAND is a relative measure, it may be a more appropriate measure of landscape composition than class area for comparing among landscapes of varying sizes

Number of Patches (NP)

$$NP = n_i$$

ni number of patches in the landscape of patch type (class) i.

Description NP equals the number of patches of the corresponding patch type (class).

Units None

Range $NP \geq 1$, without limit.

NP = 1 when the landscape contains only 1 patch of the corresponding patch type; that is, when the class consists of a single patch.

Comments Number of patches of a particular patch type is a simple measure of the extent of subdivision or fragmentation of the patch type. Although the number of patches in a class may be fundamentally important to a number of ecological processes, often it has limited interpretive value by itself because it conveys no information about area, distribution, or density of patches. Of course, if total landscape area and class area are held constant, then number of patches conveys the same information as patch density or mean patch size and may be a useful index to interpret. Number of patches is probably most valuable, however, as the basis for computing other, more interpretable, metrics. Note that the choice of the 4-neighbor or 8-neighbor rule for delineating patches will have an impact on this metric.

Metrics of Shape

Shape Index (SHAPE_AM)

$$SHAPE = \frac{p_{ij}}{min\ p_{ij}}$$

pij = perimeter of patch ij in terms of number of cell surfaces.
min pij = minimum perimeter of patch ij in terms of number of cell surfaces (see below).

Description SHAPE equals patch perimeter (given in number of cell surfaces) divided by the minimum perimeter (given in number of cell surfaces) possible for a maximally compact patch (in a square raster format) of the corresponding patch area. If aij is the area of patch ij (in terms of number of cells) and n is the side of a largest integer square smaller than aij, and m = aij - n2, then the minimum perimeter of patch ij, min-pii will take one of the three forms (Milne 1991, Bogaert et al. 2000):

min-pii = 4n, when m = 0, or
min-pii = 4n + 2, when n2 < aij ≤ n(1+n), or
min-pii = 4n + 4, when aij > n(1+n).

Units None

Range SHAPE ≥ 1, without limit.

SHAPE = 1 when the patch is maximally compact (i.e., square or almost square) and increases without limit as patch shape becomes more irregular.

Comments Shape index corrects for the size problem of the perimeter-area ratio index (see previous description) by adjusting for a square (or almost square) standard and, as a result, is the simplest and perhaps most straightforward measure of overall shape complexity. Note, the minimum perimeter for an aggregate of like-valued square pixels (aij) is calculated as above. For large patches, say aij > 100 pixels, the minimum perimeter asymptotically approaches, the perimeter of an exact square of size aij. Previous versions of FRAGSTATS used this large patch approximation in the shape index. Thus, the results will not agree exactly with previous runs, although the differences will be nontrivial only in cases involving very small patches.

Fractal Dimension Index (FRAC_AM)

$$FRAC = \frac{2\ ln(.25\, p_{ij})}{ln\ a_{ij}}$$

pij = perimeter (m) of patch ij.

aij = area (m2) of patch ij.

Description FRAC equals 2 times the logarithm of patch perimeter (m) divided by the logarithm of patch area (m2); the perimeter is adjusted to correct for the raster bias in perimeter.

Units None

Range $1 \leq FRAC \leq 2$

A fractal dimension greater than 1 for a 2-dimensional patch indicates a departure from Euclidean geometry (i.e., an increase in shape complexity). FRAC approaches 1 for shapes with very simple perimeters such as squares, and approaches 2 for shapes with highly convoluted, plane-filling perimeters.

Comments Fractal dimension index is appealing because it reflects shape complexity across a range of spatial scales (patch sizes). Thus, like the shape index (SHAPE), it overcomes one of the major limitations of the straight perimeter-area ratio as a measure of shape complexity.

Metrics of Proximity/ Isolation

Proximity Index (PROX_MN)

$$PROX = \sum_{g=1}^{n} \frac{a_{ijg}}{h_{ijg}^{2}}$$

aijs = area (m2) of patch ijs within specified

neighborhood (m) of patch ij.
hijs = distance (m) between patch ijs and patch ijs, based on patch edge-to-edge distance, computed from cell center to cell center.

Description PROX equals the sum of patch area (m2) divided by the nearest edge-to-edge distance squared (m2) between the patch and the focal patch of all patches of the corresponding patch type whose edges are within a specified distance (m) of the focal patch. Note, when the search buffer extends beyond the landscape boundary, only patches contained within the landscape are considered in the computations. In addition, note that the edge-to-edge distances are from cell center to cell center.

Units None

Range PROX ≥ 0.

PROX = 0 if a patch has no neighbors of the same patch type within the specified search radius. PROX increases as the neighborhood (defined by the specified search radius) is increasingly occupied by patches of the same type and as those patches become closer and more contiguous (or less fragmented) in distribution. The upper limit of PROX is affected by the search radius and the minimum distance between patches.

Comments Proximity index was developed by Gustafson and Parker (1992) and considers the size and proximity of all patches whose edges are within a specified search radius of the focal patch. Note that FRAGSTATS uses the distance between the focal patch and each of the other patches within the search radius, similar to the isolation index of Whitcomb et al. (1981), rather than the nearest-neighbor distance of each patch within the search radius (which could be to a patch other than the focal patch), as in Gustafson and Parker (1992). The index is dimensionless (i.e., has no units) and therefore the

Euclidean Nearest-Neighbor Distance (ENN_MN)

$$ENN = h_{ij}$$

hij = distance (m) from patch ij to nearest neighboring patch of the same type (class), based on patch edge-to-edge distance, computed from cell center to cell center.

Description ENN equals the distance (m) to the nearest neighboring patch of the same type, based on shortest edge-to-edge distance. Note that the edge-to-edge distances are from cell center to cell center.

Units Meters

Range ENN > 0, without limit.

ENN approaches 0 as the distance to the nearest neighbor decreases. The minium ENN is constrained by the cell size, and is equal to twice the cell size when the 8-neighbor patch rule is used or the distance between diagonal neighbors when the 4-neighbor rule is used. The upper limit is constrained by the extent of the landscape. ENN is undefined and reported as "N/A" in the “basename”.patch file if the patch has no neighbors (i.e., no other patches of the same class).

Comments Euclidean nearest-neighbor distance is perhaps the simplest measure of patch context and has been used extensively to quantify patch isolation. Here, nearest neighbor distance is defined using simple Euclidean geometry as the shortest straight-line distance between the focal patch and its nearest neighbor of the same class.

Metrics of Contagion/ Interspersion

Interspersion and Juxtaposition Index (IJI)

$$IJI = \frac{-\sum_{k=1}^{m}\left[\left(\frac{e_{ik}}{\sum_{k=1}^{m} e_{ik}}\right) ln\left(\frac{e_{ik}}{\sum_{k=1}^{m} e_{ik}}\right)\right]}{\ln\,(m-1)}(100)$$

eik = total length (m) of edge in landscape between patch types (classes) i and k.
m = number of patch types (classes) present in the landscape, including the landscape border, if present.

Description IJI equals minus the sum of the length (m) of each unique edge type involving the corresponding patch type divided by the total length (m) of edge (m) involving the same type, multiplied by the logarithm of the same quantity, summed over each unique edge type; divided by the logarithm of the number of patch types minus 1; multiplied by 100 (to convert to a percentage). In other words, the observed interspersion over the maximum possible interspersion for the given number of patch types. Note, IJI considers all patch types present on an image, including any present in the landscape border, if present. All background edge segments are ignored, as are landscape boundary segments if a border is not provided, because adjacency information for these edge segments is not available and the intermixing of the focal class with background is assumed to be irrelevant.

Units Percent

Range $0 < IJI \leq 100$

IJI approaches 0 when the corresponding patch type is adjacent to only 1 other patch type and the number of patch types increases. IJI = 100 when the corresponding patch type is equally adjacent to all other patch types (i.e., maximally interspersed and juxtaposed to other patch types). IJI is undefined and reported as “N/A" in the "basename".class file if the number of patch types is less than 3.

Comments Interspersion and juxtaposition index is based on patch adjacencies, not cell adjacencies like the contagion index. As such, it does not provide a measure of class aggregation like the contagion index, but rather isolates the interspersion or intermixing of patch types.

Metrics at Landscape level

Landscape metrics are computed for entire patch mosaic; the resulting landscape output file contains a single row (observation vector) for the landscape, where the columns (fields) represent the individual metrics.

Like class metrics, there are two basic types of metrics at the landscape level: (1) indices of the composition and spatial configuration of the landscape, and (2) distribution statistics that provide first- and second-order statistical summaries of the patch metrics for the entire landscape. The latter are used to summarize the mean, area-weighted mean, median, range, standard deviation, and coefficient of variation in the patch attributes across all patches in the landscape. Because the distribution statistics are computed similarly for all landscape metrics, they are described in common below:

Landscape Distribution Statistics.--Landscape metrics measure the aggregate properties of the entire patch mosaic. Some landscape metrics go about this by characterizing the aggregate properties without distinction among the separate patches that comprise the mosaic. These metrics are defined elsewhere. Another way to quantify the configuration of patches at the landscape level is to summarize the aggregate distribution of the patch metrics for all patches in the landscape. In other words, since the landscape represents an aggregation of patches, we can characterize the landscape by summarizing the patch metrics. There are many possible first- and second-order statistics that can be used to summarize the patch distribution. FRAGSTATS computes the following: (1) mean (MN), (2) area-weighted mean (AM), (3) median (MD), (4) range (RA), (5) standard deviation (SD), and (6) coefficient of variation (CV). FRAGSTATS computes these distribution statistics for all patch metrics at the landscape level. In the landscape output file, these metrics are labeled by concatenating the metric acronym with an underscore and the distribution statistic acronym. For example, patch area (AREA) is summarized at the class level by each of the distribution statistics and reported in the class output file as follows: mean patch area (AREA_MN), area-weighted mean patch area (AREA_AM), median patch area (AREA_MD), range in patch area (AREA_RA), standard deviation in patch area (AREA_SD), and coefficient of variation in patch area (AREA_CV).

$$MN = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} x_{ij}}{N}$$

MN (Mean) equals the sum, across all patches in the landscape, of the corresponding patch metric values, divided by the total number of patches. MN is given in the same units as the corresponding patch metric.

$$AM = \sum_{i=1}^{m}\sum_{j=1}^{n}\left[x_{ij}\left(\frac{a_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij}}\right)\right]$$

AM (area-weighted mean) equals the sum, across all patches in the landscape, of the corresponding patch metric value multiplied by the proportional abundance of the patch [i.e., patch area (m^2)

divided by the sum of patch areas]. Note, the proportional abundance of each patch is determined from the sum of patch areas rather than the total landscape area, because the latter may include internal background area not associated with any patch.

Metrics of area, density and edge

Total Area (TA)

$$TA = A\left(\frac{1}{10{,}000}\right)$$

TA = total landscape area (m^2).

Description TA equals the total area (m^2) of the landscape, divided by 10,000 (to convert to hectares). Note, total landscape area (A) includes any internal background present.

Units Hectares

Range TA > 0, without limit.

Comments Total area (TA) often does not have a great deal of interpretive value with regards to evaluating landscape pattern, but it is important because it defines the extent of the landscape. Moreover, total landscape area is used in the computations for many of the class and landscape metrics.

Number of Patches (NP)

$$NP = N$$

N = total number of patches in the landscape.

Description NP equals the number of patches in the landscape. Note, NP does not include any internal background patches (i.e., within the landscape boundary) or any patches at all in the landscape border, if present.

Units None

Range NP ≥ 1, without limit.

NP = 1 when the landscape contains only 1 patch.

Comments Number of patches often has limited interpretive value by itself because it conveys no information about area, distribution, or density of patches. Of course, if total landscape area is held constant, then number of patches conveys the same information as patch density or mean patch size and may be a useful index to interpret. Number of patches is probably most valuable, however, as the basis for computing other, more interpretable, metrics. Note that the choice of the 4-neighbor or 8-neighbor rule for delineating patches will have an impact on this metric.

Largest Patch Index (LPI)

$$LPI = \frac{\max(a_{ij})}{A} 100$$

aij = area (m^2) of patch ij.

A = total landscape area (m^2).

Description LPI equals the area (m2) of the largest patch in the landscape divided by total landscape area (m2), multiplied by 100 (to convert to a percentage); in other words, LPI equals the percent of the landscape that the largest patch comprises. Note, total landscape area (A) includes any internal background present.

Units Percent

Range $0 < LPI \leq 100$

LPI approaches 0 when the largest patch in the landscape is increasingly small. LPI = 100 when the entire landscape consists of a single patch; that is, when the largest patch comprises 100% of the landscape.

Comments Largest patch index quantifies the percentage of total landscape area comprised by the largest patch. As such, it is a simple measure of dominance.

Metrics of Contagion/Interspersion

Contagion Index (CONTAG)

$$CONTAG = \left[1 + \frac{\sum_{i=1}^{m}\sum_{j=1}^{m}\left[(P_i)\left(\frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}}\right)\right]\left[ln(P_i)\left(\frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}}\right)\right]}{2ln(m)}\right](100)$$

Pi =proportion of the landscape occupied by patch type (class) i.
gik =number of adjacencies (joins) between pixels of patch types (classes) i and k based on the double-count method.
m =number of patch types (classes) present in the landscape, including the landscape border if present.

Description CONTAG equals minus the sum of the proportional abundance of each patch type multiplied by the proportion of adjacencies between cells of that patch type and another patch type, multiplied by the logarithm of the same quantity, summed over each unique adjacency type and each patch type; divided by 2 times the logarithm of the number of patch types; multiplied by 100 (to convert to a percentage). In other words, the observed contagion over the maximum possible contagion for the given number of patch types. Note, CONTAG considers all patch types present on an image, including any present in the landscape border, if present, and considers like adjacencies (i.e., cells of a patch type adjacent to cells of the same type). All background edge segments are ignored, as are landscape boundary segments if a border is not provided, because adjacency information for these edge segments is not available and the intermixing of the classes with background is assumed to be irrelevant. Cell adjacencies are tallied using the double-count method in which pixel order is preserved, at least for all internal adjacencies (i.e., involving cells on the inside of the landscape). If a landscape border is present, adjacencies on the landscape boundary are counted only once as are all adjacencies with background. Note, Pi is based on the total landscape area (A) excluding any internal background present.

Units Percent

Range $0 < CONTAG \leq 100$

CONTAG approaches 0 when the patch types are maximally disaggregated (i.e., every cell is a different patch type) and interspersed (equal proportions of all pairwise adjacencies). CONTAG = 100 when all patch types are maximally aggregated; i.e., when the landscape consists of single patch. CONTAG is undefined and reported as "N/A" in the "basename".land file if the number of patch types is less than 2, or all classes consist of one cell patches adjacent to only background.

Comments Contagion is inversely related to edge density. When edge density is very low, for example, when a single class occupies a very large percentage of the landscape, contagion is high, and vice versa. In addition, note that contagion is affected by both the dispersion and interspersion of patch types. Low levels of patch type dispersion (i.e., high proportion of like adjacencies) and low levels of patch type interspersion (i.e., inequitable distribution of pairwise adjacencies results in high contagion, and vice versa.

Metrics of Diversity

Patch Richness (PR)

$$PR = m$$

m = number of patch types (classes) present in the landscape, excluding the landscape border if present.

Description PR equals the number of different patch types present within the landscape boundary.

Units None

Range PR ≥ 1, without limit

Comments Patch richness is perhaps the simplest measure of landscape composition, but note that it does not reflect the relative abundances of patch types. Note, this metric is redundant with both patch richness density and relative patch richness.

Shannon's Diversity Index (SHDI)

$$SHDI - -\sum_{i=1}^{m}(P_i * lnP_i)$$

Pi = proportion of the landscape occupied by patch type (class) i.

Description SHDI equals minus the sum, across all patch types, of the proportional abundance of each patch type multiplied by that proportion. Note, Pi is based on total landscape area (A) excluding any internal background present.

Units None

Range SHDI ≥ 0, without limit

SHDI = 0 when the landscape contains only 1 patch (i.e., no diversity). SHDI increases as the number of different patch types (i.e., patch richness, PR) increases and/or the proportional distribution of area among patch types become more equitable.
Comments Shannon’s diversity index is a popular measure of diversity in community ecology, applied here to landscapes. Shannon’s index is somewhat more sensitive to rare patch types than Simpson’s diversity index.

Shannon's Evenness Index (SHEI)

$$SHEI = \frac{-\sum_{i=1}^{m}(P_i * lnP_i)}{\ln m}$$

Pi = proportion of the landscape occupied by patch type (class) i.
m =bnumber of patch types (classes) present in the landscape, excluding the landscape border if present.

Description SHEI equals minus the sum, across all patch types, of the proportional abundance of each patch type multiplied by that proportion, divided by the logarithm of the number of patch types. In other words, the observed Shannon's Diversity Index divided by the maximum Shannon's Diversity Index for that number of patch types. Note, Pi is based on total landscape area (A) excluding any internal background present.

Units None

Range $0 \leq SHEI \leq 1$

SHDI = 0 when the landscape contains only 1 patch (i.e., no diversity) and approaches 0 as the distribution of area among the different patch types becomes increasingly uneven (i.e., dominated by 1 type). SHDI = 1 when distribution of area among patch types is perfectly even (i.e., proportional abundances are the same).

Comments Shannon's evenness index is expressed such that an even distribution of area among patch types results in maximum evenness. As such, evenness is the complement of dominance.