CORAL REEFS DAMAGES CAUSED BY HURRICANES IN THE CARIBBEAN AND THEIR CORRELATION WITH THE CHARACTERISTICS OF HURRICANES AND REEFS

2020

Mesoamerian Reef Rescue Initiative (RRI)

Coastal Risk and Reslience Initiative, The Nature Conservancy

Esmeralda Pérez Cervantes, Fernando Pardo Urrutia, Lorenzo Álvarez Filip, Fernando Secaira Fajardo, Claudia Ruiz Alvarado, Mariana Alvarez Rocha

CORAL REEFS DAMAGES CAUSED BY HURRICANES IN THE CARIBBEAN **AND THEIR CORRELATION WITH THE CHARACTERISTICS OF HURRICANES AND REEFS**

2020

Mesoamerian Reef Rescue Initiative (RRI)
Coastal Risk and Reslience Initiative, The Nature Conservancy

Esmeralda Pérez Cervantes, Fernando Pardo Urrutia, Lorenzo Álvarez Filip, Fernando Secaira Fajardo, Claudia Ruiz Alvarado, Mariana Alvarez Rocha

AUTHORS
Esmeralda Pérez Cervantes - Consultant
Fernando Pardo Urrutia -Consultant
Lorenzo Álvarez Filip -UNAM- Laboratorio de Biodiversidad Arrecifal y Conservación
Fernando Secaira Fajardo -The Nature Conservancy - CRR
Claudia Ruiz Alvarado -MAR Fund - RRI
Mariana Alvarez Rocha -Universidad Autónoma de Yucatán

DESIGN
Karla Paola Vazquez Mendoza

SUGGESTED CITATION
Pérez-Cervantes, Esmeralda; Pardo-Urrutia, Fernando; Alvarez-Filip, Lorenzo; Secaira Fajardo, Fernando; Ruiz Alvarado, Claudia y Álvarez Rocha, Mariana. 2020. Coral reefs damages caused by hurricanes in the Caribbean and their correlation with the characteristics of hurricanes and reefs. Mesoamerican Reef Rescue Initiative - MAR Fund, UNAM and The Nature Conservancy.

With the financial support of The Central American Commission for Environment and Development (CCAD), the German Government, through KfW and the International Coral Reef Initiative (ICRI) through the United Nations Environment Programme (UN/UNEP).

CONTENT

1

IMPACT OF HURRICANES ON CORAL REEFS

Coral reefs damages caused by hurricanes in the Caribbean and their correlation with the characteristics of hurricanes and reefs

IMPACT OF HURRICANES ON CORAL REEFS

Coral reefs possess high biodiversity and provide numerous environmental benefits and services to humanity. Their global economic value is approximately thirty-six trillion USD per year (Spalding et. al., 2017). Climate change, human activities and natural phenomena have affected reefs in the Caribbean, decreasing coral cover by 80% from 1970 to 2003 (Gardner et al., 2003; Alvarez-Filip et al., 2011).

Figure 1. Gradual decrease of reef complexity (extracted from Rogers, et. al. 2017).

Hurricanes are natural phenomena that destroy coral colonies and cause severe damage (Hughes, 1994); corals have not been able to recover from such damage due to current conditions that hinder reef regeneration. The Caribbean is impacted by an average of 6.2 hurricanes per year, therefore many reefs are frequently impacted (Taylor and Alfaro, 2005). High intensity hurricanes cause an abrupt decrease in live coral cover, between 15% up to 60% (Gardner et al., 2005 in Figure 2); the affected sites do not show cover recovery during the following 8 years (Gardner et al., 2005), which is the average return period of a hurricane. Similarly, rugosity in the Caribbean has declined since 1969 (Alvarez-Filip et al., 2009). Reefs have lost between 3% and 17% of their rugosity due to the impact of a single hurricane (Alvarez-Filip et al., 2011 in Figure 3).

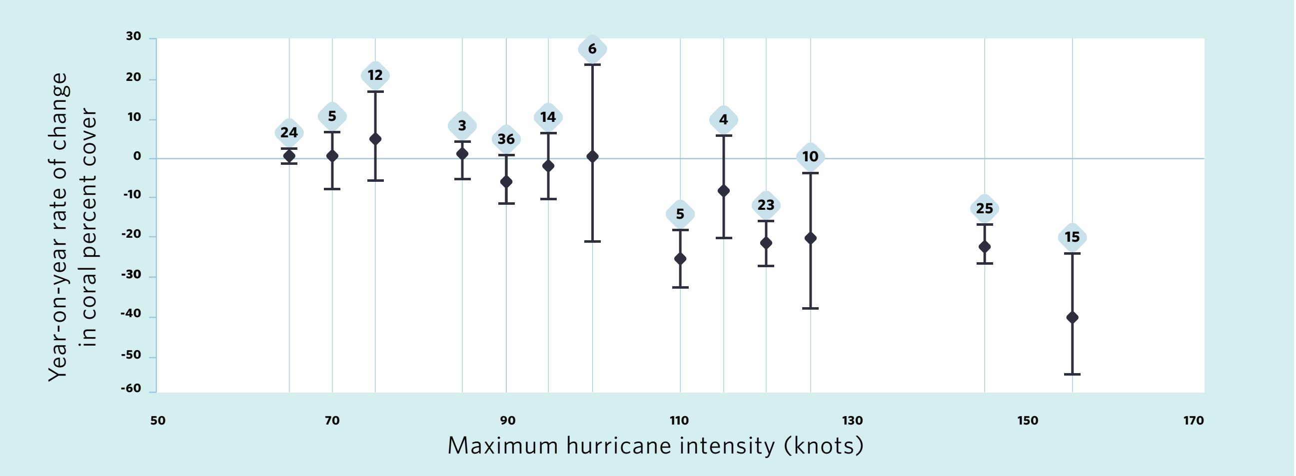


Figure 2. Relationship between annual rate of change of live coral cover and maximum hurricane wind speed (extracted from Gardner et al., 2005).

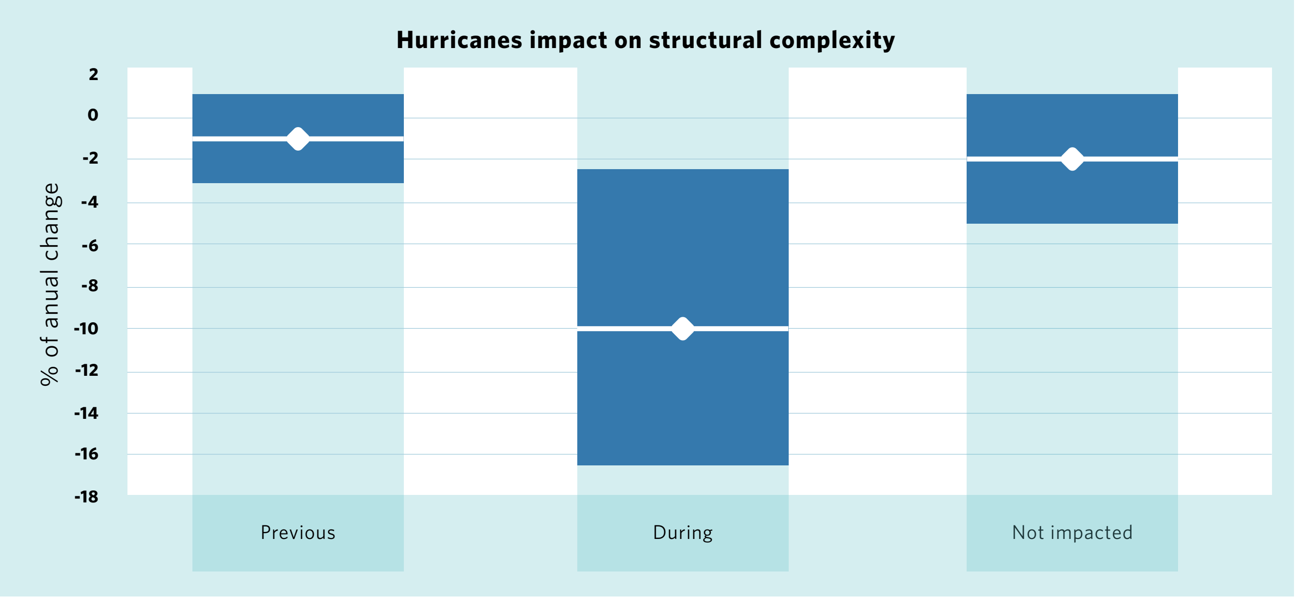


Figura 3. . Change in rugosity (extracted from Álvarez-Filip, et. al. 2011): Sites were grouped by the time of hurricane impact: "previous": impacted during the 10 years prior to monitoring and "during": impacts during the period between monitoring, or "not impacted": sites that were not impacted.

The objective of this work is to estimate hurricane damage to reefs in the Caribbean and to identify if there is a correlation between hurricane and reef characteristics and the damage caused (see Figure 3). The results will contribute to understand the severity of hurricane damage and to define the parameters that can trigger a parametric insurance whose funds are used to repair the damage caused to reefs.

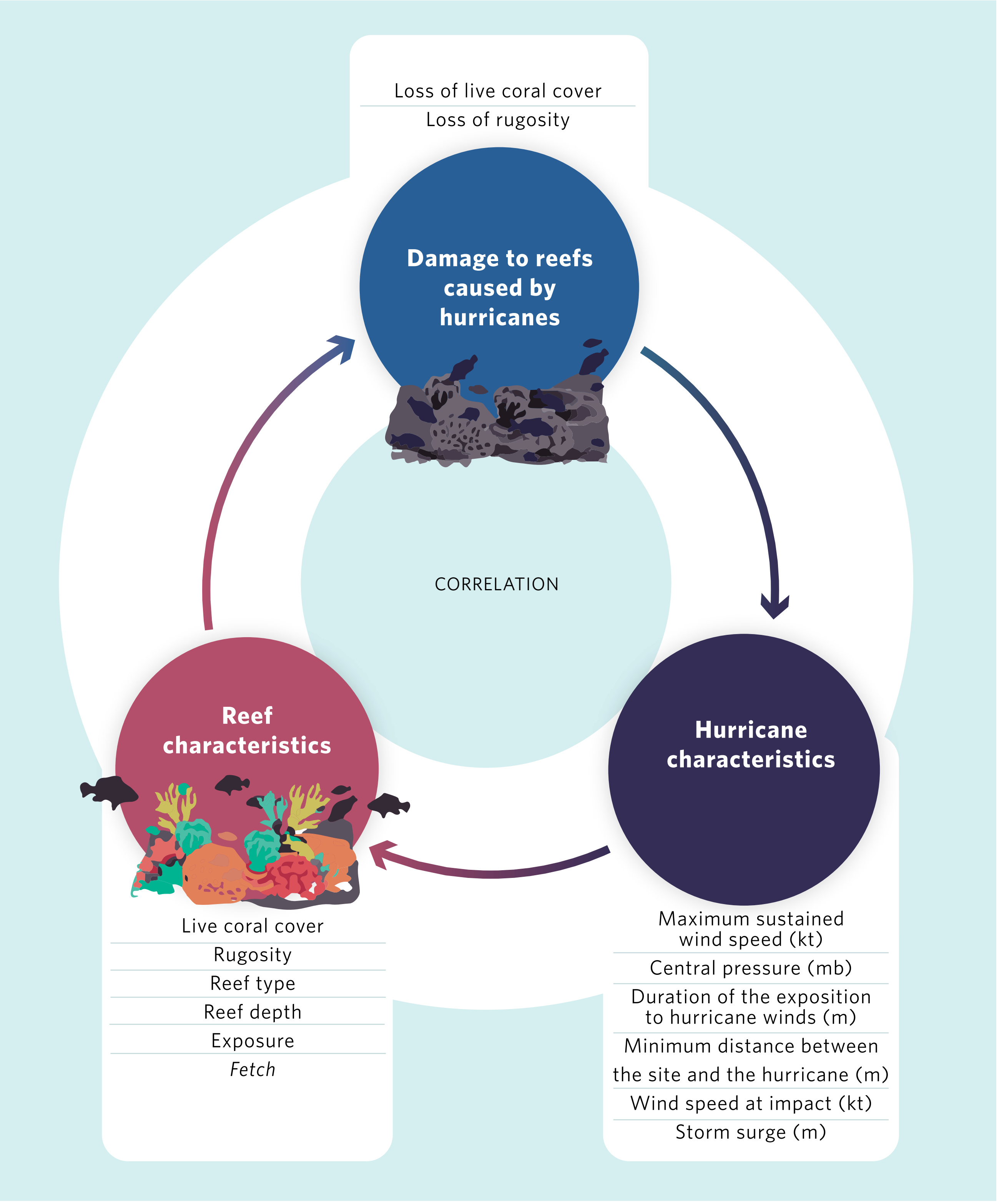


Figura 4. Scheme of correlation between hurricane damage, reef characteristics and hurricane characteristics (own elaboration).

2
METHODOLOGY

2.1 ANALYSIS OF THE IMPACT OF A HURRICANE ON REEFS

The reef characteristics used to quantify hurricane damage are live coral cover (LCC) and reef rugosity. Both characteristics are key indicators of reef health, they are affected by hurricanes (see Figure 2 and Figure 3) and the majority of sites have live coral cover data for extended periods of time, some for as long as 50 years. This study defines hurricane impact as the difference between pre-hurricane and post-hurricane conditions of live coral cover and reef rugosity.

Sites impacted by a single hurricane and with pre-impact and post-impact cover or rugosity data were used. Reefs are considered to be impacted by a hurricane when they are 100 km or less from the track of a hurricane (Gardner et. al. 2005; Alvarez-Filip et. al. 2011). To select the sites, a 100 km circumference radius was drawn around each site and overlapped with the hurricane tracks (see Figure 5).

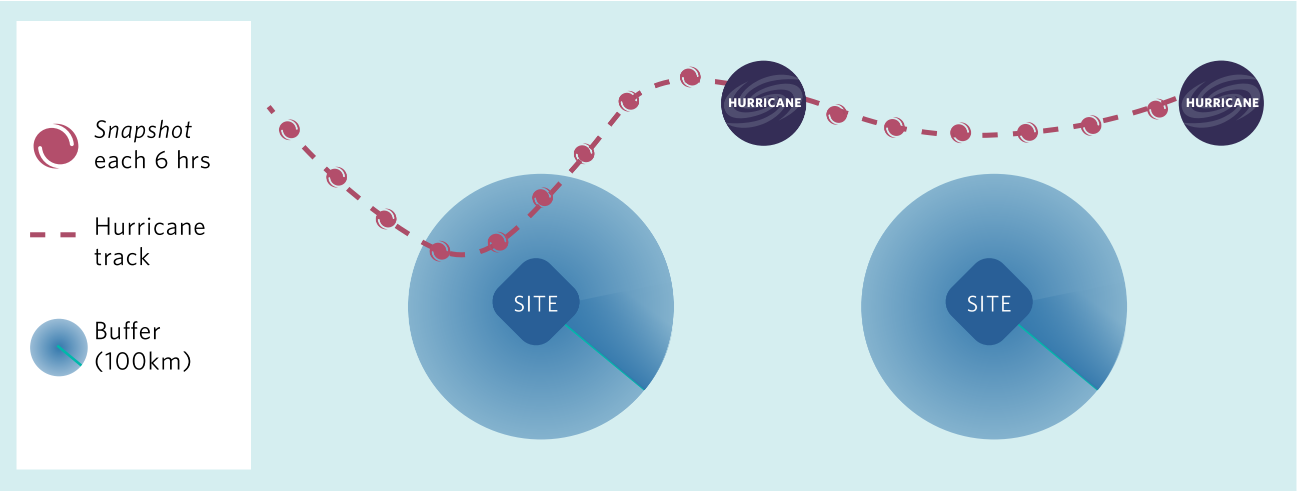


Figura 5. .Determinación de sitios impactados con un polígono de 100 km de diámetro alrededor de un arrecife (elaboración propia). Sitio izquierdo se considera impactado y sitio derecho no impactado.

2.2 REEF CHARACTERISTICS.

The characteristics of the reefs are conditions of the site structure, its health, degree of development, and its location in relation to its surroundings. In this analysis, the characteristics were chosen considering that they could be correlated with hurricane damage and that sufficient data exist. The characteristics are as follows:

2.2.1 Live Coral Cover

Live coral cover is the proportion of live hard coral area within a reef. It is obtained by dividing the live coral area by the total area analyzed and is expressed as a percentage (i.e. 20% live coral cover). This percentage is independent of sample size so it applies equally to small sites or sites with large reef patches. Live coral cover is one of the best indicators of reef health (Huang et al., 2018) although it does not include the diversity of species or coral types nor the degree of reef development. It has been commonly used in the study, conservation and management of coral reefs for more than 50 years (Eddy et al., 2018). Methodologies for assessing live coral cover are video transects, quadrats, and single transects.

Sites were grouped according to their initial live coral cover using the classification proposed by Healthy Reef Initiative (HRI) in their reef health reports (2008, 2010, 2012, 2014, 2016, and 2018) (see Table 1).

Tabla 1. Categories of live coral cover (Healthy Reefs Initiative [HRI], 2012).

CATEGORY	Live coral cover
CRITICAL	0 - 5%
POOR	5% - 10%
FAIR	10% - 20%
GOOD	20% - 40%
VERY GOOD	40% - 100%

2.2.2 Rugosity

The rugosity index is a measure of reef complexity and is the ratio of the length of a reef profile outline to the linear distance between the start and end point of the profile. It is estimated using a chain to measure the corresponding outline over the reef and it is compared to the straight line distance between the start and end point (see Figure 6). Rugosity creates diversity of microhabitats on reefs and provides shelter for many species in different life cycles, which attracts a high diversity of species. The friction caused by reef rugosity on waves significantly decreases their energy (between 40 and 60%, according to Ruiz de Alegria-Arzaburu et al., 2013), which contributes to coastal protection (Secaira & Acevedo,2017). Therefore, rugosity is a key characteristic of reef functionality and suffers severe damage upon hurricane impact. Values close to 1 indicate low rugosity or complexity and higher values are more complex, for example 3.

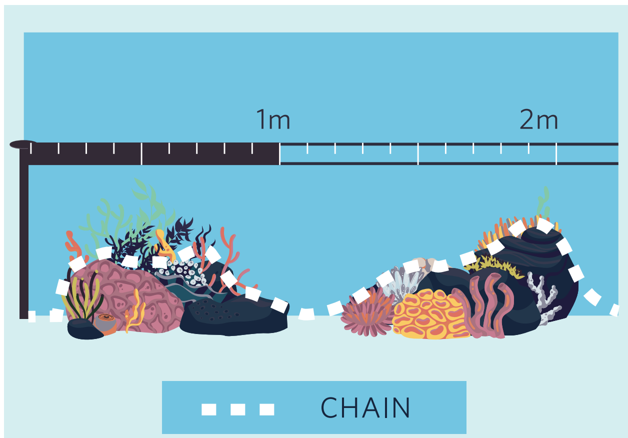
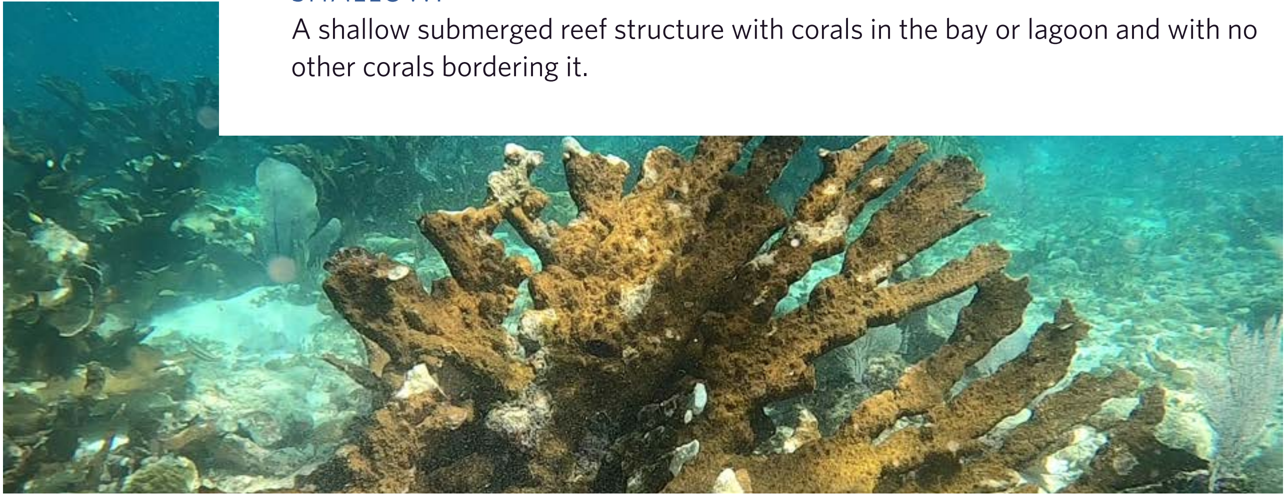


Figura 6. Methodology for the determination of the rugosity index (taken and modified from Rogers, C. S. 1994).

2.2.3 Reef Type

Reefs have different geological and morphological origins and Lang et. al. (2010) classifies them into: atoll, barrier, shore, platform, bank, patch and shallow, which are detailed below:

- ATOLL
  An irregular ovoid reef system surrounded by deep water. The reef crest is along the windward edge and they have a central lagoon with patch reefs.
- BARRIER:
  Characterized by a linear, medium or border reef system with a nearly continuous intertidal crest. The component reefs are oriented almost parallel to the coast and are separated by a lagoon.
- SHORE:
  They are adjacent to the coast and close to it. They finish seaward, forming a bay or lagoon.
- PLATFORM:
  They are characterized by being large, shallow and irregular. Some have an intertidal crest, sand cays or islands, and shallow lagoons.
- BANK:
  Refers to a linear system of shore reefs with an intertidal crest that is more or less parallel to the shore.
- PATCH
  An isolated and/or merged reef structure that rises above the surrounding seafloor and independent of a larger reef system.
- SHALLOW:
  A shallow submerged reef structure with corals in the bay or lagoon and with no other corals bordering it.



2.2.4 Reef Zone

It refers to the location between the open sea and the coast, they are classified into: fore reef, reef crest, reef lagoon and back reef (Lang, et. al. 2010) (see Figure 7).

- FORE REEF:
  This is the part of the reef exposed to the open sea.
- REEF CREST:
  This is the shallowest zone and sometimes exposed to the air.
- BACK REEF:
  The part of the reef that faces the coast.
- REEF LAGOON:
  The shallow area between the open sea and the coast, delimited by the reef crest.

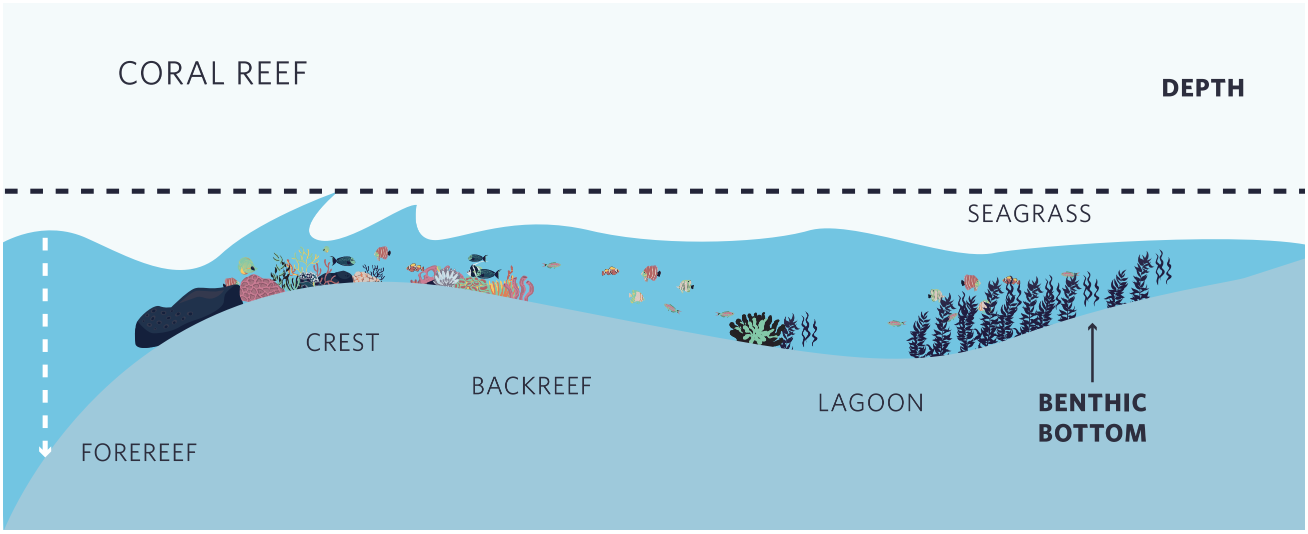


Figura 7. Reef zones: fore reef, crest, back reef and reef lagoon (taken and modified from Navarro, E. E., 2020).

2.2.5 Reef Depth

The vertical distance between mean sea level and the benthic reef bottom (see Figure 7).

2.2.6 Wind and Wave Exposure

It refers to the exposure of the site in relation to the dominant wind direction, that defines the wave energy impacting the reef and the ability of the reef to adapt to that energy (Lang et. al., 2010). The dominant wind in the area of study is the east-west direction, therefore, sites located on the east or windward coasts are considered exposed to the wind and those located on the west leeward are considered not exposed.

Sites located on the north or south coasts are considered "intermediate" (see Figure 8).

2.2.7 *Fetch*

Fetch is defined as the distance over the water where the wind can blow without interruption from a land feature such as an island or peninsula and form waves. The wind can generate waves with greater energy and height when there is a greater unobstructed distance (more *fetch*) (see Figure 9). To calculate it, we used the "R" "Waver" package (InVEST Coastal Vulnerability Model and Rohweder J. 2008), on the layer of the American continent (Porto Tapiquén C. E., 2015) and the database of the coordinates of the sites analyzed. For the present study, the *fetch* was estimated for wind directions coming from north, northeast, east, southeast, south, southwest and west.

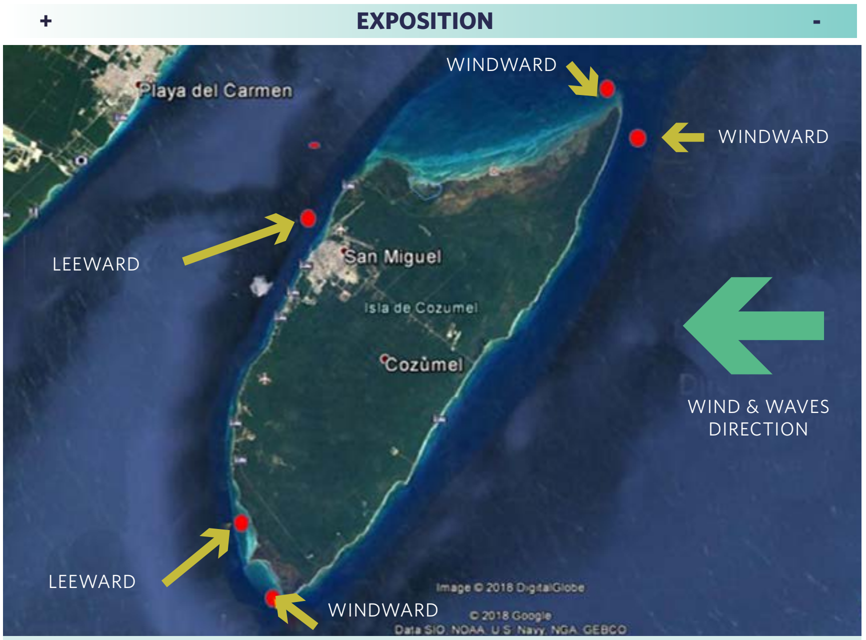


Figura 8. Example of wind and wave exposure on Cozumel Island.

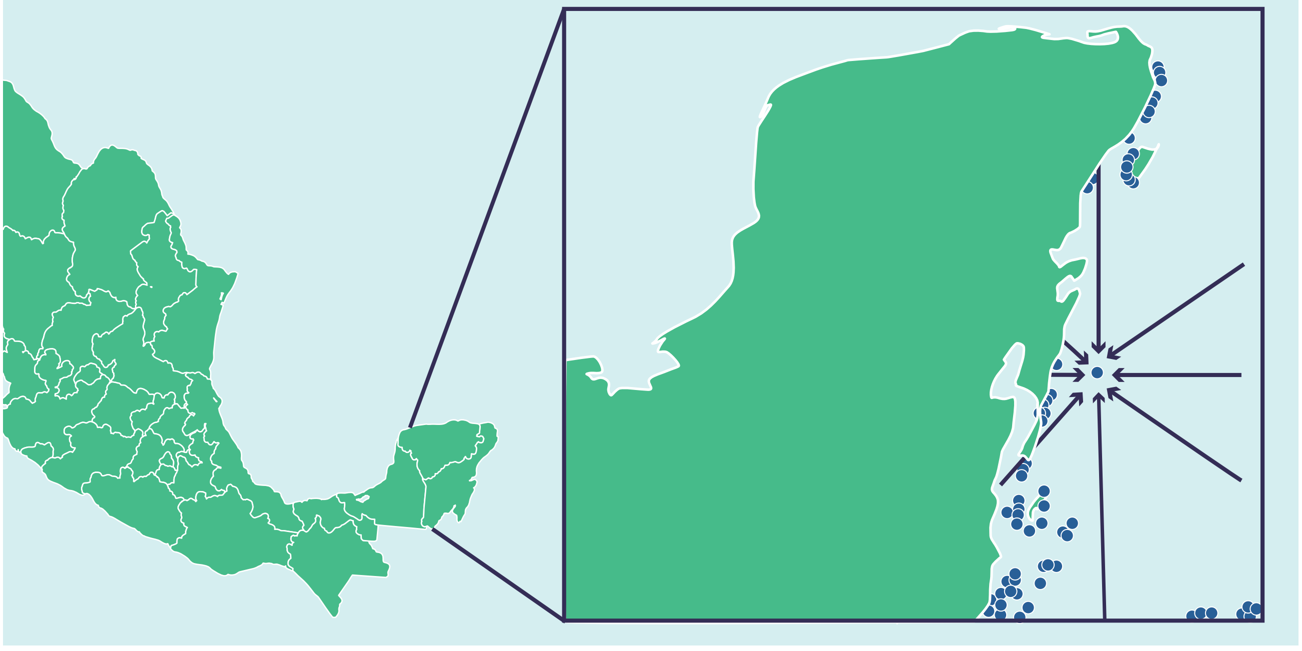


Figura 9. Example of *fetch* calculation. The dots represent the sites and the arrows represent the wind directions: north, northeast, east, southeast, south, southwest and west.

2.2.8 Reef Data

Live coral cover information was found for 414 sites: 48 sites in scientific articles, 356 sites in databases, 5 sites in reports and 5 sites in degree thesis. Rugosity data were found for 44 sites: 29 sites in scientific articles, 27 sites in databases and 3 sites in reports. The databases used are: Sistema de Información Arrecifal del Caribe (SIAC) (base of the Laboratorio de Biodiversidad y Conservación Arrecifal of UNAM) and the database: "Time-series coral-cover data from Hawaii, Florida, Mo'orea, and the Virgin Islands": U.S. Geological Survey (Guest, J.R, et al. 2018).

For the final analysis, 245 sites were chosen, with time series and coral cover data, and 37 sites with reef rugosity data. For the selection of these sites, only those that presented impacts by a single hurricane between two consecutive samplings were chosen in order to establish a cause-effect relationship. Data were not used for sites that 1) were affected by more than one hurricane between samplings, 2) were not affected by hurricanes, or 3) the samplings did not indicate when they were conducted. The sites are distributed across 24 countries in the Caribbean Basin (see Figure 10 and Table 2).

The inter-sampling period of the 245 sites with coral cover data ranged from 40 days to 10 years; 40.3% of the sites had periods of less than 1 year, 26.5% had periods of 1 to 2 years, 24% had periods of 2 to 3 years, and 9.2% had periods of more than 3 years. The influence of data with a period of more than 3 years was analyzed because it is likely that in such a long period other factors may cause changes in coral cover, so the reported change is not attributable to the hurricane. Damage to coral cover was analyzed breaking it down by period between samplings and excluding data with a period longer than three years and it was observed that the trend of the impact does not change (see Annex 1). However, there are changes in the maximum damage values, showing that some reefs continued to deteriorate significantly. This analysis was only elaborated for coral cover data.

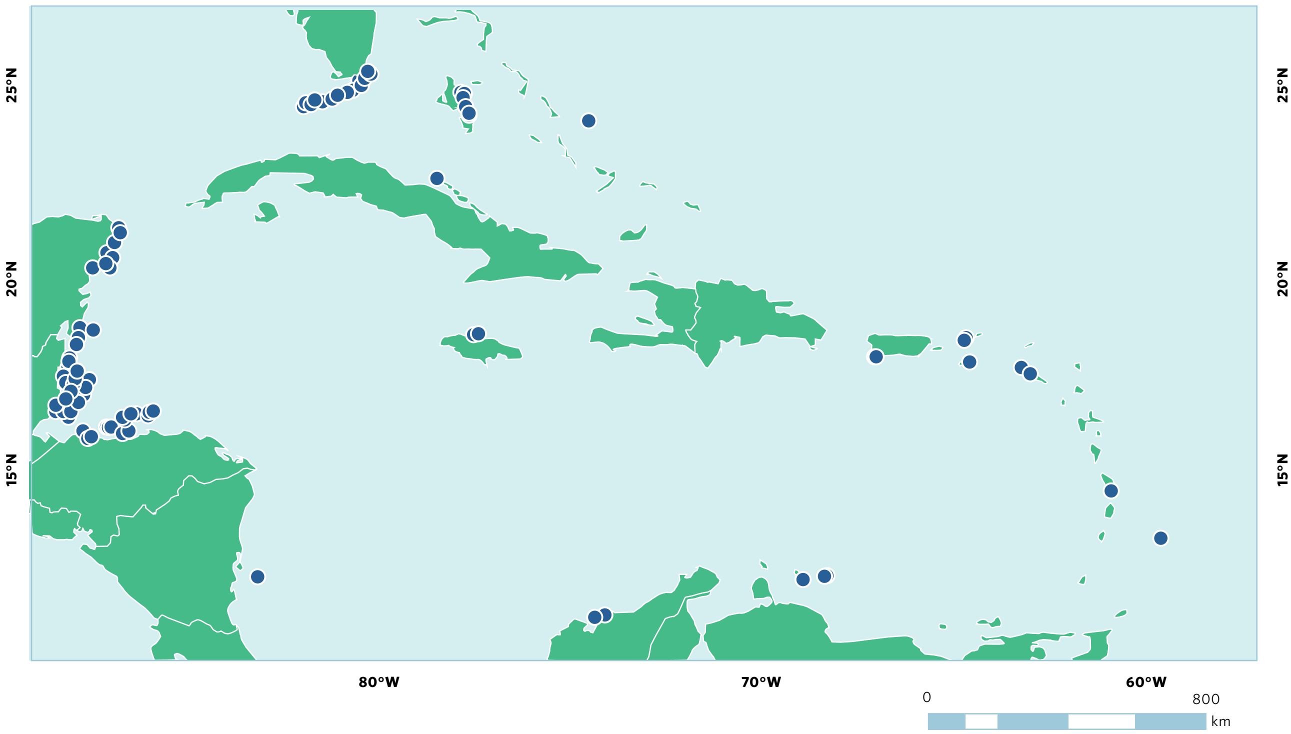


Figura 10. Location of monitoring sites obtained from the databases consulted.

Tabla 2. List of the number of sites obtained per country and per year. Countries with ISO 3166-1 alpha-3 code.

COUNTRY	1973	1974	1978	1979	1980	1981	1982	1983	1985	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
BLZ																	4	4	2	2									84		18	68		44	4	18	48			
GTM																													6						4	5				
MEX									5		15	5	15			2	2	1	1	1	1						6	111	63	24	24	48	18	32	16	14	14			2
HND																													78			18	16	52	34	12	70			
BHS																														33	23	34		35	1					
BRB																1	2																							
BMU																2	2	2		1	2																			
BES		4						4						3	1		2	2	2	6		1		3	4						4				4					
COL																4	2	2	2	2	2																			
CUB																	4	2	2	2				8						8										
CUW	4							4						3	1		1	4		4					4						4				4					
USA																			32	31	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32		
NI-CS															1			1		1	1																			
CYM																		2		2																				
VIR				3	6	3				9	16	11	12	4	4	4	4	4	4	4	4	6	7	7	7	8	8	9	9	9	9	9	9	7	7	7	7	7		
JAM			7		5		2									1	1	1	2	2																				
MTQ																														2										
PRI																	2	3	3	2	2																			
DOM																			2	1																				
NL-BQ2																1	2	2	2		2																			
NL-BQ3																						1						1		1	1							1	1	
SLV																	2	4	2	2	2																			
TTO																	2	2	2	2	1																			
VEN																		4	6	2	2																			
TOTAL	4	4	7	3	11	3	2	8	5	9	31	16	27	10	6	16	32	40	64	67	51	40	39	50	47	40	46	153	272	109	115	209	75	202	106	97	171	40	1	2

2.3 HURRICANE CHARACTERISTICS

The National Hurricane Center (NHC) of the National Oceanic and Atmospheric Administration (NOAA) publishes hurricane characteristics. For this work we used Atlantic hurricane data from 1851 to 2017, the data are found in the HURDAT 2 database (https://www.nhc.noaa.gov/data/), (Landsea and Franklin, 2013). Since 2004, data are recorded every 6 hours referring to a particular point in the track of the hurricane eye; each data series is called "*Snapshot*". By overlapping the hurricane trajectories on the 100 km radius polygons around the sites under study, 44 hurricanes were identified (see Figure 5).

The hurricane variables used for this study are as follows:

2.3.1 Maximum Sustained Wind

It is the average of the maximum wind speed at 10 meters of altitude sustained for 1 minute. It is measured in knots (kt).

The maximum speed assigned to the site is the maximum speed reported at the center of the hurricane that passed within the 100 km polygon.

2.3.2 Central Pressure

Refers to the barometric pressure at the center of the hurricane. It is measured in millibars (mb). This variable is highly correlated with the maximum sustained wind speed (r= -0.91, for all HURDAT 2 data); the lower the central pressure, the higher the sustained wind speed.

The central pressure assigned to the site is the pressure reported at the center of the hurricane that passed within the 100-km polygon.

2.3.3 Duration of the Exposition to Hurricane Winds

This characteristic seeks to establish the length of time the hurricane was impacting a site. To indicate the duration of a hurricane at the site, a proxy indicator was used, which is the number of *snapshots* occurring within the 100 km polygon. As indicated, the HURDAT 2 database reports a *snapshot* every 6 hours, therefore, the number of *snapshots* reported within the polygon allows inferring the time the hurricane was impacting the site.

This proxy (number of *snapshots*) cannot be converted into hours of impact because a *snapshot* within the polygon can mean that the hurricane was from few minutes to less than 12 hours (see Figure 11).

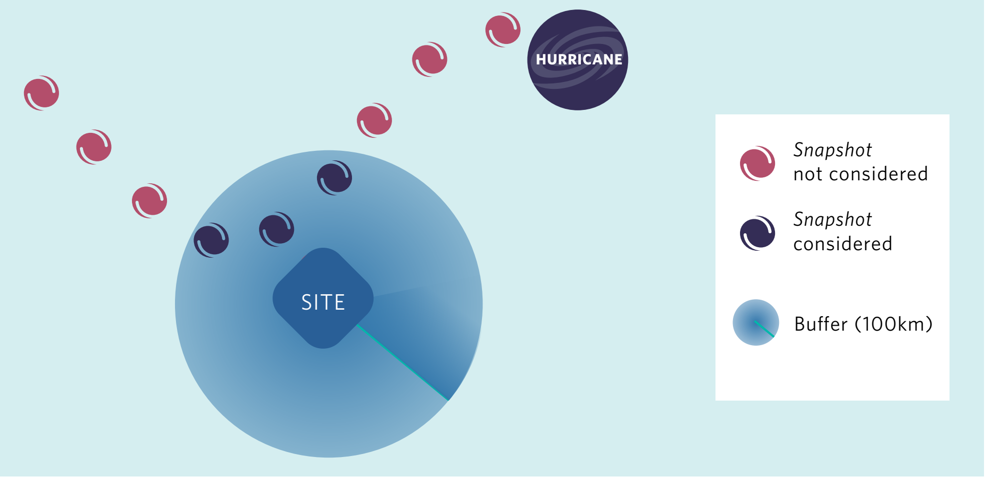


Figura 11. Proxy indicator for estimating the duration of the site's exposure of the site to the hurricane (own elaboration). The elapsed time is the number of snapshot of the hurricane that occur within a radius of 100 km around the site (color blue).

2.3.4 Minimum Distance Between the Site and the Hurricane

Refers to the distance between the site and the eye of the hurricane. The minimum distance between the site and the hurricane is the weighted average of the inverse of the distance from the site to the eye of the hurricane of each *snapshot* recorded within the polygon (see Figure 12).

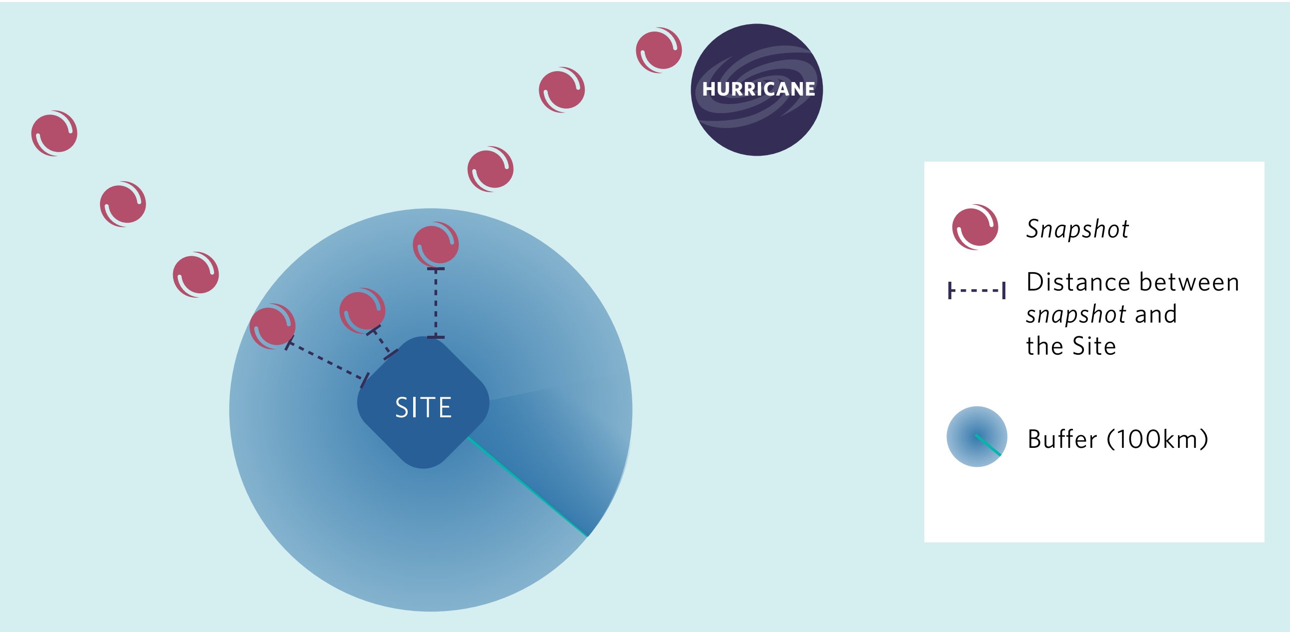


Figura 12. Method for estimating the minimum distance between the hurricane and the site (own elaboration).

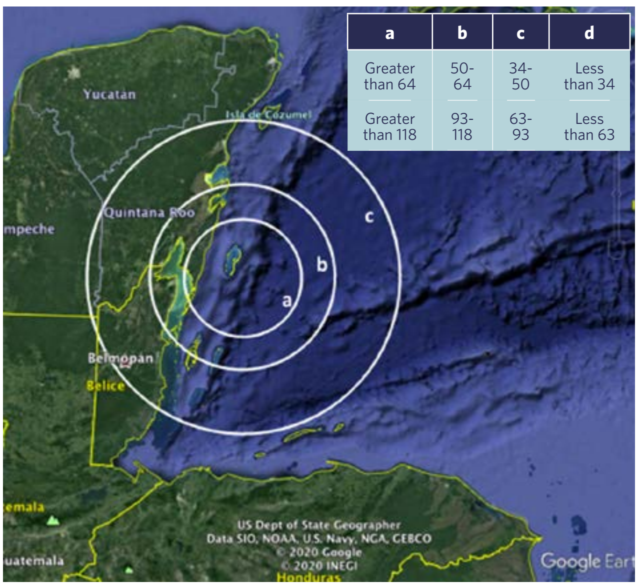


Figura 13. Speed range of each polygon (own elaboration).

2.3.5 Wind Speed at Impact

Hurricane winds decrease as they move away from the center of the hurricane. This characteristic makes it necessary to establish whether the damage to the reef is correlated to the wind over the site or to the maximum wind at the center of the hurricane. To obtain the wind speed over the site, the wind speed dispersion around each selected hurricane was calculated. NHC provides the distance from the center of the hurricane to points located to the northeast (NE), northwest (NW), southeast (SE) and southwest (SW) where wind speeds greater than 64, 50-64 , 34-50 and less than 32 knots occur. With this information, polygons were generated around the center of the hurricane for each wind speed range (see Figure 13). Therefore, the wind speed at impact is the wind speed range occurring over the study site.

2.3.6 Storm Surge

Storm surge is the rise above sea level due to the action of wind forcing on the water surface (Meza-Padilla et. al. 2015). Storm surge was obtained from the SURGEDAT database (The World's Storm Surge Data Center at Louisiana State University). SURGEDAT has data from around the world since 1880 for more than 700 hurricanes and storms (Needham & Keim, 2012).

2.4 INDICATORS AND RATES TO MEASURE THE DAMAGE CAUSED BY HURRICANES

There are several ways to measure change before and after an event, as they must consider several factors to be able to compare data between different sites:

1. The change compared to the initial value.
2. The direction of the change, i.e., whether the value increased or decreased.
3. The time elapsed between the pre- and post-event measurements.

We analyzed the advantages and disadvantages of different rates for measuring change (see Table 3) and confirmed the use of the effective and logarithmic rates as the most appropriate for indicating changes in coral cover and rugosity. Both the logarithmic rate and effective rate are widely used for reef change analysis (Côté, et. al. 2005, Côté, et. al. 2006, Álvarez-Filip et. al. 2011, Paddack et. al. 2009, Suchley et. al. 2016, Gardner et. al. 2003, Gardner et. al. 2005 and Grahan & Nash 2013).

Tabla 3. Different rates for measuring change. Where v0 is its initial value and vf is the final value (coral coverage or rugosity) and t= is the time elapsed between the measurement of the values V_f y V_0.

NAME	FORMULA	INTERPRETATION	DOES IT REFER TO THE INITIAL VALUE?
Gross change or ΔV	$\Delta V = V_f - V_0$	Total change.	No
Gross change rate or o i	$i = (V_f - V_0)/t$	Average total change per unit of time.	No
Rate of change or p	$p = (V_f - V_0)/V_0$	Percentage change from initial sample.	Yes
Simple change rate or i'	$i' = (V_f - V_0)/tV_0$	Percentage change per unit of time.	Yes
Logarithmic rate or δ	$\delta = \frac{\log(V_f) - \log(V_0)}{t}$	Total change in logarithms per unit of time.	Yes
Effective rate or i''	$i'' = e^{\delta} - 1$	The way to interpret δ as a cumulative percentage change similar to compound interest.	Yes

2.5 INFERENTIAL ANALYSIS

The logarithmic rate was selected as an indicator of changes in coral cover and rugosity. Exploratory analysis were then conducted to identify hurricane or reef characteristics (referred to as variables in this section) that might be correlated or disassociated. This analysis consisted of generating:

a. Box diagrams, which indicate the median and quartiles of data dispersion.

b. Scatter plots, with local regressions (LOESS), which show the confidence interval of the trend found.

The final step was to perform inferential analysis of the variables or combinations of variables identified in the exploratory analysis. Inferential analysis are used to identify which variables are statistically significant with rates of change in coral cover and rugosity. The association of the variables with damage to live coral cover was performed using a linear mixed model. The loss of coral cover is a multicausal phenomenon and the linear mixed model allows including fixed and random factors, as well as involving different spaces and times (Dicovskiy-Riobóo & Pedroza-Pacheco, 2017). Only those variables with the least amount of missing data were considered in order to avoid reducing the sample size in the analysis.

The association of the variables with rugosity damage was analyzed using the multiple linear regression model. Outliers were removed so that the data would reasonably fit the model, also a selection of variables was made with the help of the AIC criterion (Akaike's information criteria, a measure of the relative quality of a statistical model), since it is the best criteria for an inferential model when the sample is small and there are random factors (Graft Acquah, 2010).

Inferential models calculate the P-value of each characteristic, which indicates the robustness of the correlation. When the P-value of the characteristic is less than 0.05 it indicates that the characteristic has a statistically significant correlation.

The characteristics or variables with statistical significance are those that we can use with certainty independent of the data sample analyzed. In other words, we can select a site not included in the sample and estimate the damage caused by a hurricane based on the variables with statistical significance.

3
RESULTS

3.1 DAMAGE TO REEFS CAUSED BY HURRICANES IN THE CARIBBEAN

Data from 245 sites with coral cover information during the period 1973 to 2017 show that hurricanes caused severe damage to reefs, which lost up to 20% of the actual live coral cover after a hurricane hit. The most obvious result of the study is that sites with higher live coral cover suffered three times more actual losses than sites with lower cover (see section 3.1.1). Sites with cover in "good" and "very good" condition lost an average of 20% and 13% cover respectively. Sites in "critical" and "poor" condition lost an average of 3% and 5% live coral cover. This difference is due to the fact that sites with lower cover have less coral that can be destroyed. Another factor determining the severity of coral cover loss is the wind speed at impact, as the higher the wind speed, the greater the loss in all reef condition categories (see section 3.1.2).

Data at 37 sites during the period 1978 to 2007 indicate that rugosity can decrease up to 20% after a hurricane when rugosity is greater than 3. Sites with this value are considered highly complex (see section 3.2.11). The analysis also indicated that sites on the back reef lose more rugosity than those on the front reef (see section 3.2.13).

Section 3.2 presents exploratory results relating hurricane characteristics to live coral cover and rugosity. Section 3.3. presents a mixed linear explanatory model that integrates the joint effect of hurricane characteristics with changes in coral loss and rugosity, in order to identify the characteristics that are statistically significant (most likely to be determinant).

3.1.1 Change in Live Coral Cover by Initial Condition

The initial coral cover is the amount of coral found on the reef before the passage of a hurricane, this variable in the multiple linear explanatory model was statistically significant in relation to coral loss after the passage of a hurricane. The change in live coral cover by initial condition was analyzed with the following rates: gross change, relative change, annual logarithmic rate and effective rate of change.

GROSS CHANGE

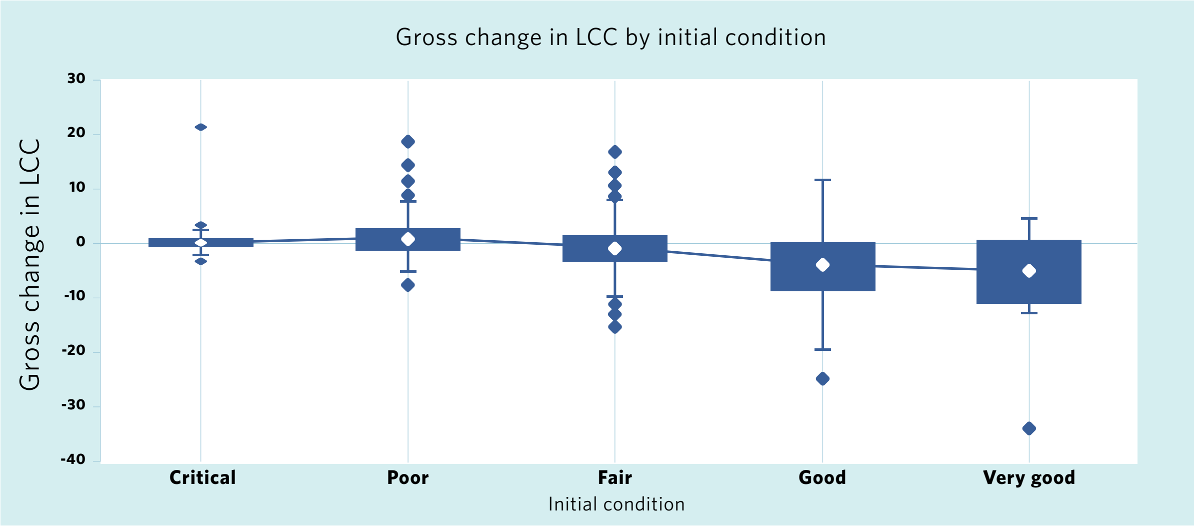


Figura 14. Gross change in live coral cover by initial condition.

PERCENT OF CHANGE

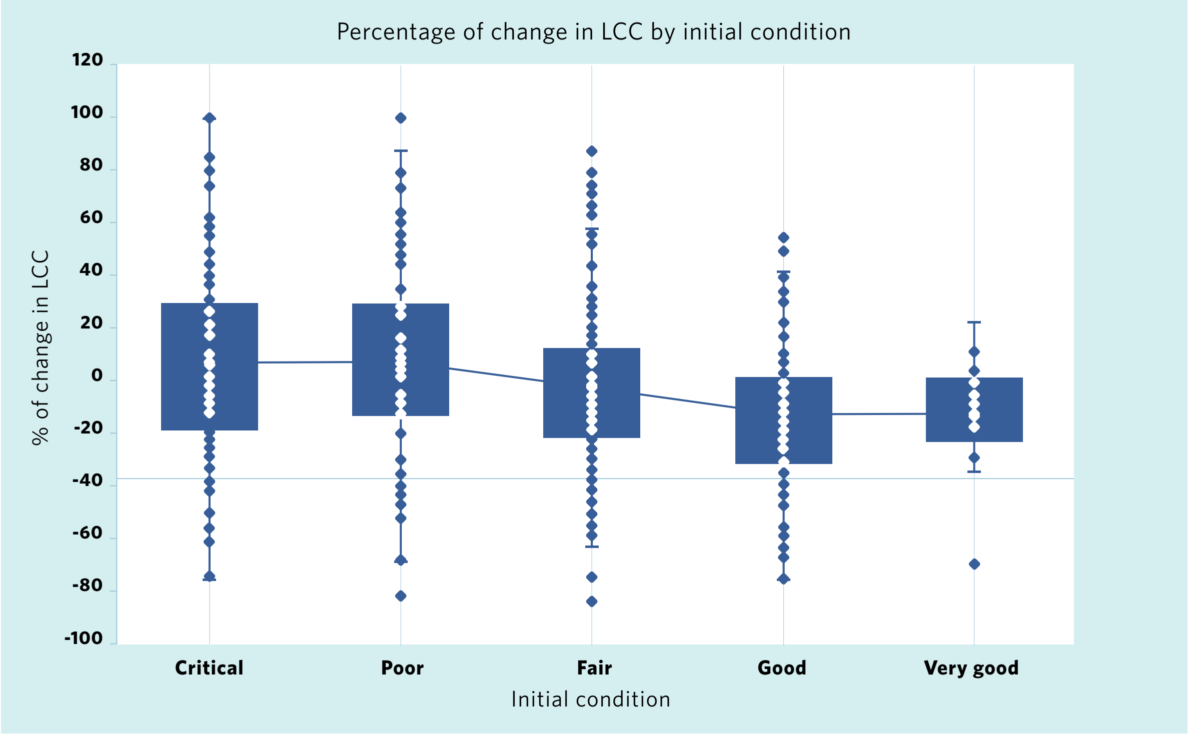


Figura 15. Percentage change in live coral cover by initial condition.

ANNUAL LOGARITHMIC RATE

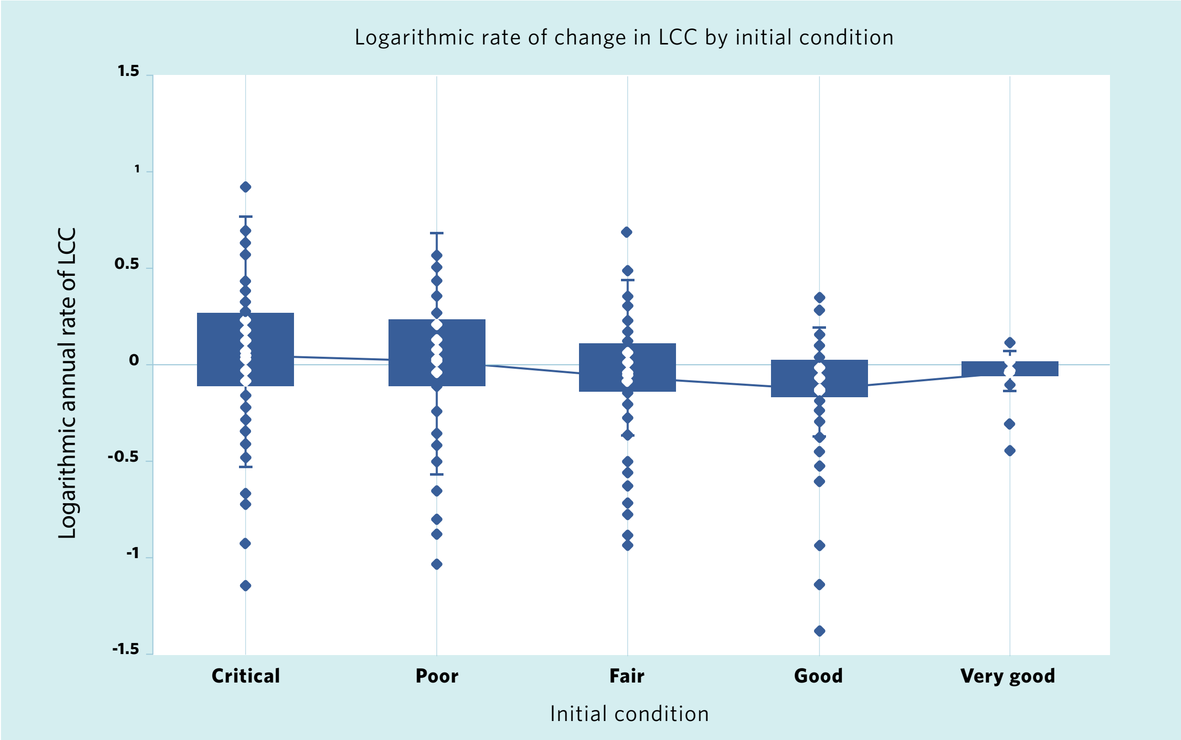


Figura 16. Annual logarithmic rate of change in live coral cover by initial condition.

EFFECTIVE ANNUAL RATE

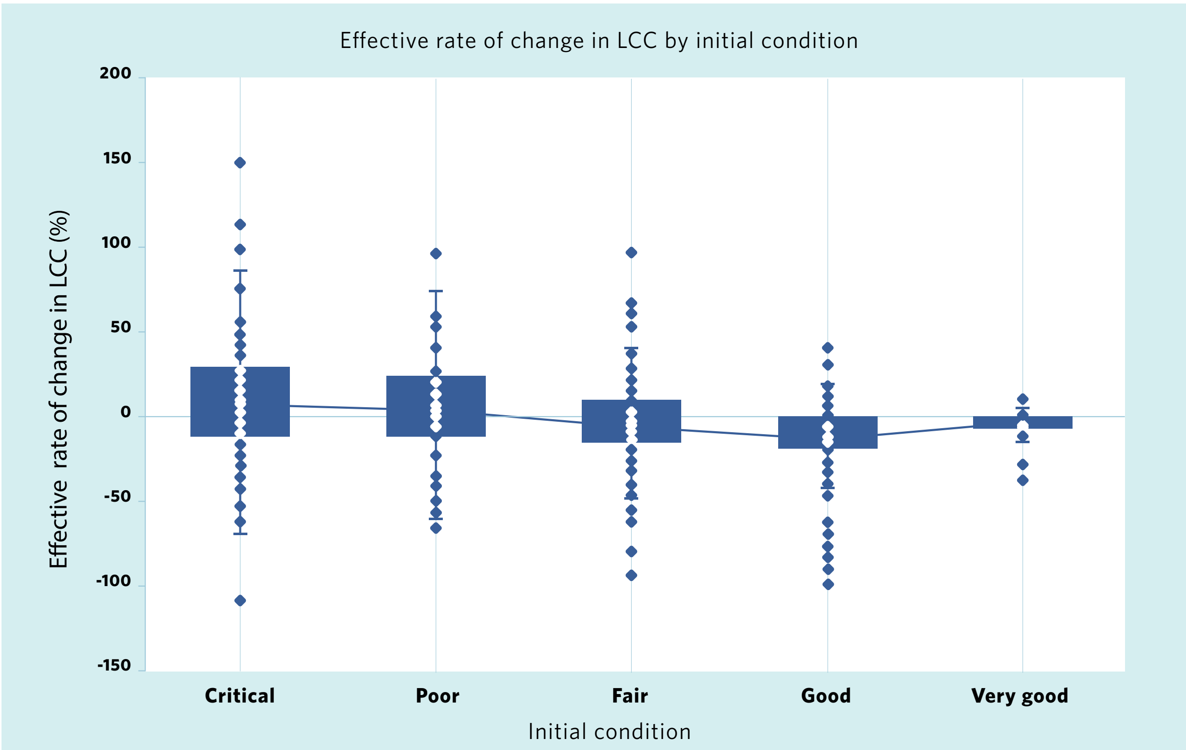


Figura 17. Effective annual rate of change in live coral cover by initial condition.

3.1.2 Change in Live Coral Cover by Wind Speed at Impact Segregated by Initial Cover

Loss of cover increases with increasing wind speed at impact for all reef condition categories. As expected, the greatest gross loss occurs on reefs with higher cover.

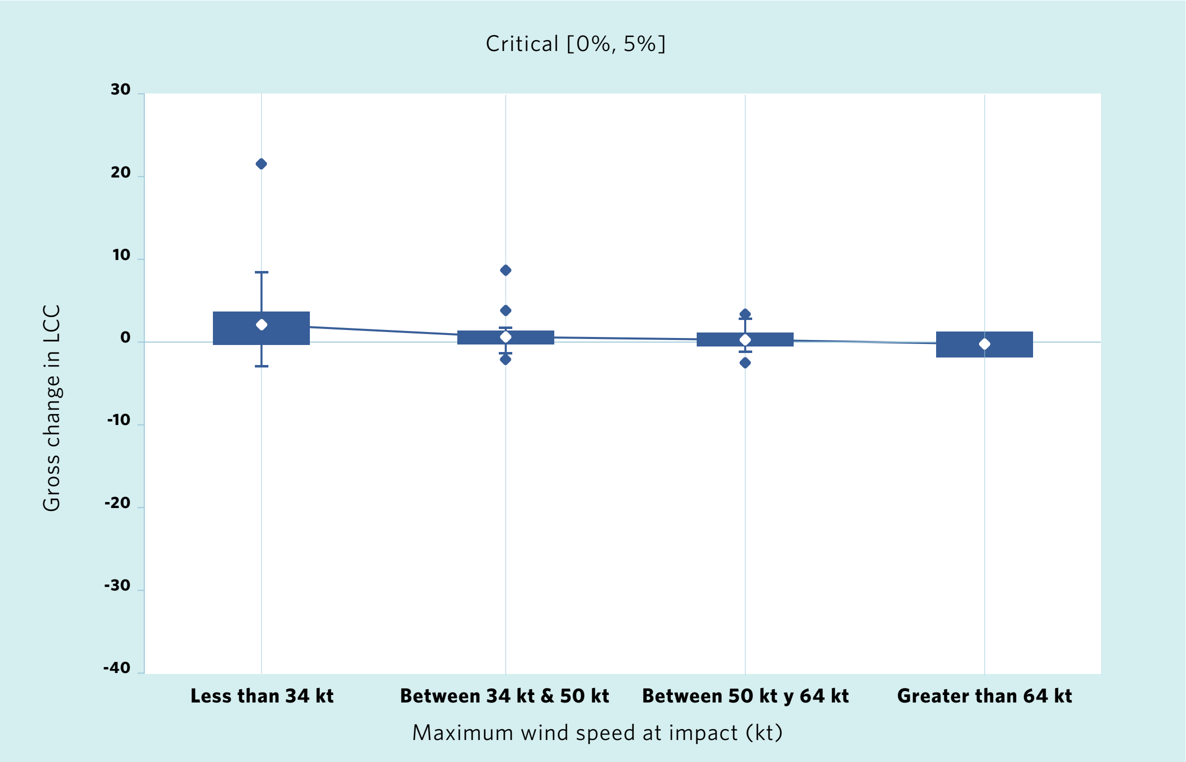


Figura 18. Gross change in live coral cover by wind at impact on reefs in critical condition.

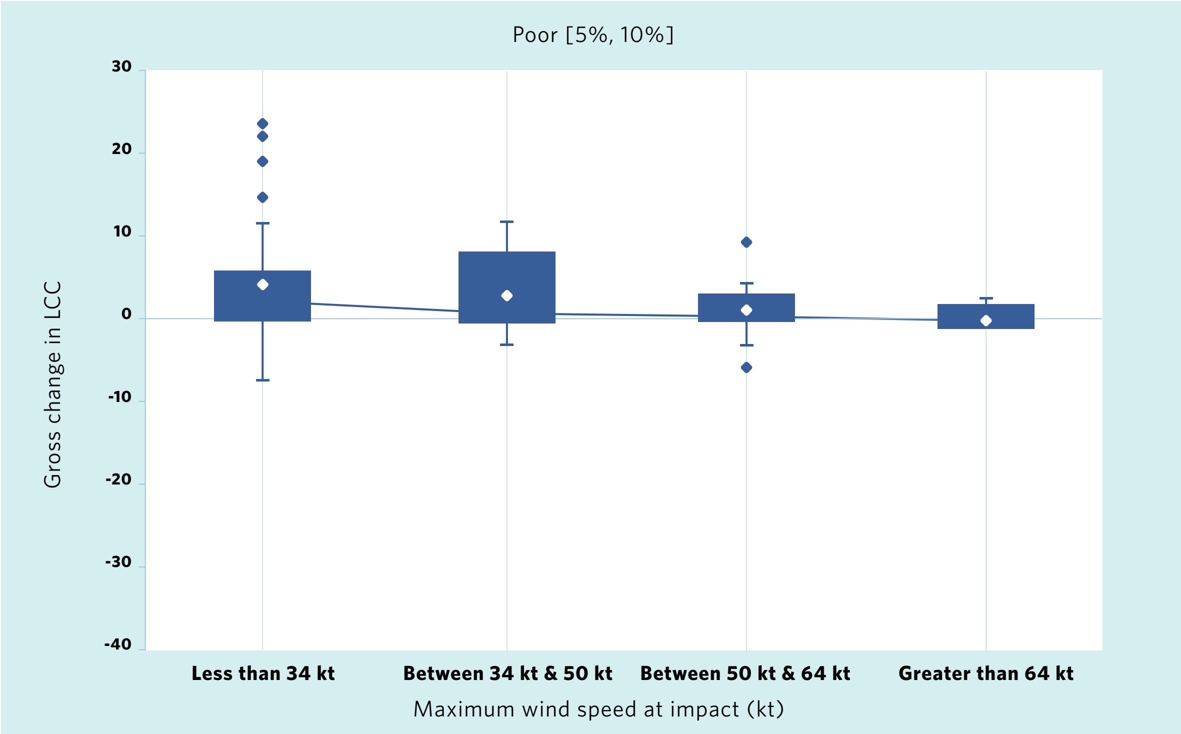


Figura 19. Gross change in live coral cover by wind at impact on reefs in poor condition.

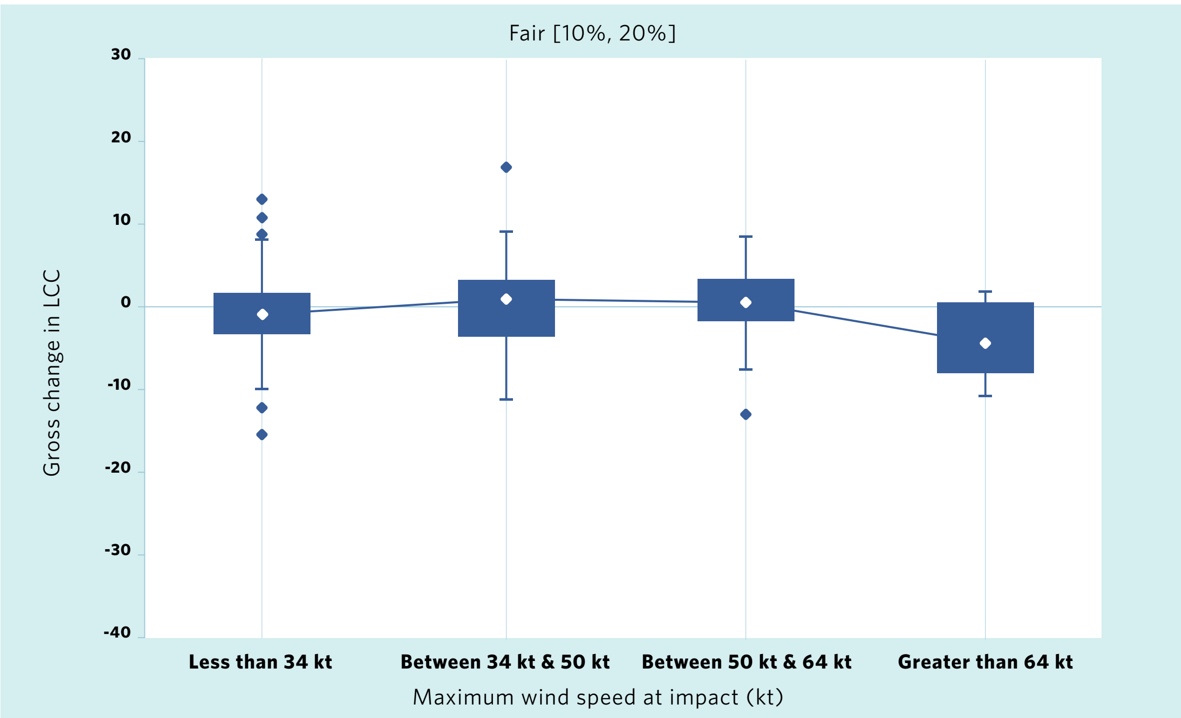


Figura 20. Gross change in live coral cover by wind at impact on reefs in regular state.

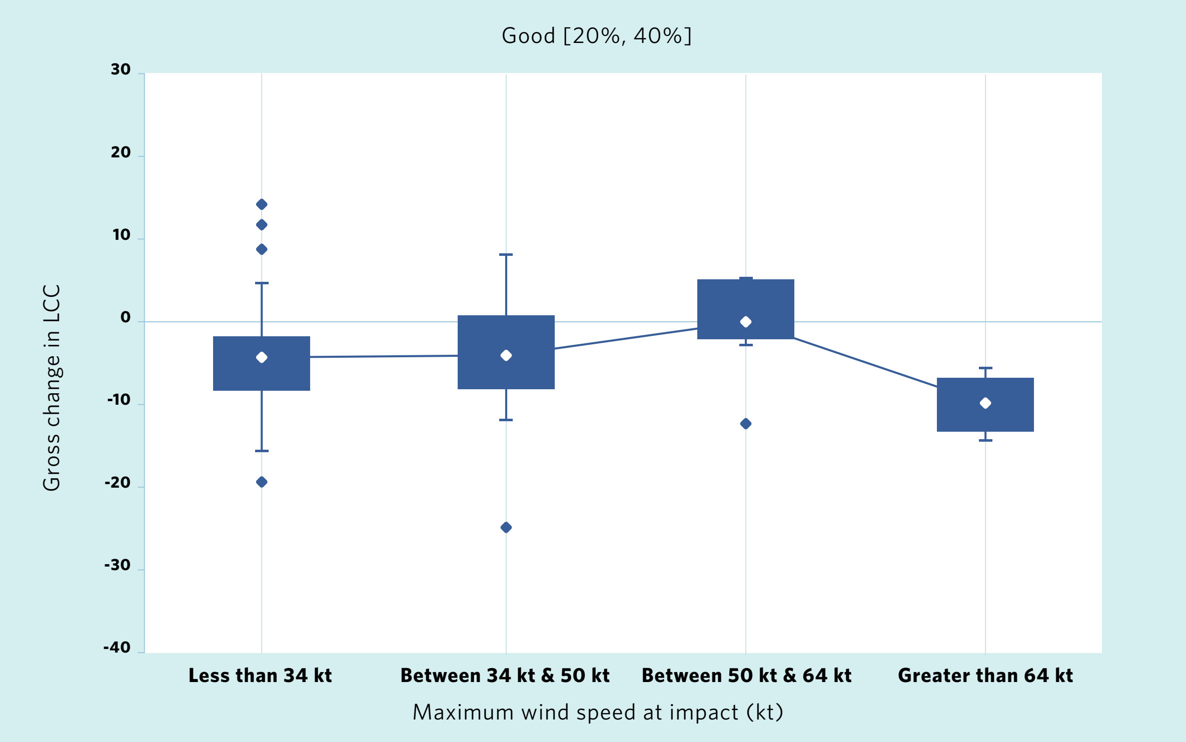


Figura 21. Gross change in live coral cover by wind at impact on reefs in good condition.

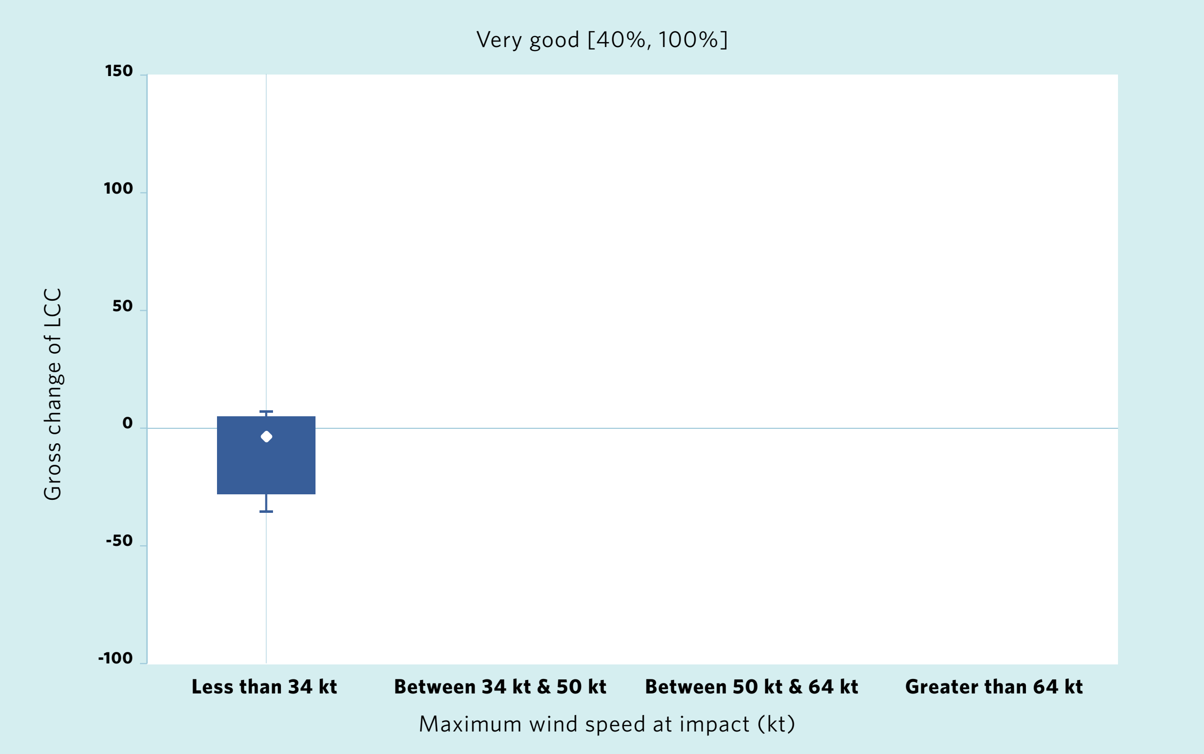


Figura 22. Gross change in live coral cover by wind at impact on reefs in very good condition.

3.2 EXPLORATORY ANALYSIS OF HURRICANE AND REEF CHARACTERISTICS

After determining the severity of hurricane damage to reefs, we proceeded to explore the relationship between that damage and the characteristics of the hurricane and the characteristics of the reef. This exploration uses linear models whose plots show the change in live coral cover or rugosity on the Y-axis, and reef or hurricane characteristics, or a combination of both, on the X-axis. The exploratory analysis uses data from all sites since the inclusion of data older than 3 years does not influence trends and extends the sample size (see Annex 1).

ANALYZED REEF CHARACTERISTICS.

1. Pre-impact live coral cover or initial condition of the site.
2. Site exposure.
3. Reef type.
4. Reef zone.
5. Average depth of the site.
6. Clear distance in front of the site or mean *fetch*.

CHARACTERISTICS OF THE HURRICANE IN RELATION TO THE SITE UNDER ANALYSIS.

7. Maximum sustained wind.
8. Wind over the site or wind at impact.
9. Hurricane duration or number of *snapshots*.
10. Minimum distance between the eye of the hurricane and the site.

As explained in the methodology, coral cover indicators and different rates were used to show the change in coral cover: gross change, proportion of change compared to the initial condition, logarithmic rate and effective rate (see Table 3), so a graph is presented for each indicator. In the case of rugosity, only the effective rate was used to show the change in rugosity, so a graph is presented for each indicator compared to the effective rate.

3.2.1 Change in Live Coral Cover by Initial Condition of Wind-Segregated Site at Impact

The analysis shows that corals in good condition sites experience more severe damage than those in degraded sites. Degraded reefs will always lose less than reefs in good condition. This difference is most evident at wind speeds below 34 knots, under which degraded reefs experience very little damage (-3%) while in good conditions they lose up to 34%.

GROSS CHANGE

Gross change in live coral cover by wind speed at impact
and segregated by initial condition

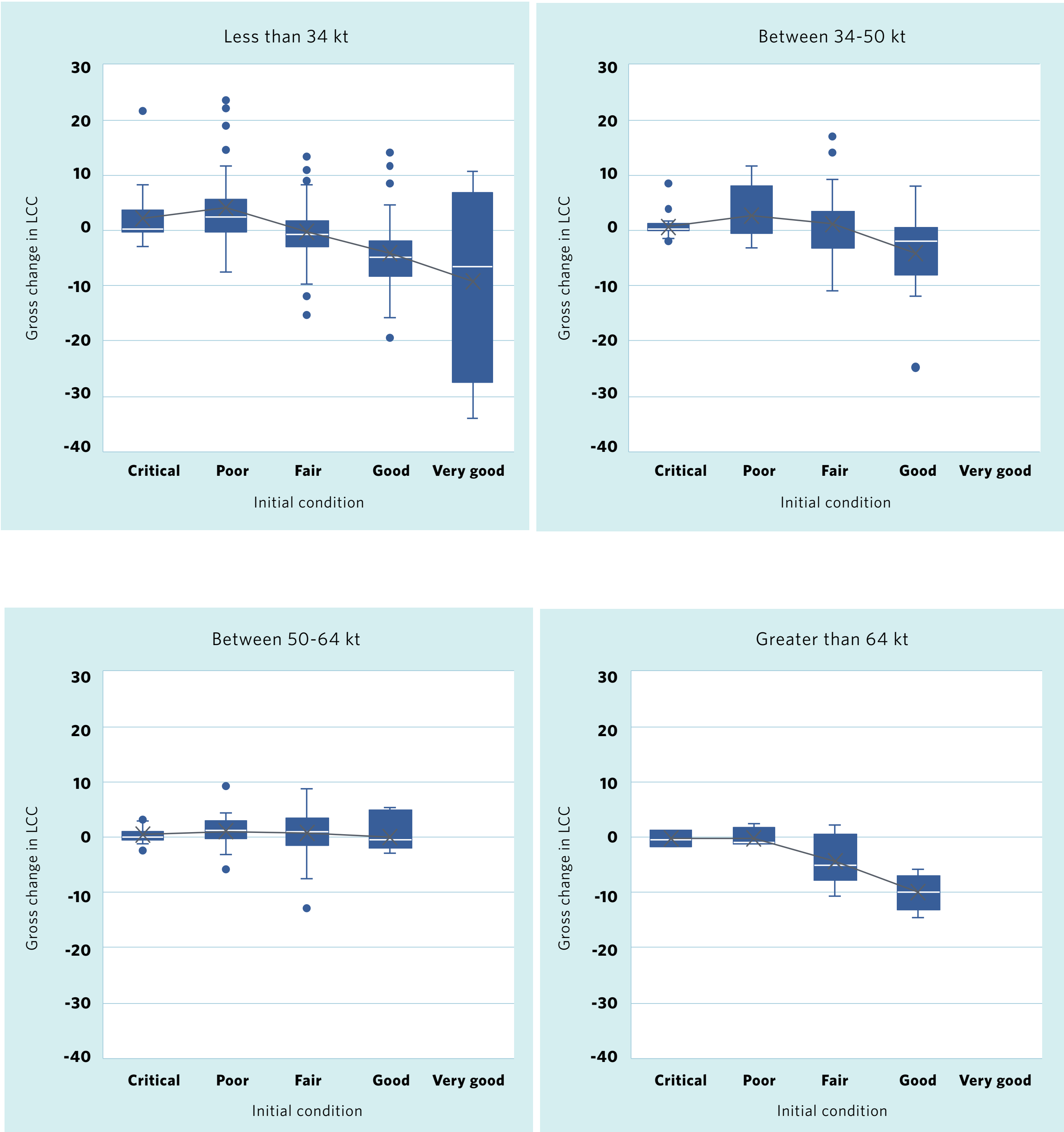


Figura 23. Gross change in live coral cover by initial condition and wind at impact.

PERCENT OF CHANGE

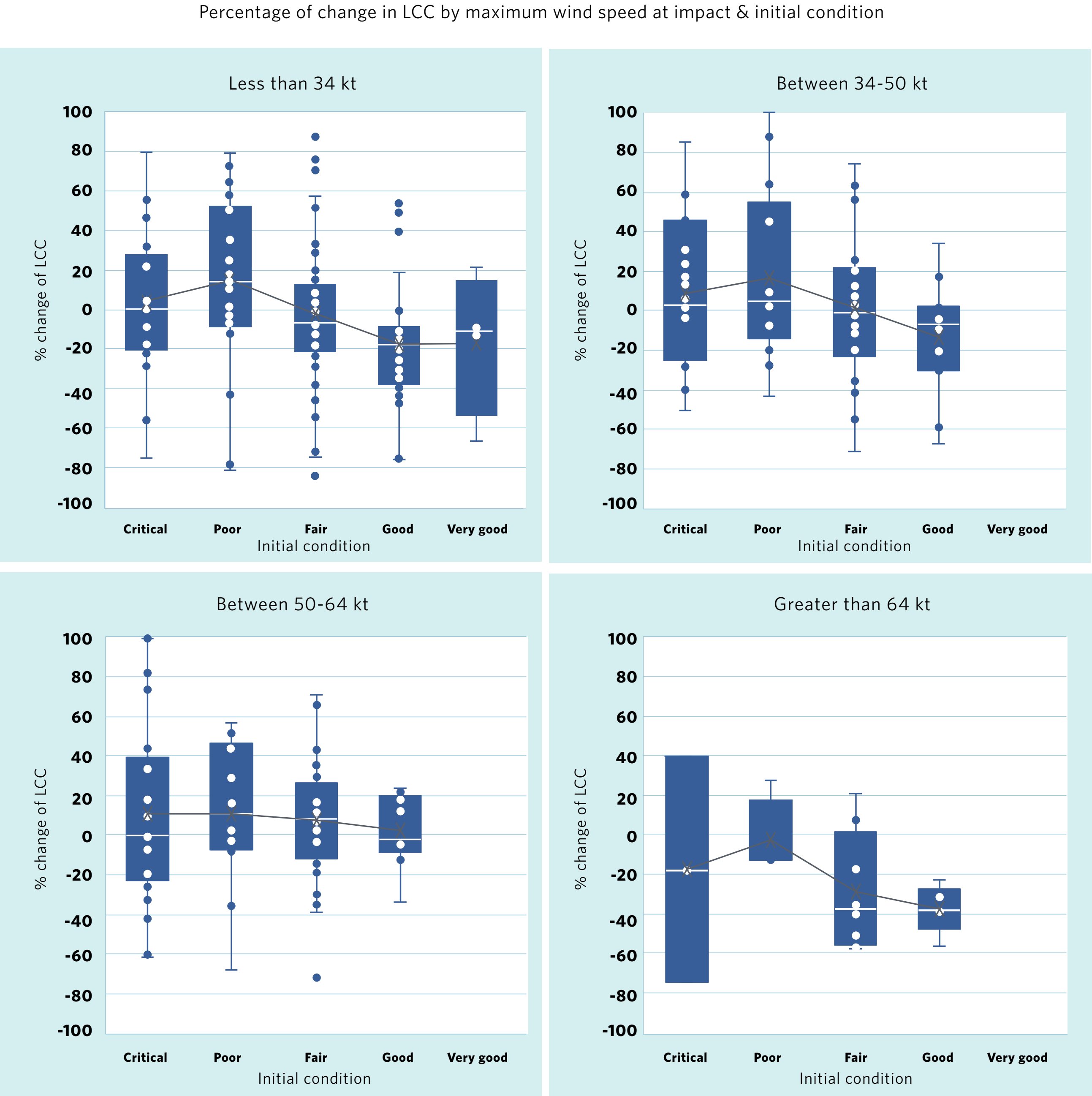


Figura 24. Percent of change in live coral cover by initial condition and wind at impact.

The analysis shows that degraded sites have experienced very severe damage (up to 74%) with wind speed at impact greater than 64 knots, losing almost all the little cover they had prior to impact. But on average sites in good condition lose significantly more than others, losing twice as much (37%) as sites in critical condition (20%), ten times more than in poor condition (2%) and more than in fair condition (28%). No data were obtained for sites in very good condition affected by impact wind greater than 64 knots.

ANNUAL LOGARITHMIC RATE

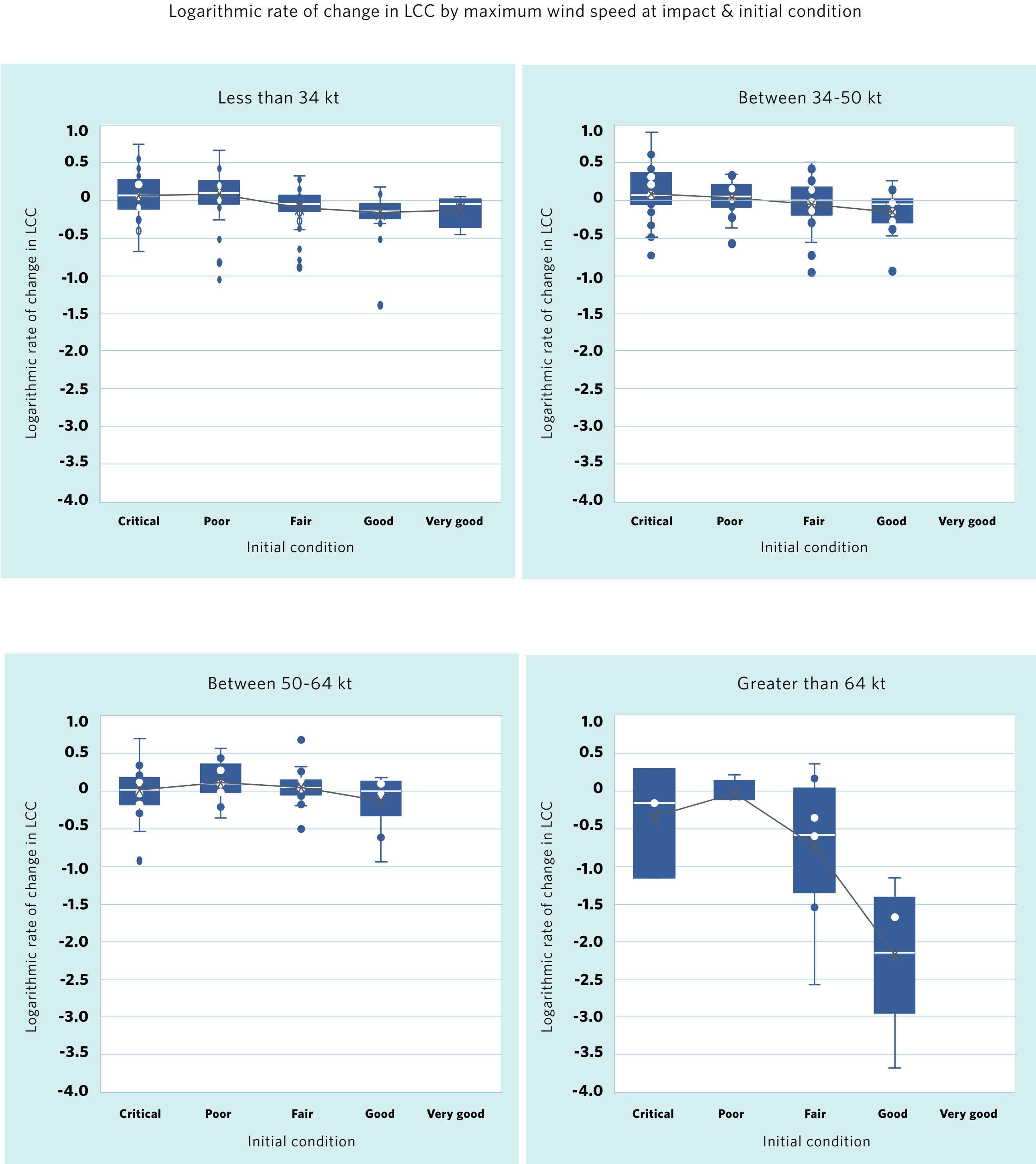


Figura 25. Annual logarithmic rate of change in live coral cover by initial condition and wind at impact.

EFFECTIVE ANNUAL RATE

Effective rate of change in LCC by maximum wind speed at impact & initial

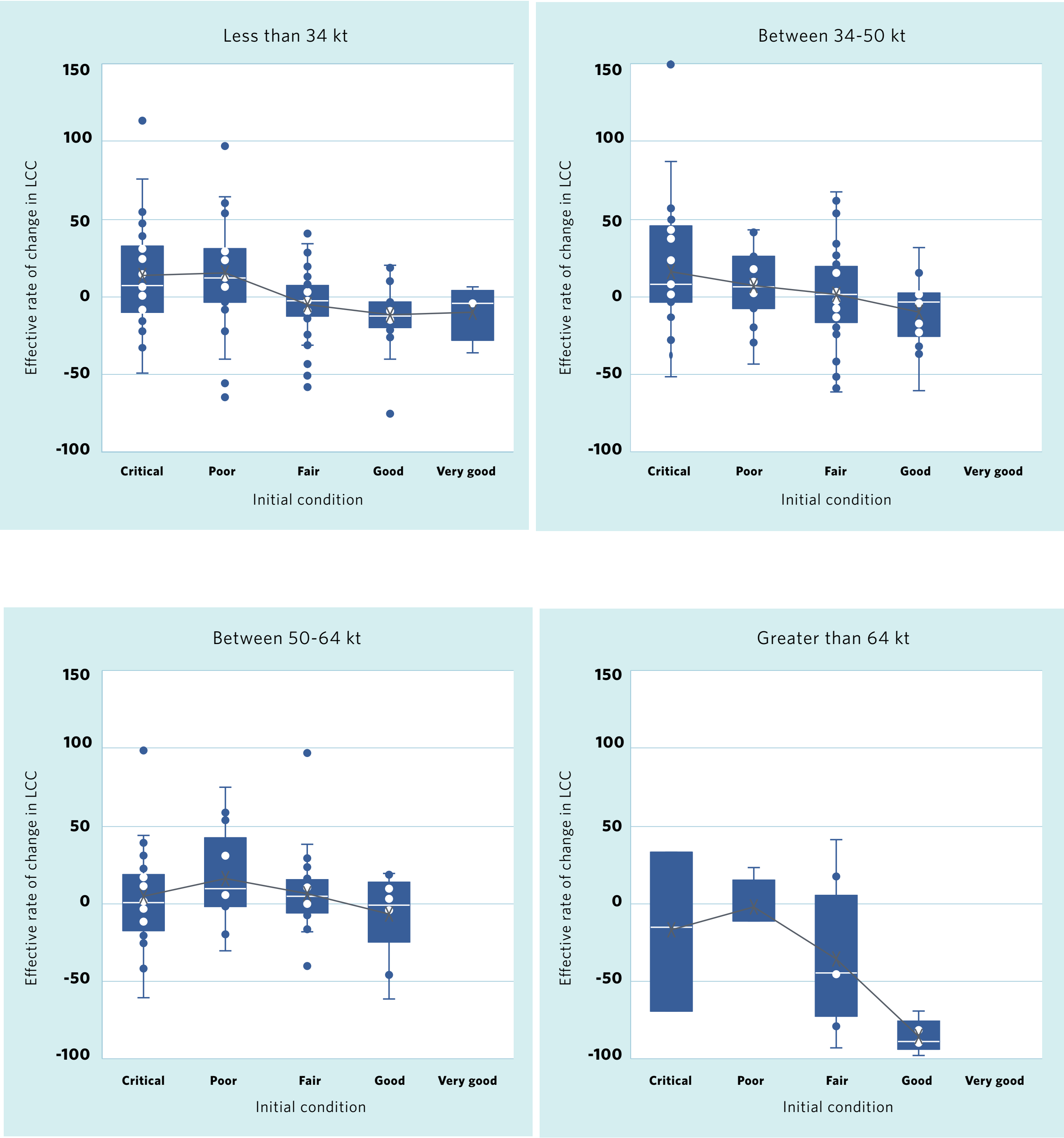


Figura 26. Effective annual rate of change in live coral cover by initial condition and wind at impact.

3.2.2 Change in Live Coral Cover by Wind Speed at Impact

When grouping all sites without differentiating the initial condition, the wind speed at impact does not significantly determine the magnitude of the caused damage. The average loss is 0% and the maximum value is -13% for winds less than 34 knots; with winds greater than 64 knots the average increases to -4% and the maximum value to -14%, data that do not show a significant trend.

GROSS CHANGE

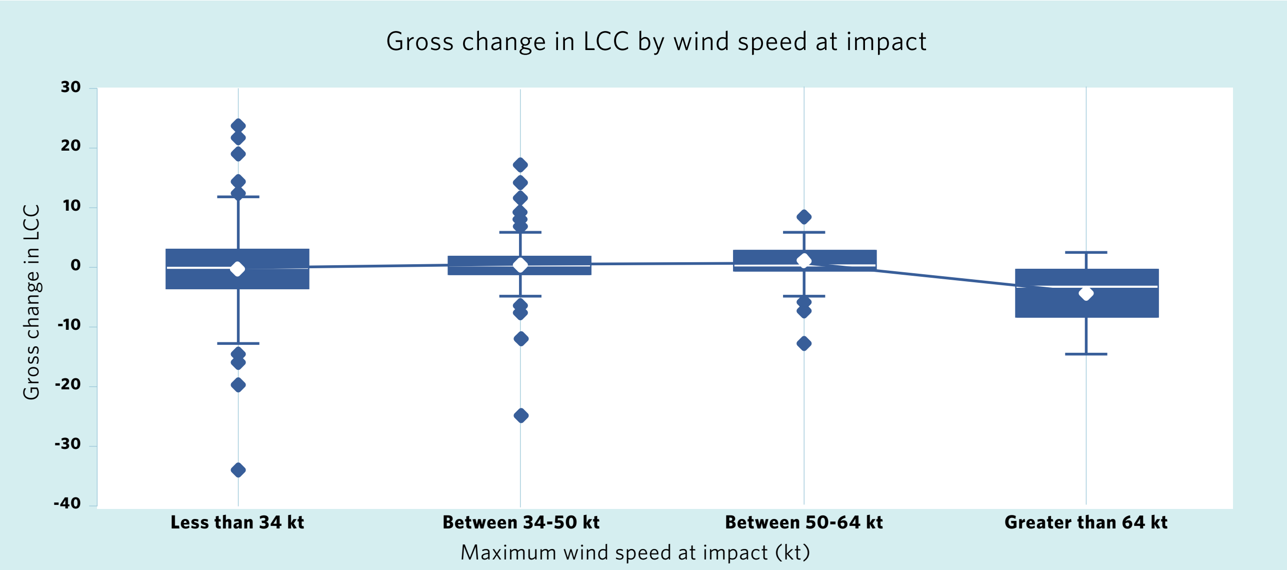


Figura 27. Gross change in live coral cover by wind speed at impact.

PERCENTAGE OF CHANGE

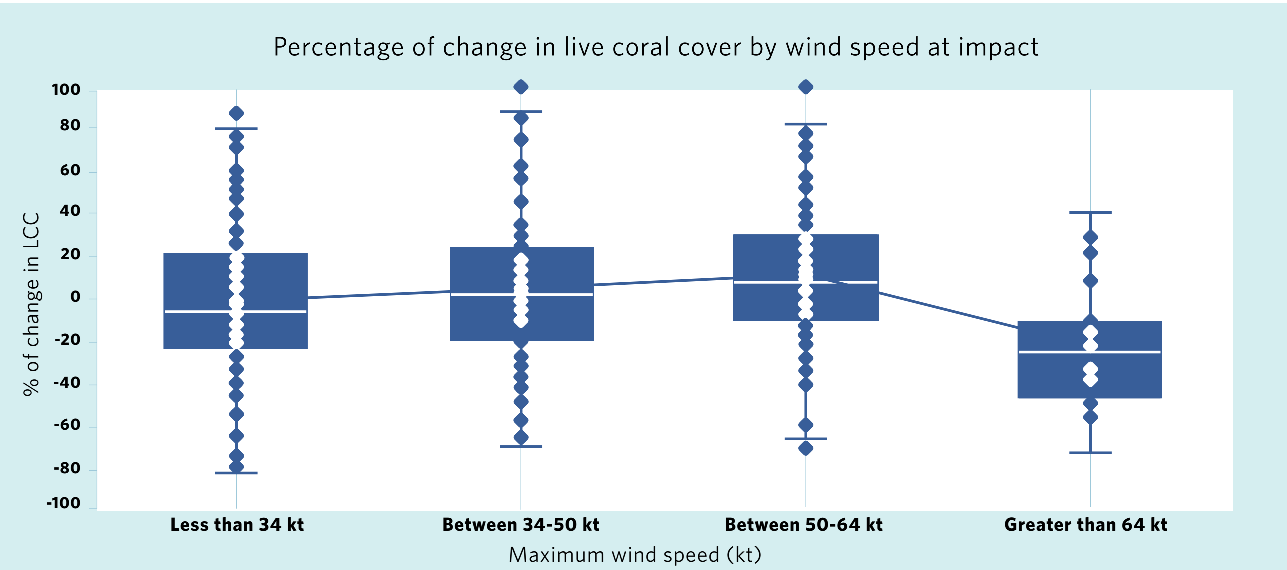


Figura 28. Percent of change in live coral cover by wind speed at impact.

The average percentage change does increase significantly with wind speed, going from -2% with wind less than 34 knots to -27% with wind greater than 64 knots. However, the maximum proportional loss is similar, with -81% for lower winds and -74% for higher winds.

ANNUAL LOGARITHMIC RATE

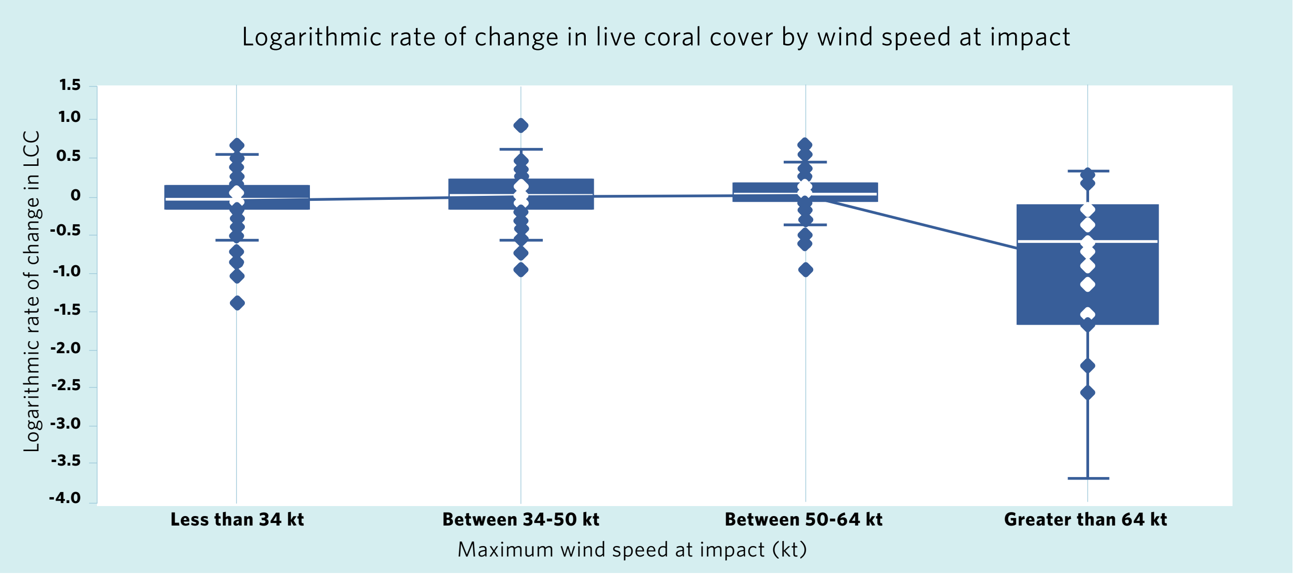


Figura 29. Annual logarithmic rate of change in live coral cover by wind speed at impact.

ANNUAL EFFECTIVE RATE

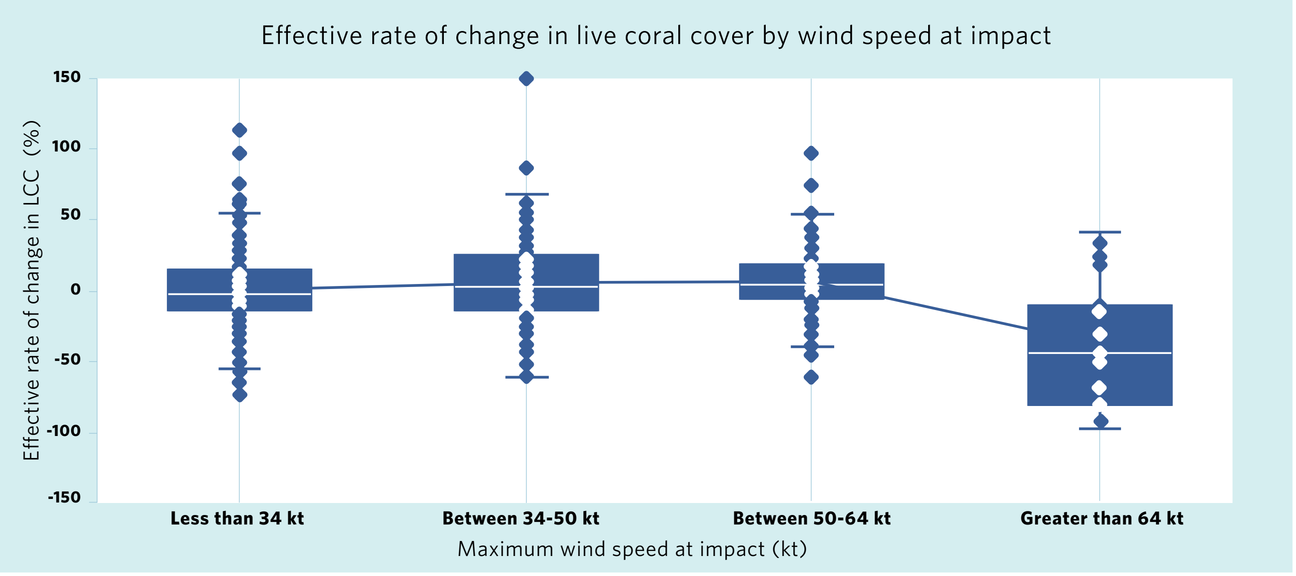


Figura 30. Effective annual rate of change in live coral cover by wind speed at impact.

Logarithmic and effective rates express more significant damage with winds greater than 64 knots.

3.2.3 Change in Live Coral Cover Due to Site Exposure

The sites were classified according to their position compared to the dominant wind. Those sites located at points oriented in both directions were classified as intermediate. The average change does not vary significantly (0% in windward and intermediate, compared to -2% in leeward). However, the maximum impact does increase in leeward (-16%) compared to windward (-5%) and intermediate (-7%).

GROSS CHANGE

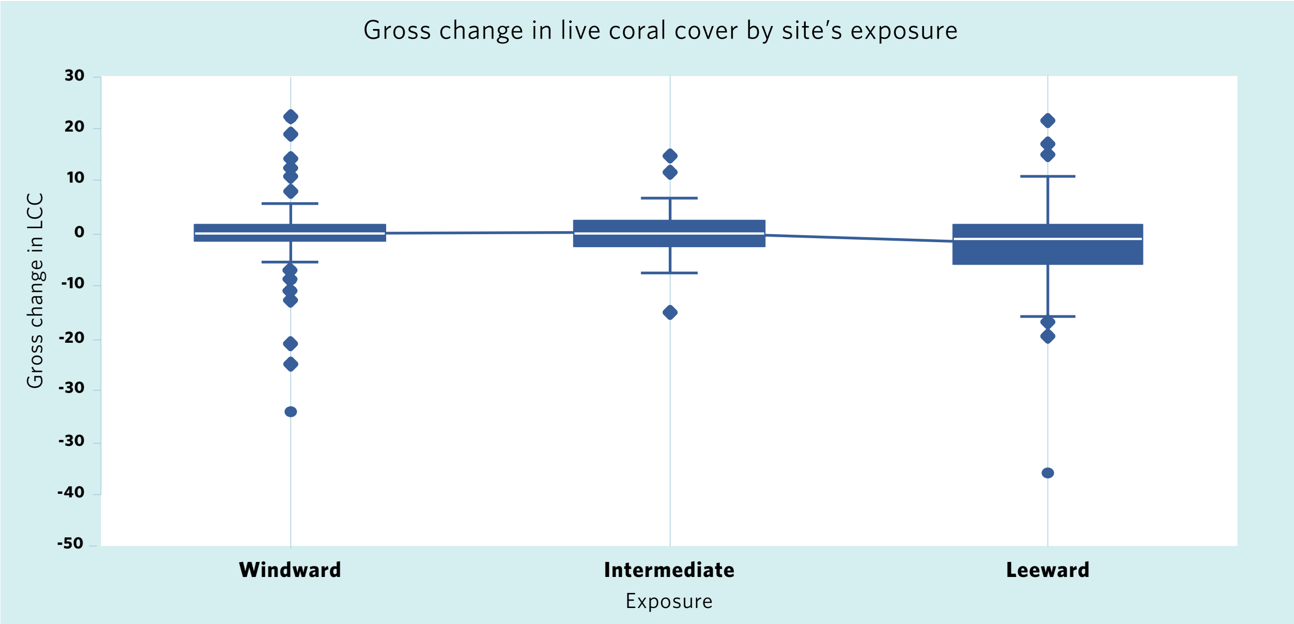


Figura 31. Gross change in live coral cover by site exposure.

PERCENTAGE OF CHANGE

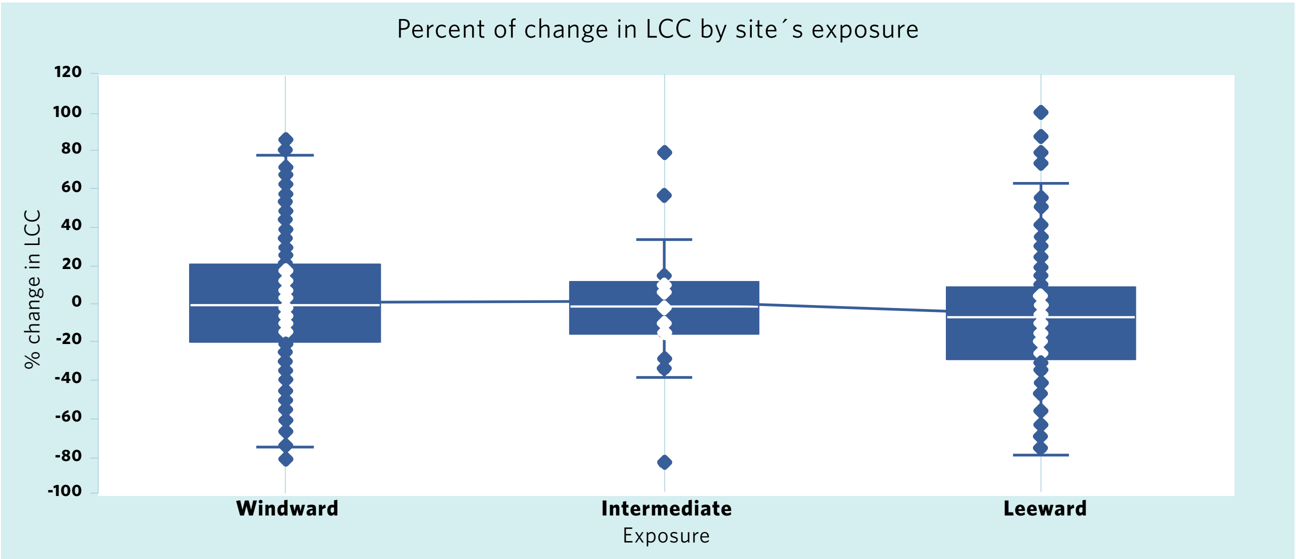


Figura 32. Percent of change in live coral cover by site exposure.

ANNUAL LOGARITHMIC RATE

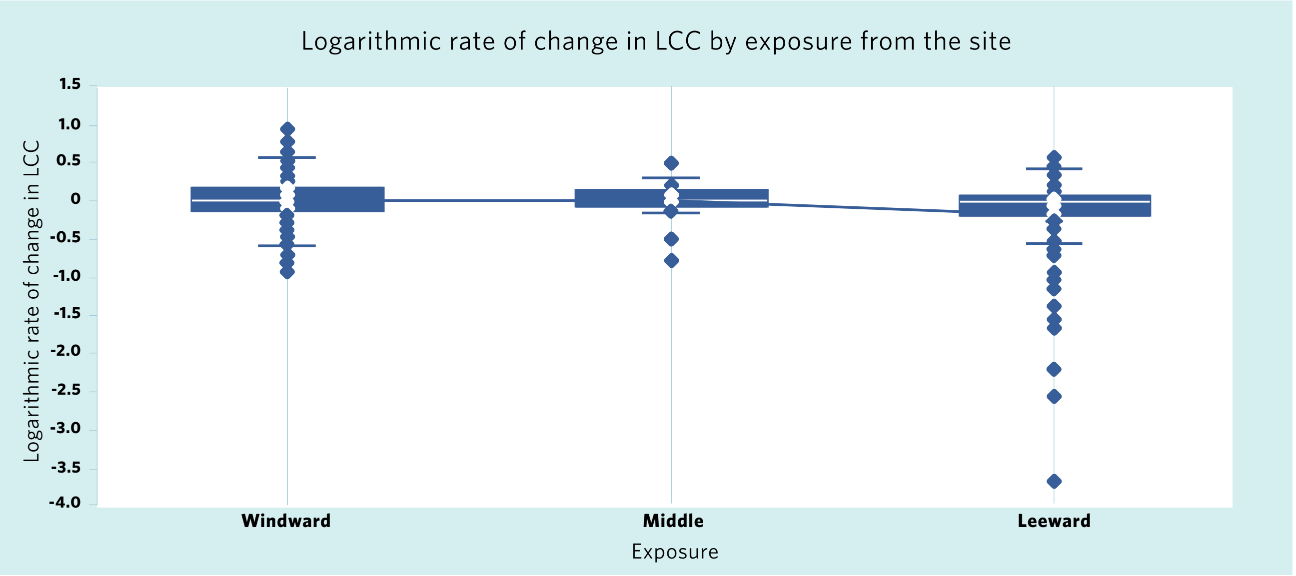


Figura 33. Annual logarithmic rate of change in live coral cover by site exposure.

EFFECTIVE ANNUAL RATE

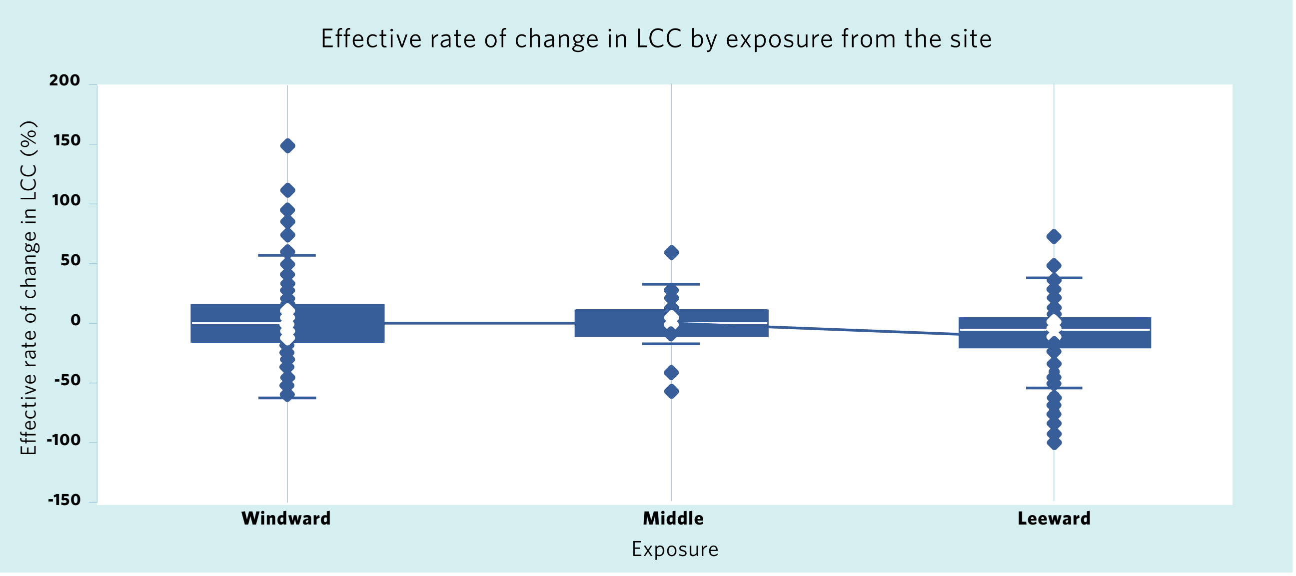


Figura 34. Effective annual rate of change in live coral cover by site exposure.

3.2.4 Change in Live Coral Coverage by Duration of Hurricane Impact (number of *snapshots*)

The analysis shows that there are no significant changes in coral cover related to the duration of the hurricane at the site. It could be interpreted that the damage is caused in the first hours of the hurricane impact, since the damage does not increase in the sites impacted for more than 54 hours (9 *snapshots*).

GROSS CHANGE

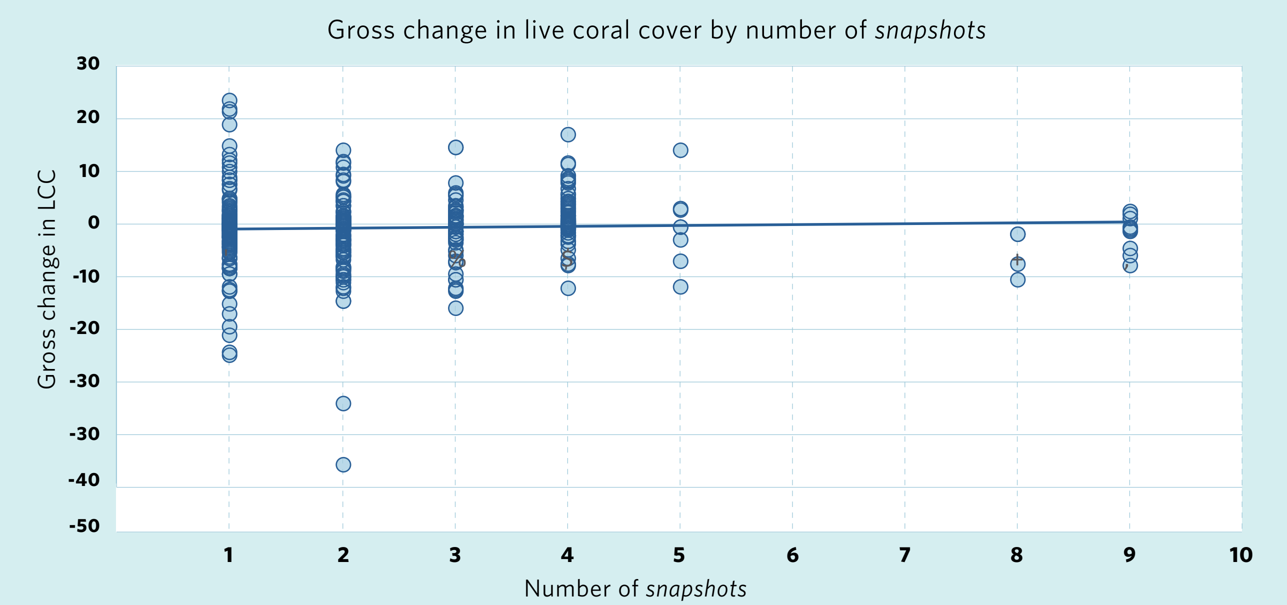


Figura 35. Gross change in live coral cover by number of *snapshots*. NOAA reports one *snapshot* every 6 hours.

PERCENTAGE OF CHANGE

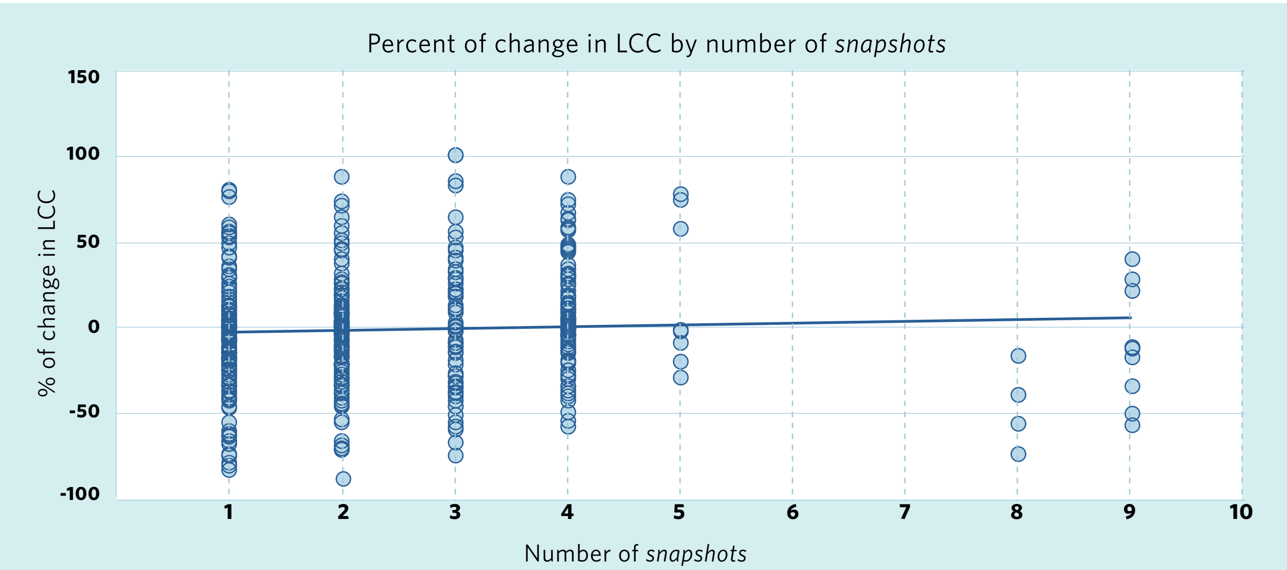


Figura 36. Percent of change in live coral cover by number of *snapshots*. NOAA reports one *snapshot* every 6 hours.

ANNUAL LOGARITHMIC RATE

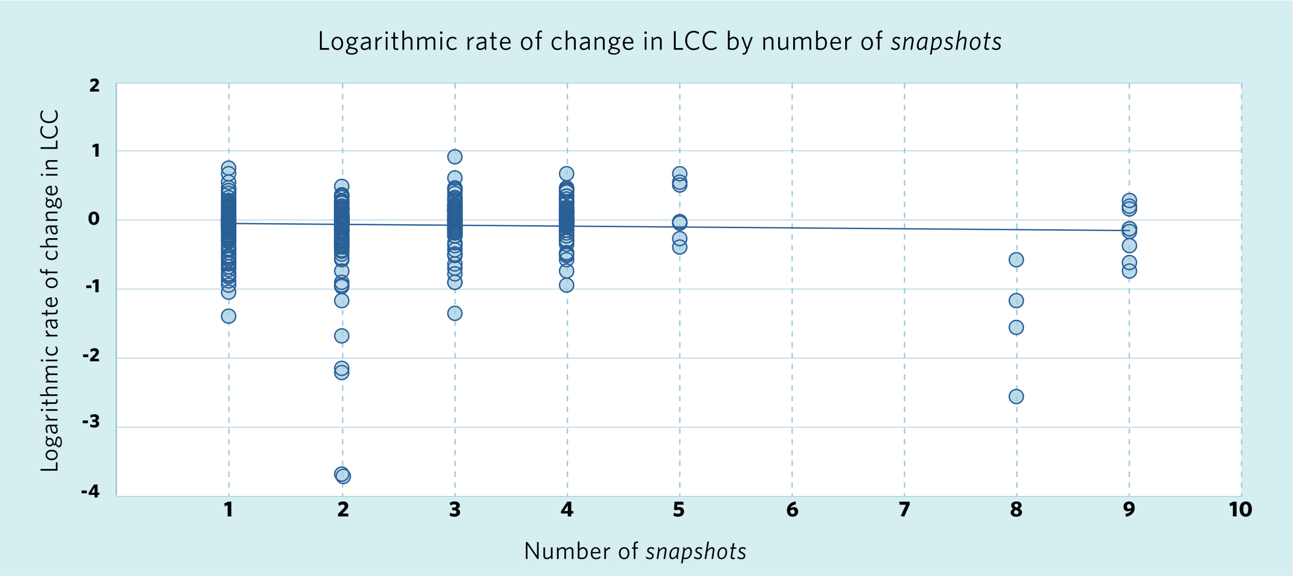


Figura 37. Logarithmic rate in live coral cover by number of *snapshots*. NOAA reports one *snapshot* every 6 hours.

EFFECTIVE ANNUAL RATE

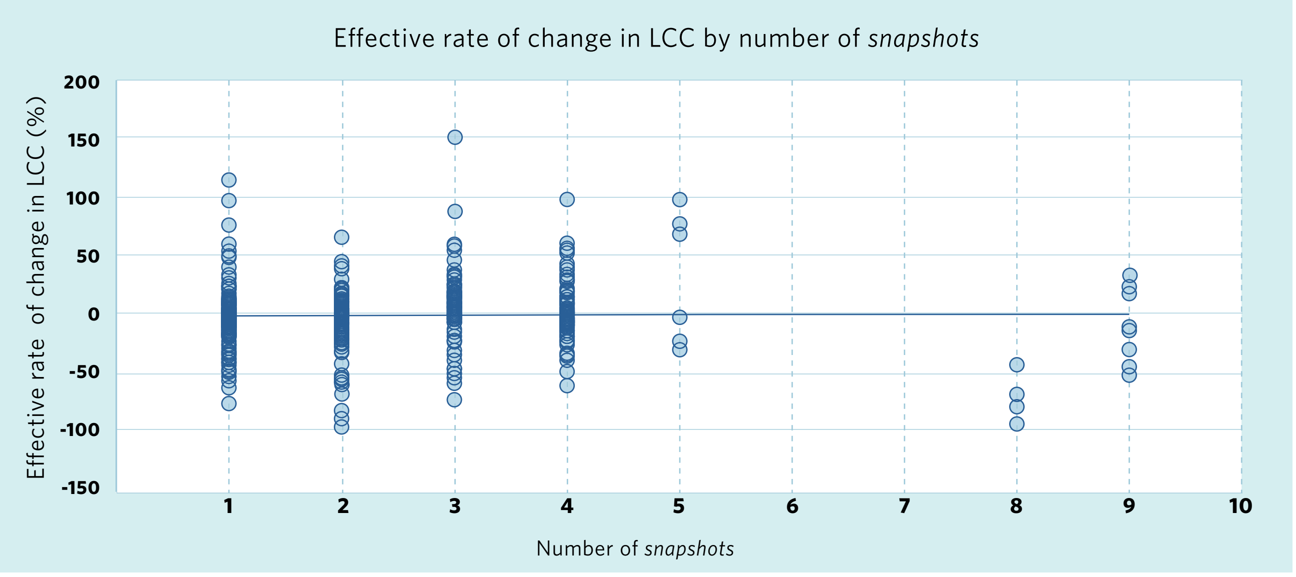


Figura 38. Effective annual rate in live coral cover by number of *snapshots*. NOAA reports one *snapshot* every 6 hours.

3.2.5 Change in Live Coral Cover by *Fetch*

The *fetch* or the degree of wave protection is the distance that the wind can blow into the water without interruption and form waves, for this analysis the wind direction used was: north, northeast, east, southeast, south, southwest and west. The analysis does not show a relationship between the *fetch* distance of the site and the damage caused by hurricanes, which means that the distance to form waves does not affect the damage caused by the hurricane.

GROSS CHANGE

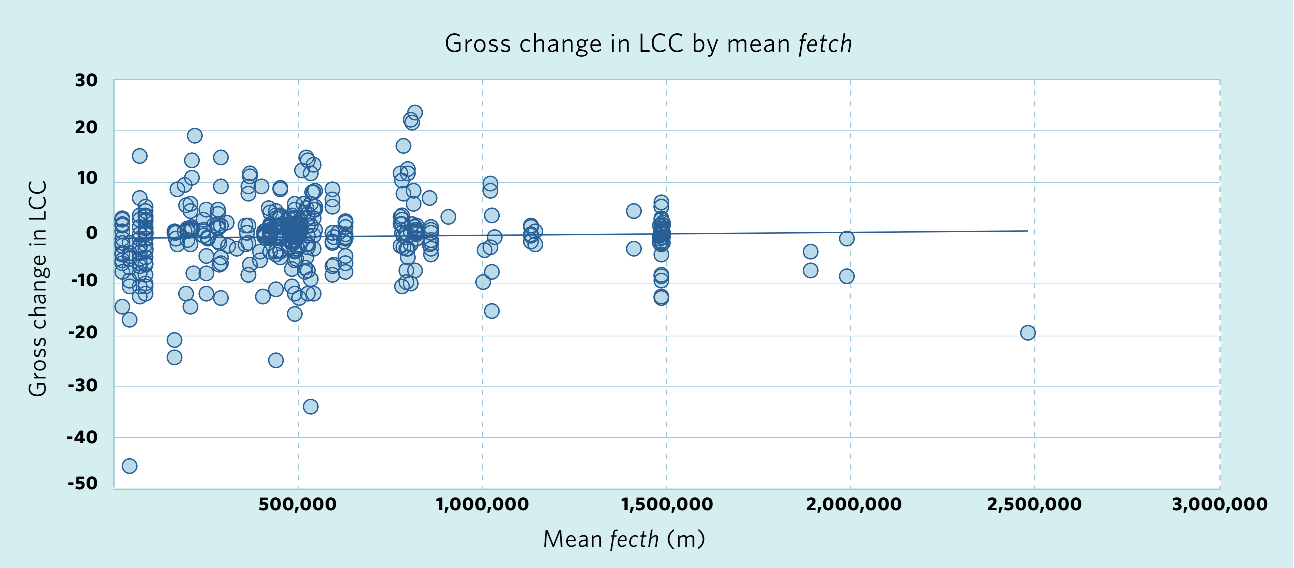


Figura 39. Gross change in live coral cover per medium *fetch*.

PERCENTAGE OF CHANGE

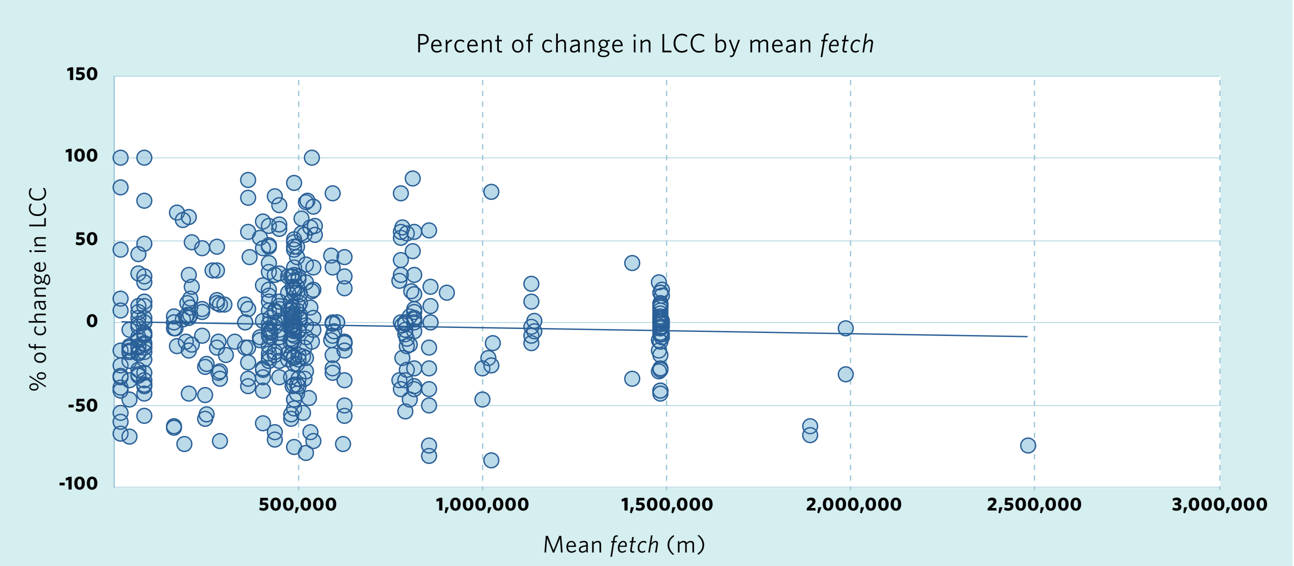


Figura 40. Percent of change in live coral cover by mean *fetch*.

ANNUAL LOGARITHMIC RATE

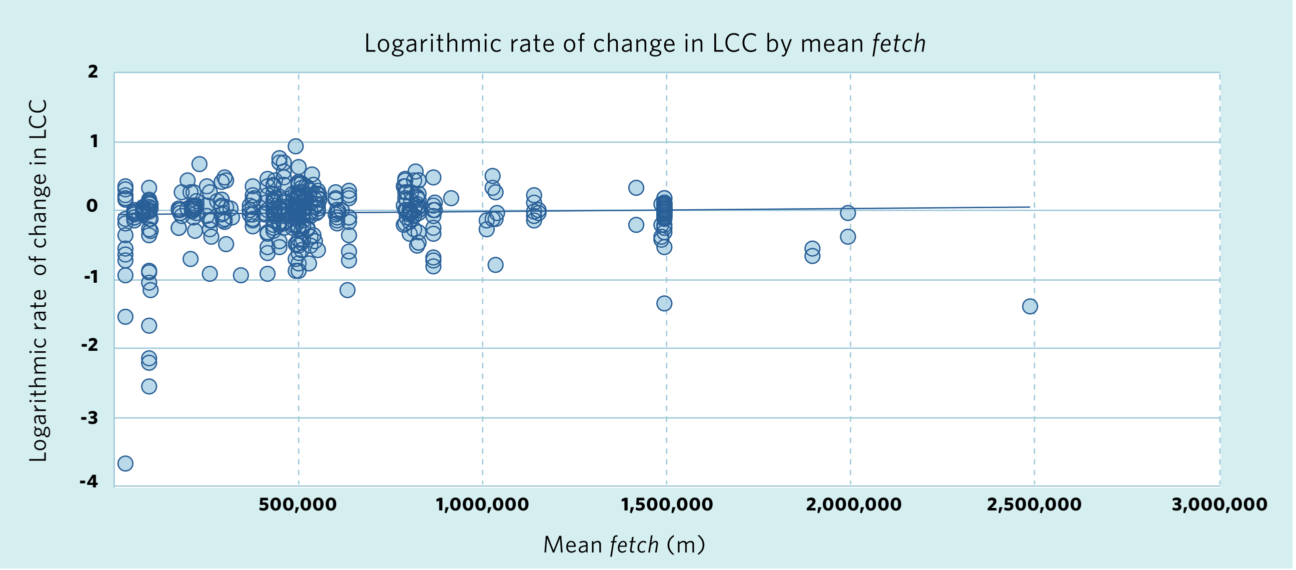


Figura 41. Logarithmic annual rate in live coral cover by mean *fetch*.

EFFECTIVE ANNUAL RATE

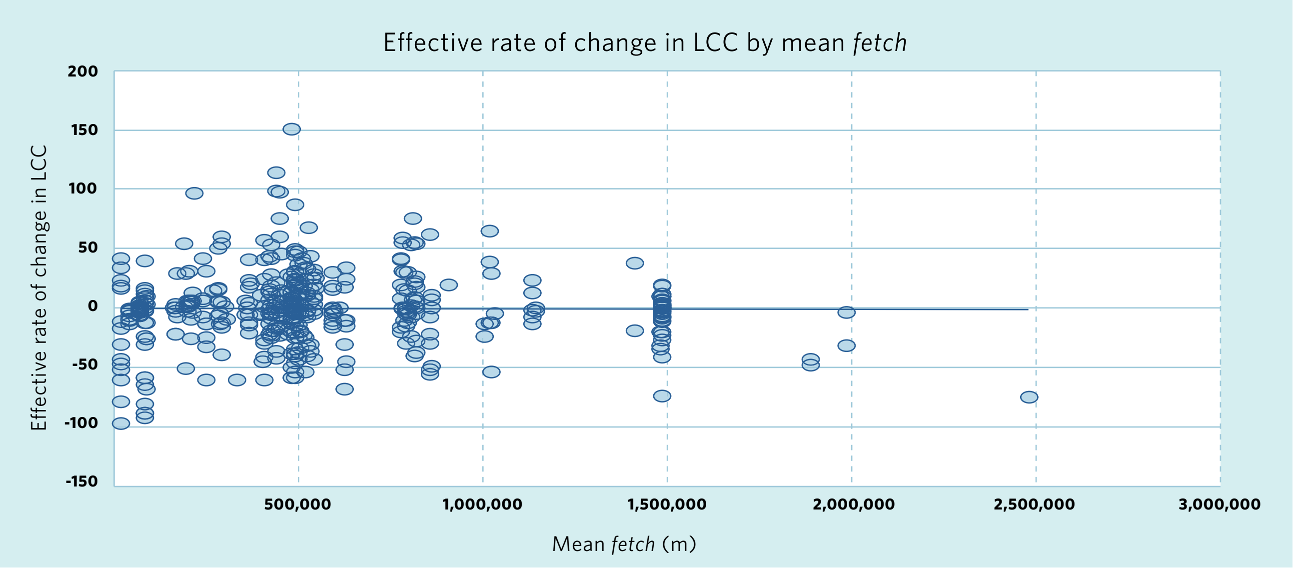


Figura 42. Effective annual rate in live coral cover per mean *fetch*.

3.2.6 Change in Live Coral Cover by Maximum Sustained Wind

The analysis shows no relationship between maximum sustained wind speed and reef damage.

GROSS CHANGE

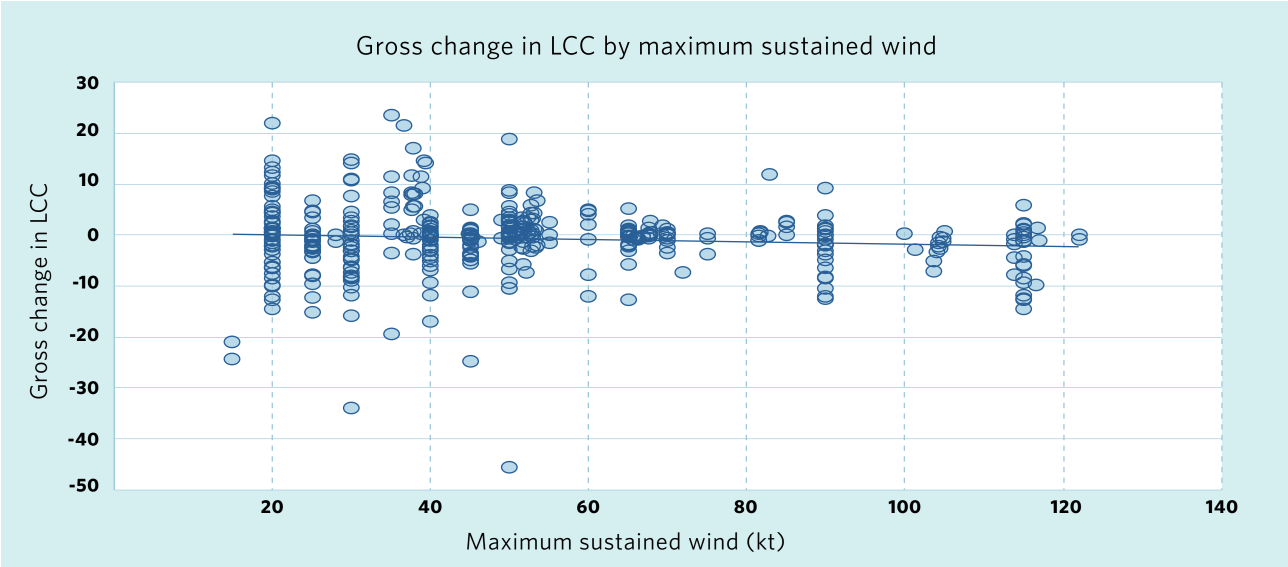


Figura 43. Gross change in live coral cover by mean maximum sustained wind.

PERCENTAGE OF CHANGE

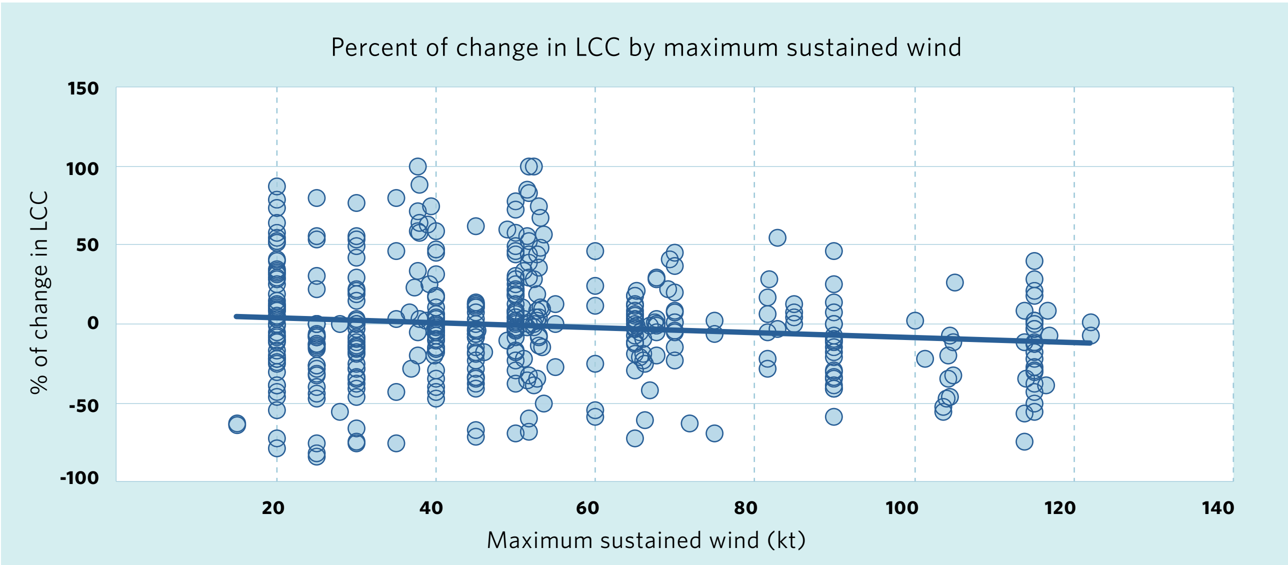


Figura 44. Percent of change in live coral cover by mean maximum sustained wind.

ANNUAL LOGARITHMIC RATE

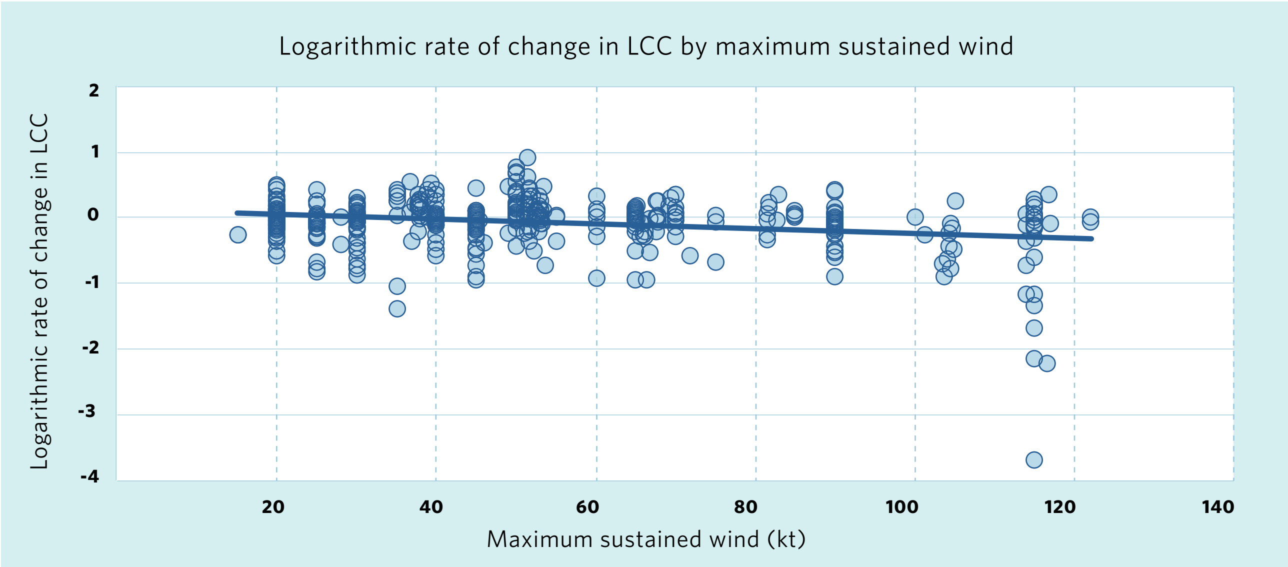


Figura 45. Logarithmic annual rate in live coral cover by mean maximum sustained wind.

EFFECTIVE ANNUAL RATE

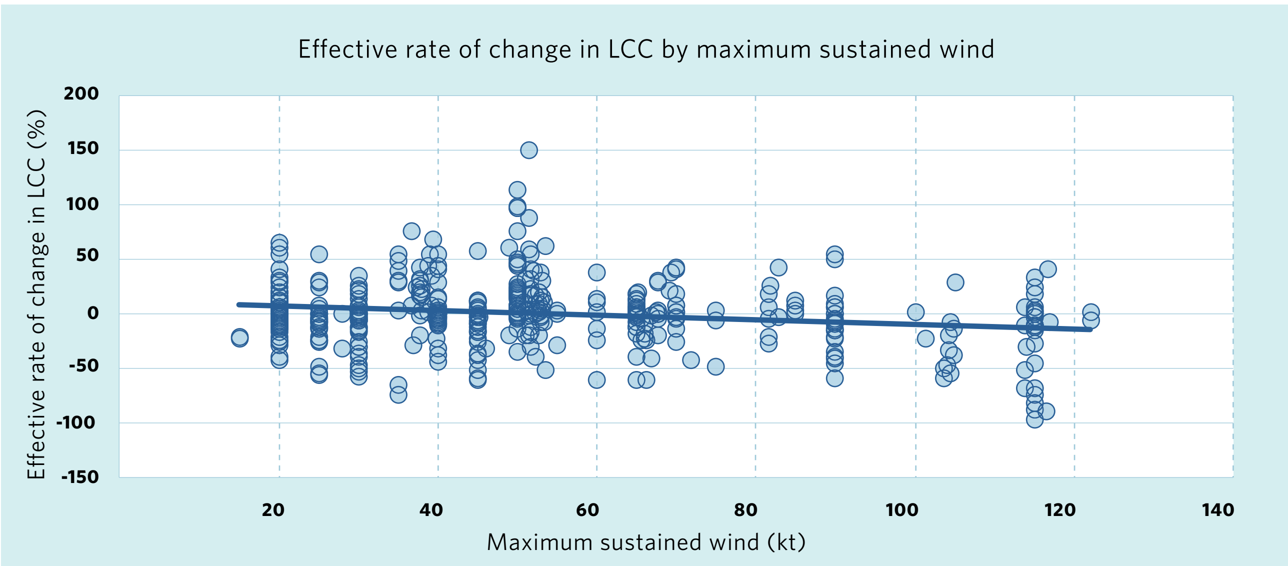


Figura 46. Effective annual rate in live coral cover by mean maximum sustained wind.

3.2.7 Change in Live Coral Cover by Minimum Distance from the Hurricane Site

The analysis does not show a relationship between the distance between the site and the eye of the hurricane, nor the damage caused to the reef.

GROSS CHANGE

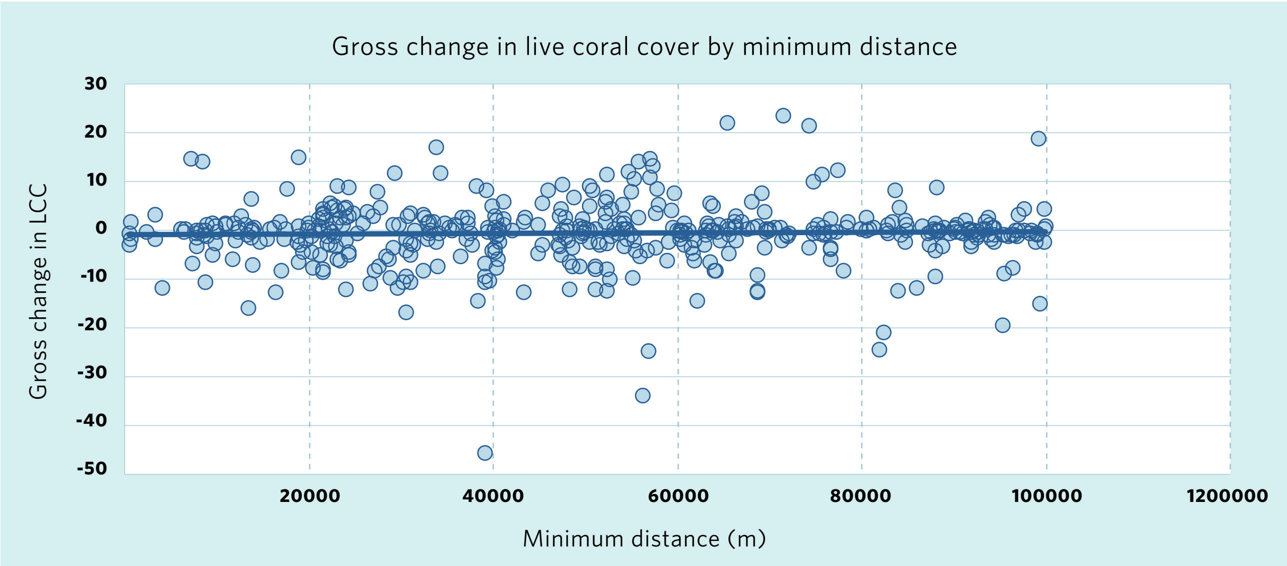


Figura 47. Gross change in live coral cover by minimum distance from site.

PERCENTAGE OF CHANGE

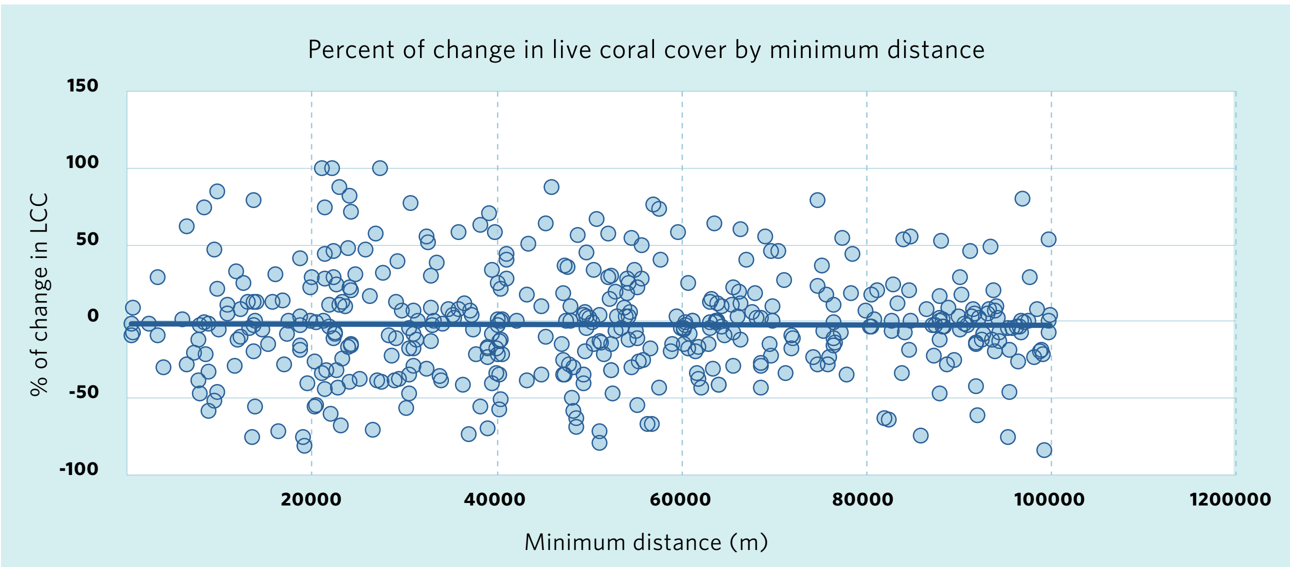


Figura 48. Percent change in live coral cover by minimum distance from site.

ANNUAL LOGARITHMIC RATE

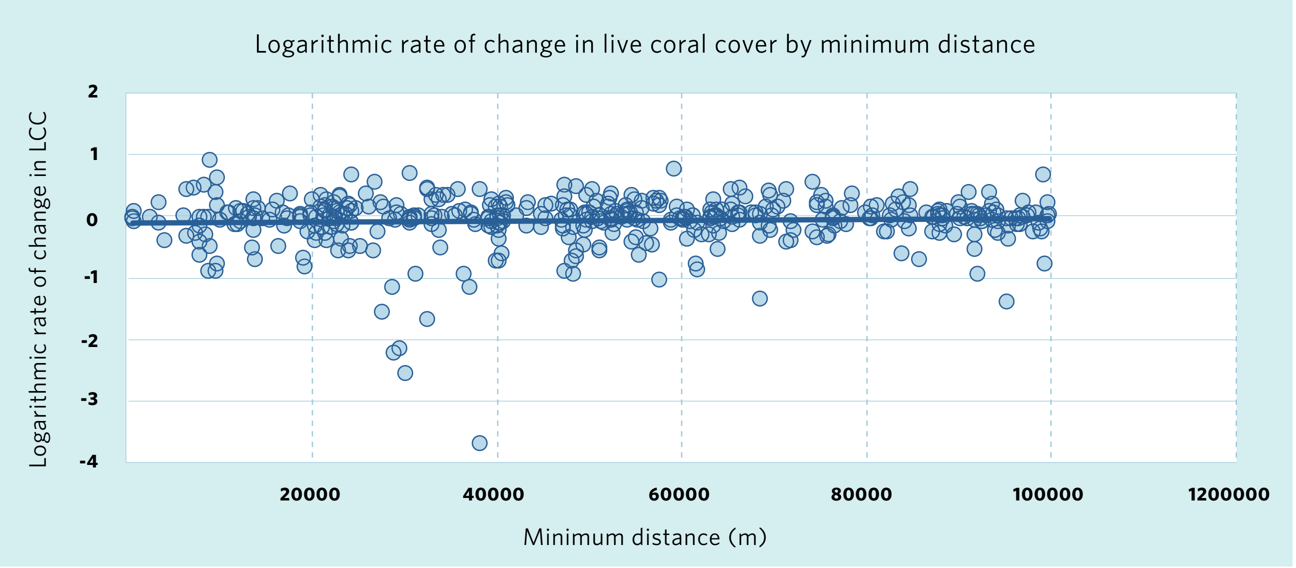


Figura 49. Logarithmic annual rate in live coral cover by minimum distance from site.

EFFECTIVE ANNUAL RATE

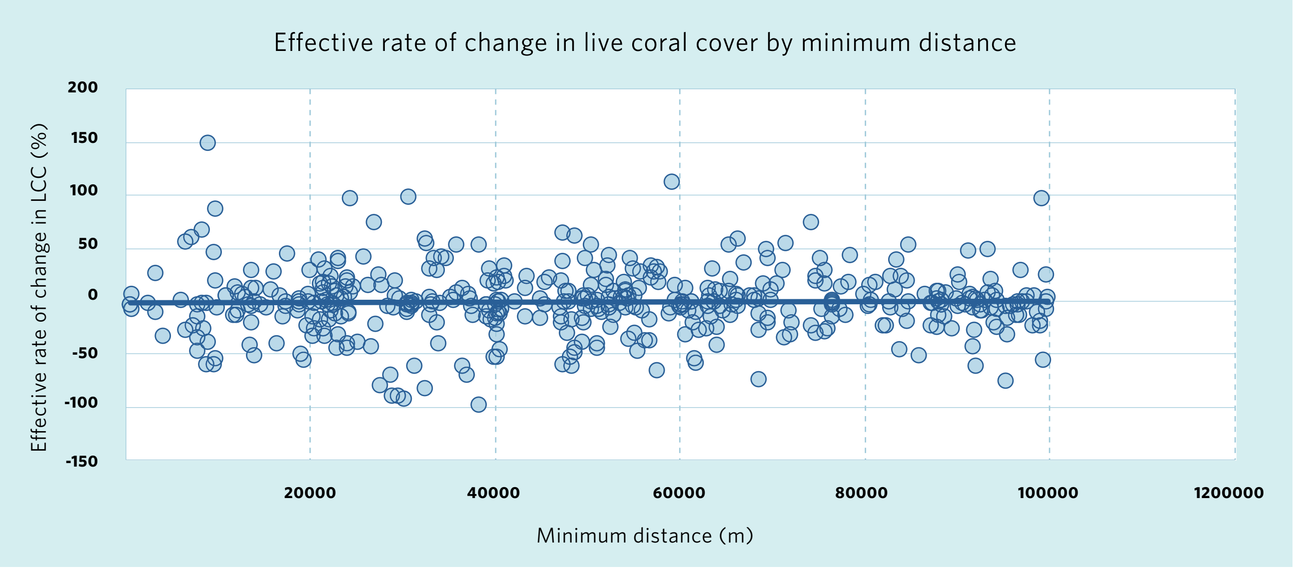


Figura 50. Effective annual rate in live coral cover by minimum distance from site.

3.2.8 Change in Live Coral Cover by Reef Type

Analysis shows that atolls experience greater damage than other reef types.

GROSS CHANGE

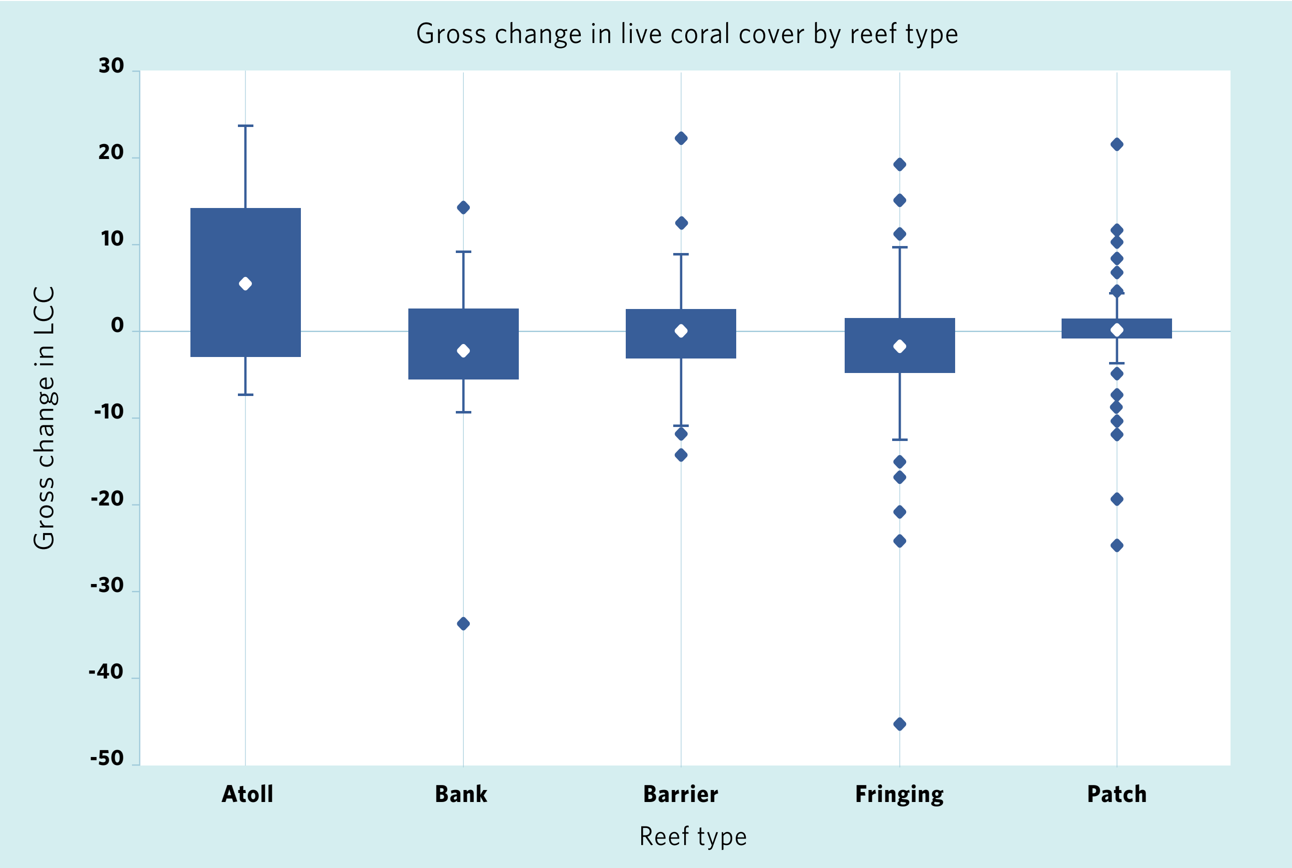


Figura 51. Gross change in live coral cover by reef type.

PERCENTAGE OF CHANGE

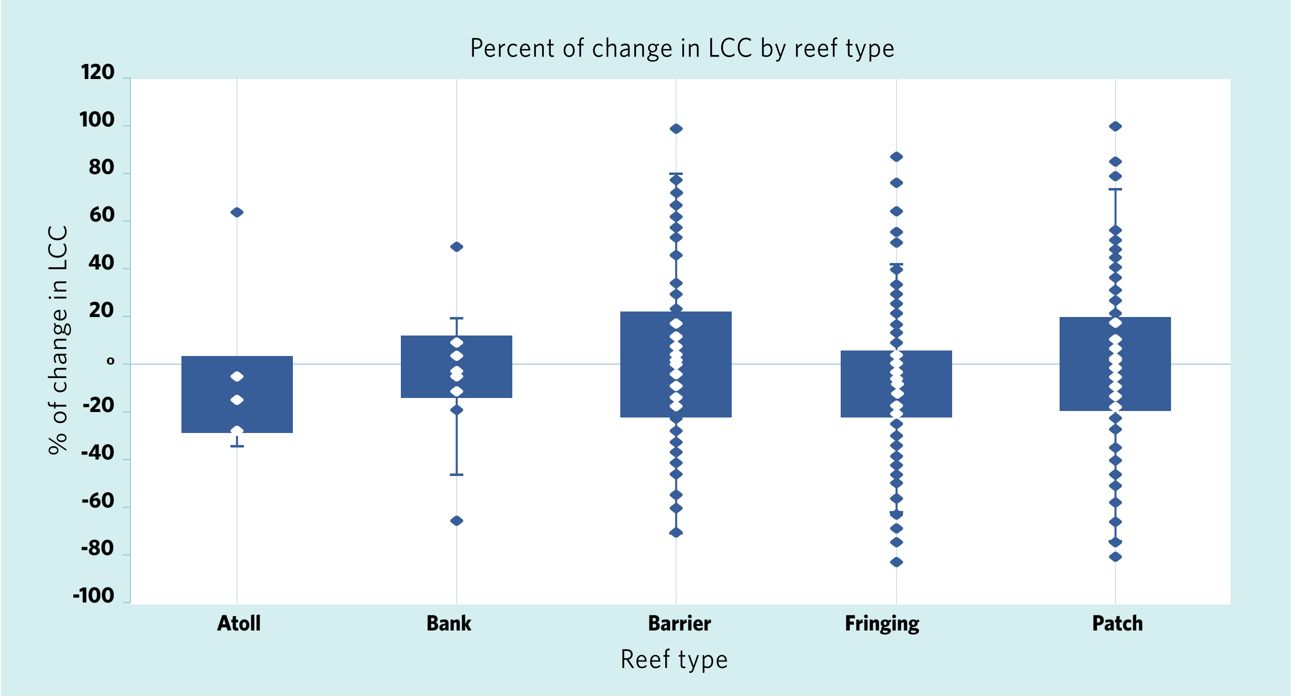


Figura 52. Percent of change in live coral cover by reef type.

ANNUAL LOGARITHMIC RATE

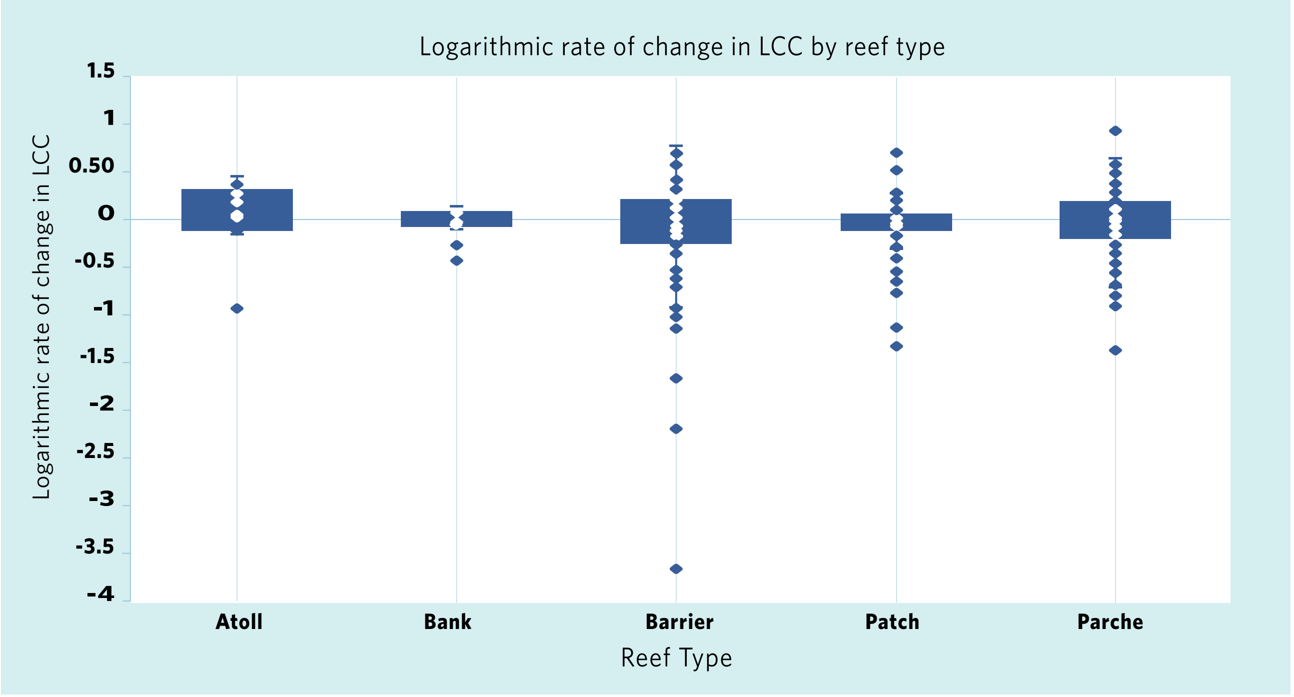


Figura 53. Logarithmic annual rate in live coral cover by reef type.

EFFECTIVE ANNUAL RATE

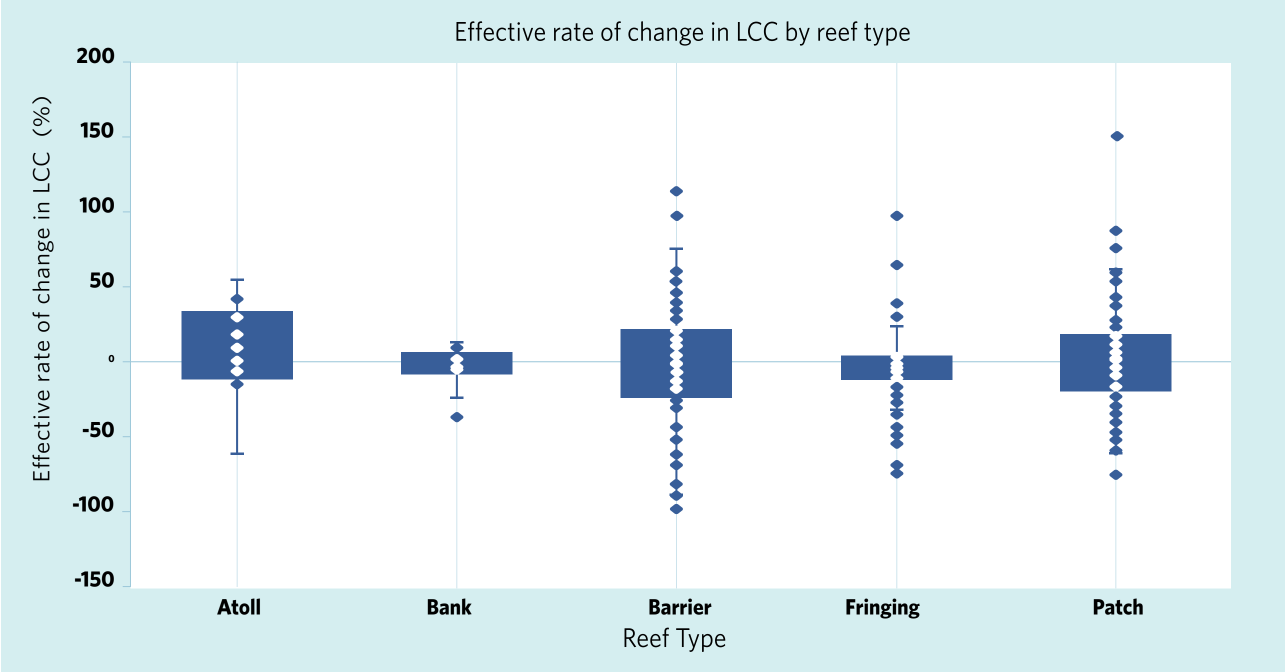


Figura 54. Effective annual rate in live coral cover by reef type.

3.2.9 Change in Live Coral Cover by Reef Zone

Analysis does not show a relationship between reef zone and reef damage.

GROSS CHANGE

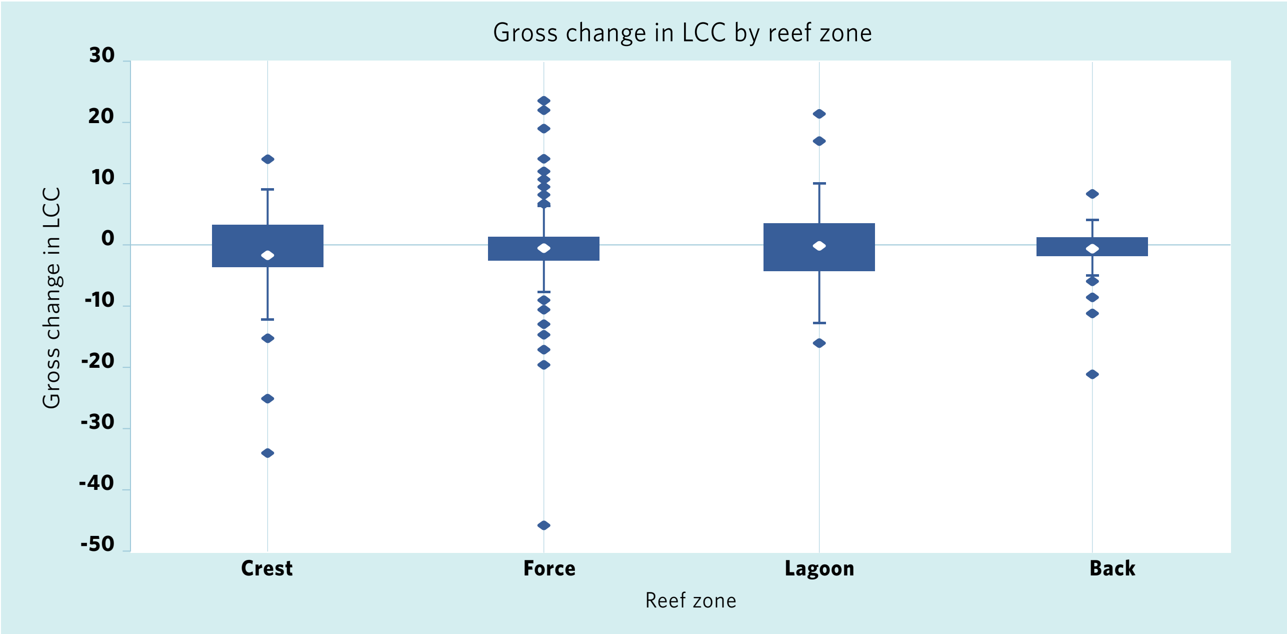


Figura 55. Gross change in live coral cover by reef zone.

PERCENTAGE OF CHANGE

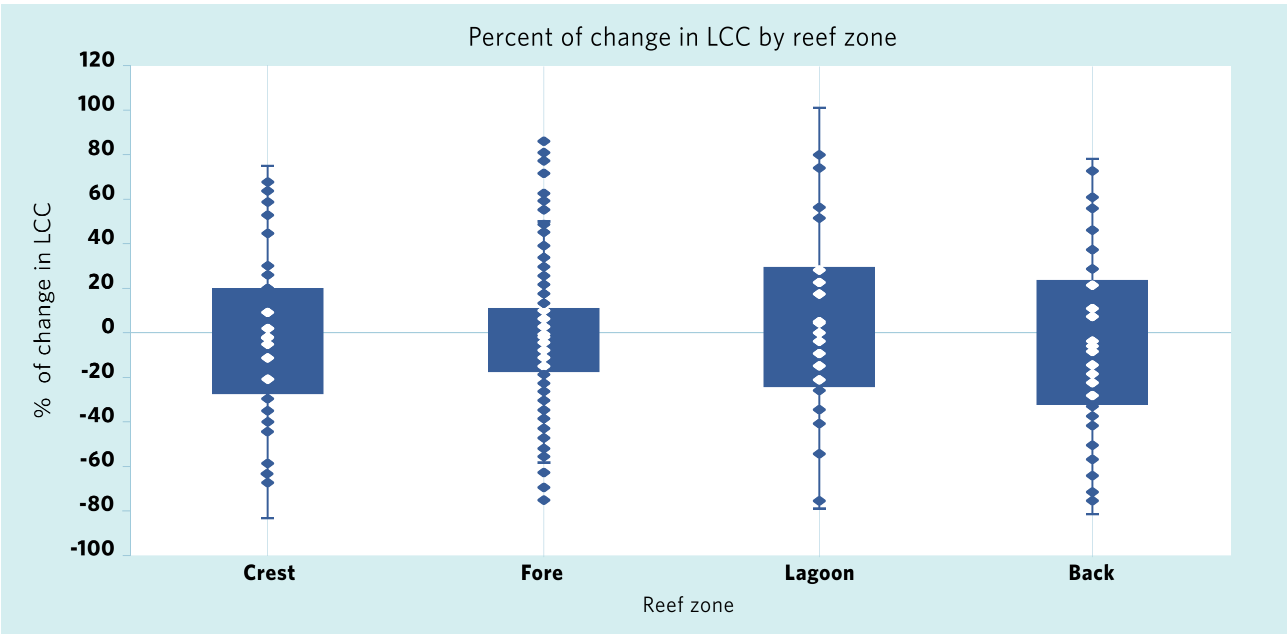


Figura 56. Percent of change in live coral cover by reef zone.

ANNUAL LOGARITHMIC RATE

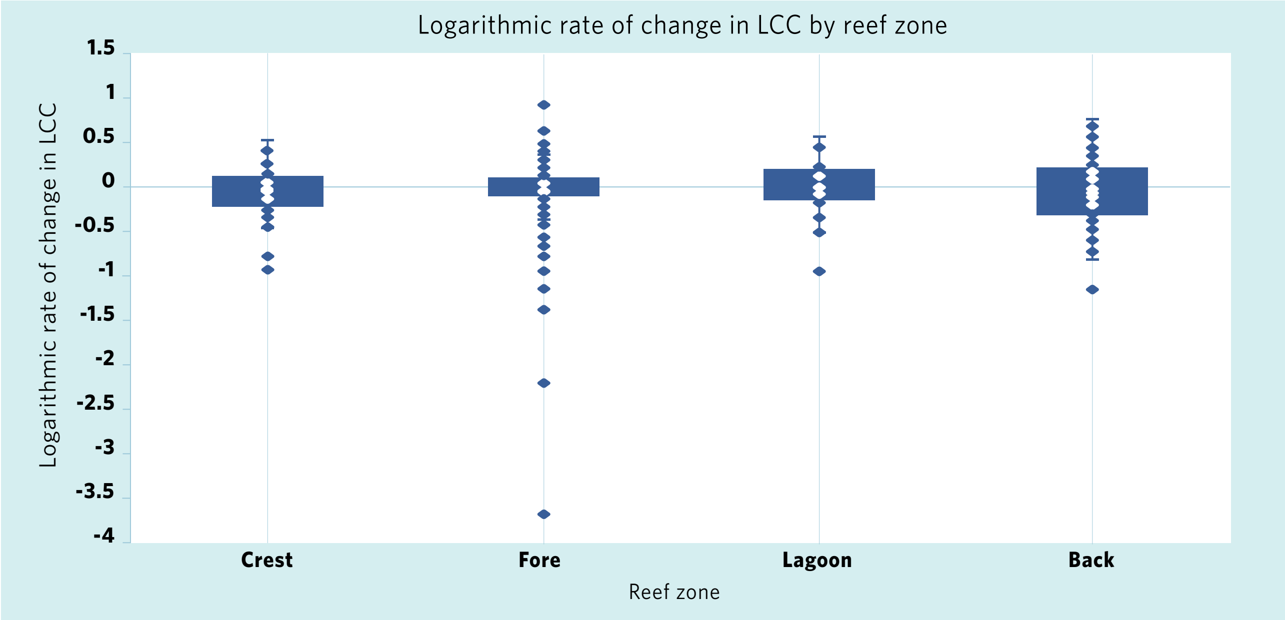


Figura 57. Logarithmic annual rate in live coral cover by reef zone.

EFFECTIVE ANNUAL RATE

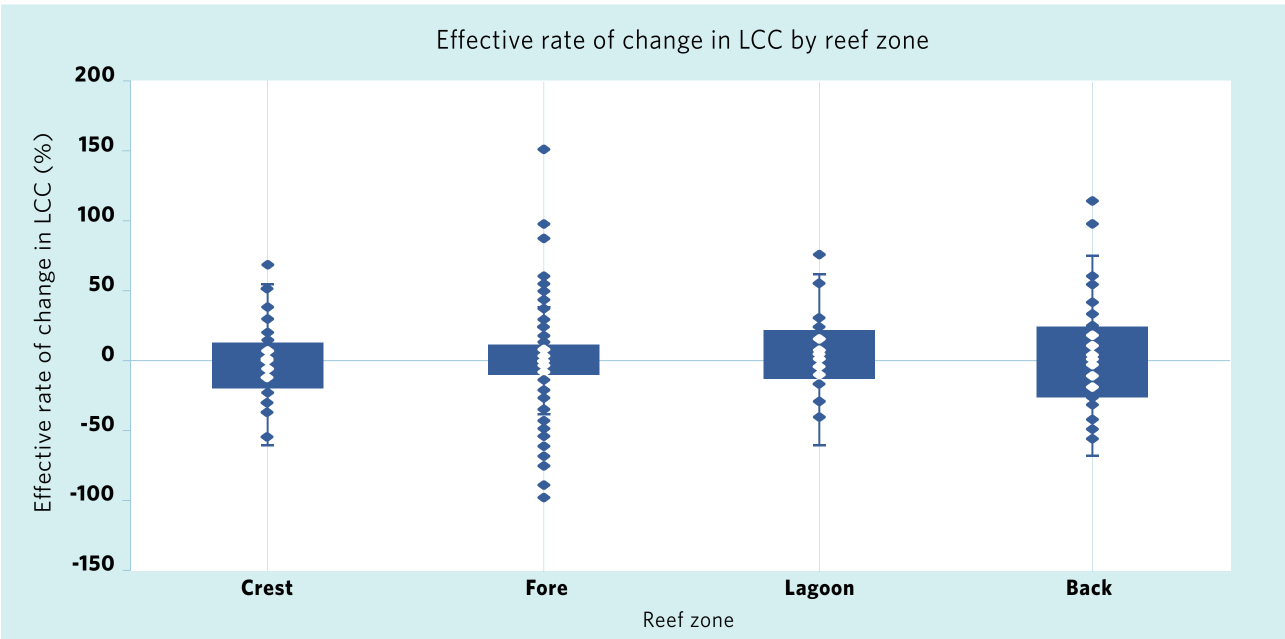


Figura 58. Effective annual rate in live coral cover by reef zone.

3.2.10 Change in Live Coral Cover by Mean Depth of Site

The analysis shows that the deeper the depth, the greater the damage to the reefs, although the difference is not significant. The average damage changes from 0% in reefs with depths less than 10 meters, to 5% loss with depths greater than 31 meters.

GROSS CHANGE

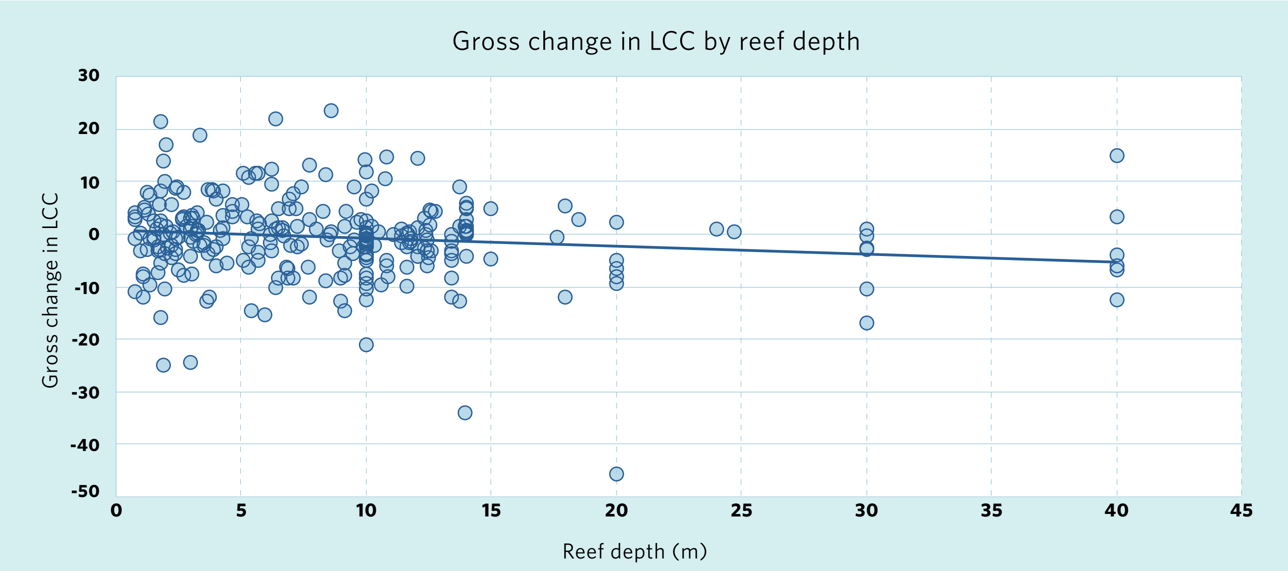


Figura 59. Gross change in live coral cover by mean depth.

PERCENTAGE OF CHANGE

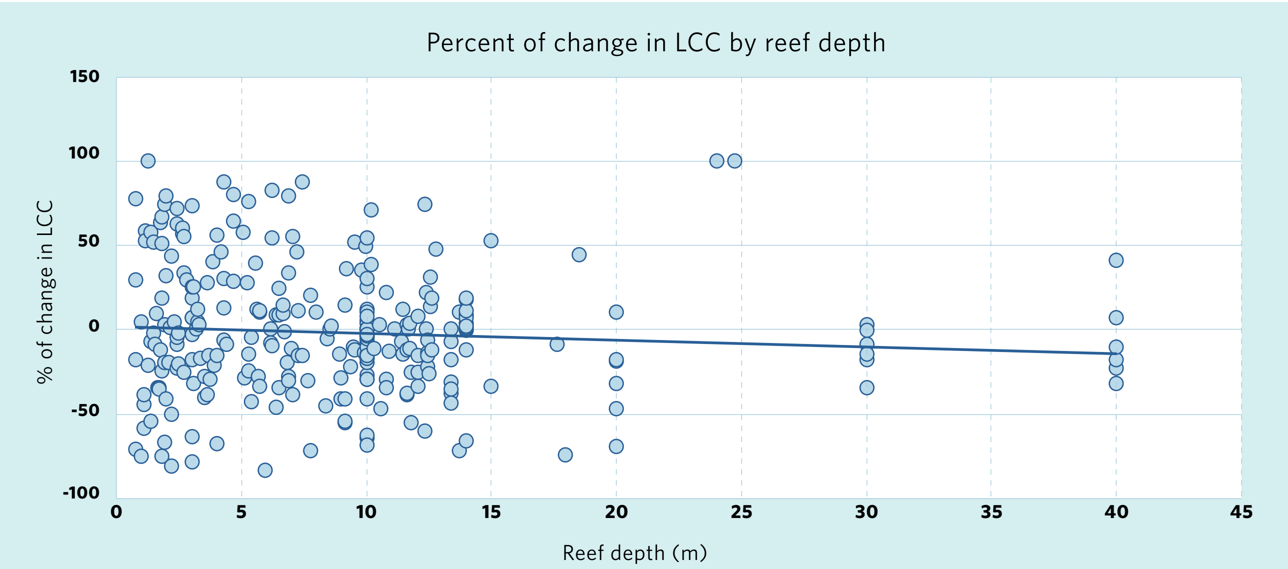


Figura 60. Percentage of change in live coral cover by mean depth.

ANNUAL LOGARITHMIC RATE

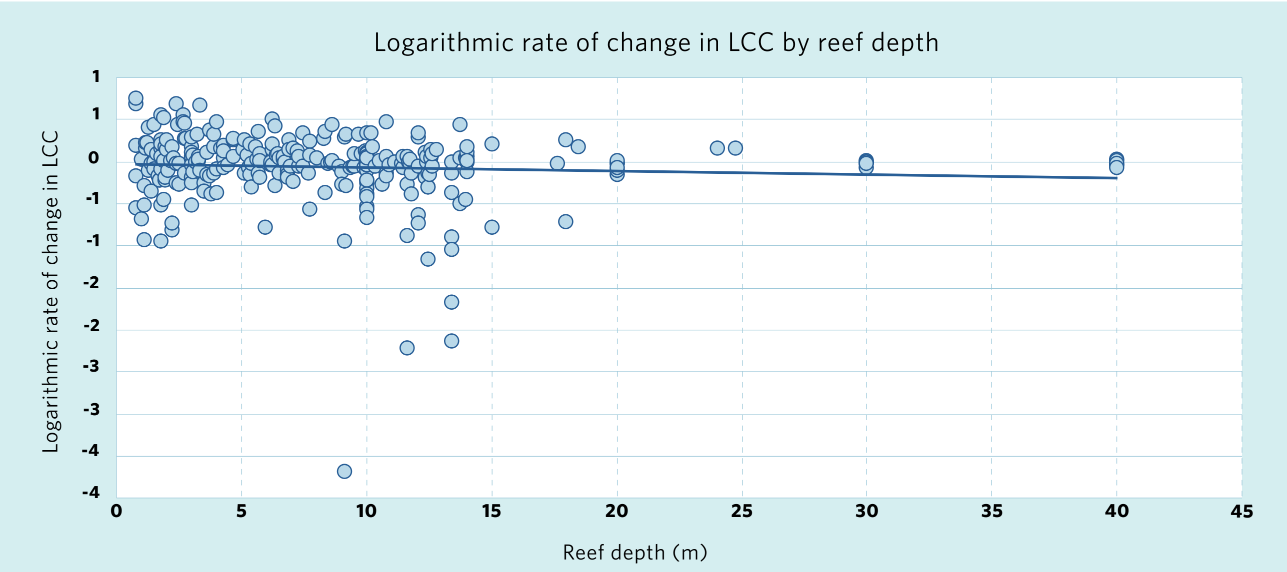


Figura 61. Annual logarithmic rate in live coral cover by mean depth.

EFFECTIVE ANNUAL RATE

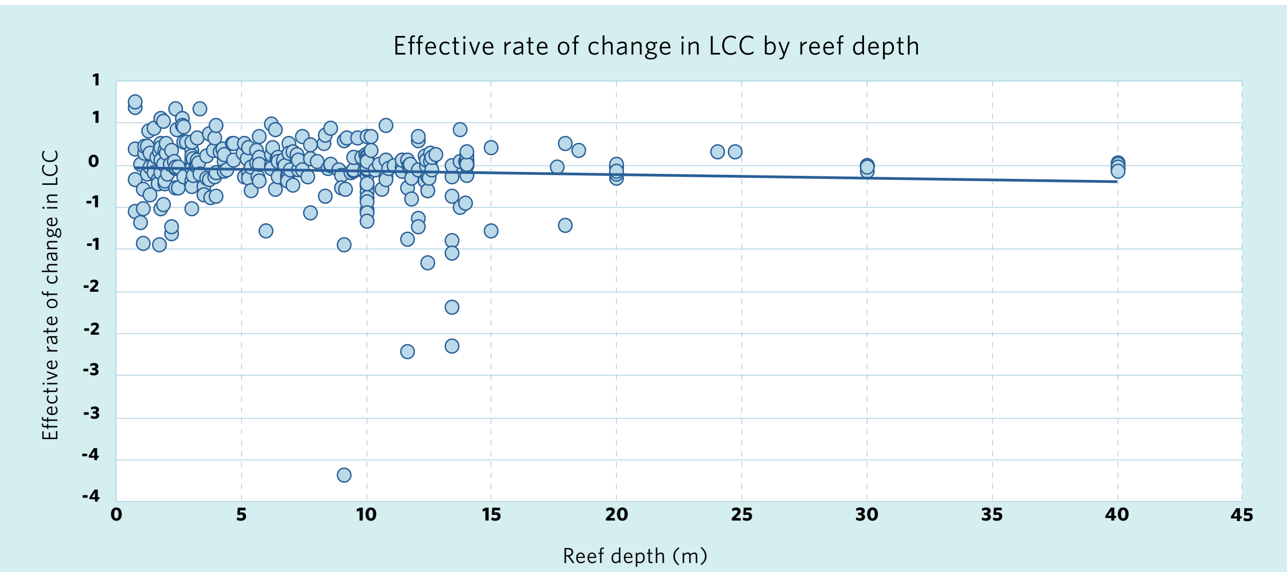


Figura 62. Effective annual rate in live coral cover by mean depth.

3.2.11 Change in Reef Rugosity by Initial Rugosity Segregated by Maximum Mean Sustained Wind

The analysis of hurricane damage to reef rugosity used data from 37 sites due to limited data availability. This contrasts with the coral cover damage analysis, that used data from 245 sites. Therefore, the information presented here describes the damage, but does not allow us to make statistical projections.

The multiple linear explanatory model analysis indicates that hurricanes cause greater damage when the pre-impact rugosity is greater, since it is the variable with the greatest statistically significant difference. The analysis also indicates that there is a wide variability in damage (see Figure 63), where the gray area indicates the dispersion of data, and the blue line indicates the average damage.

EFFECTIVE ANNUAL RATE

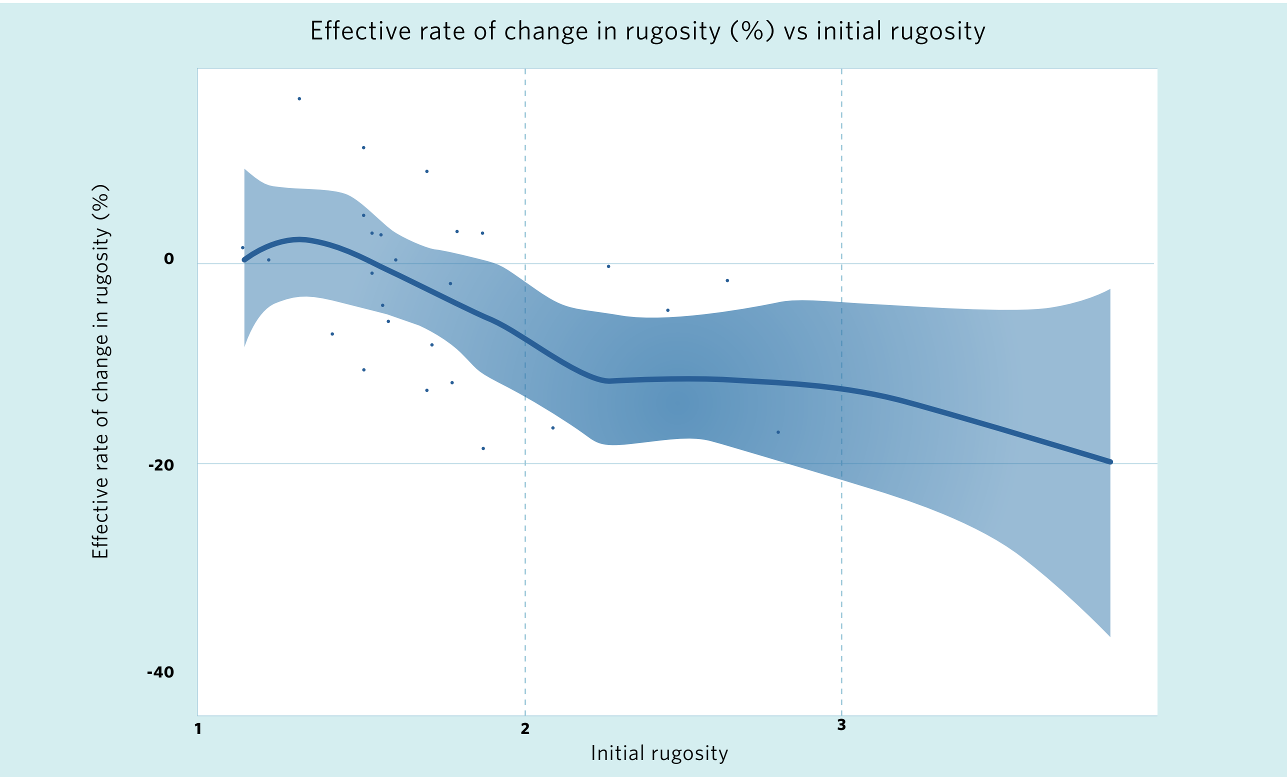


Figura 63. Effective annual rate in rugosity change by initial rugosity and mean maximum sustained wind (kt).

3.2.12 Change in Reef Rugosity by Reef Type

EFFECTIVE ANNUAL RATE

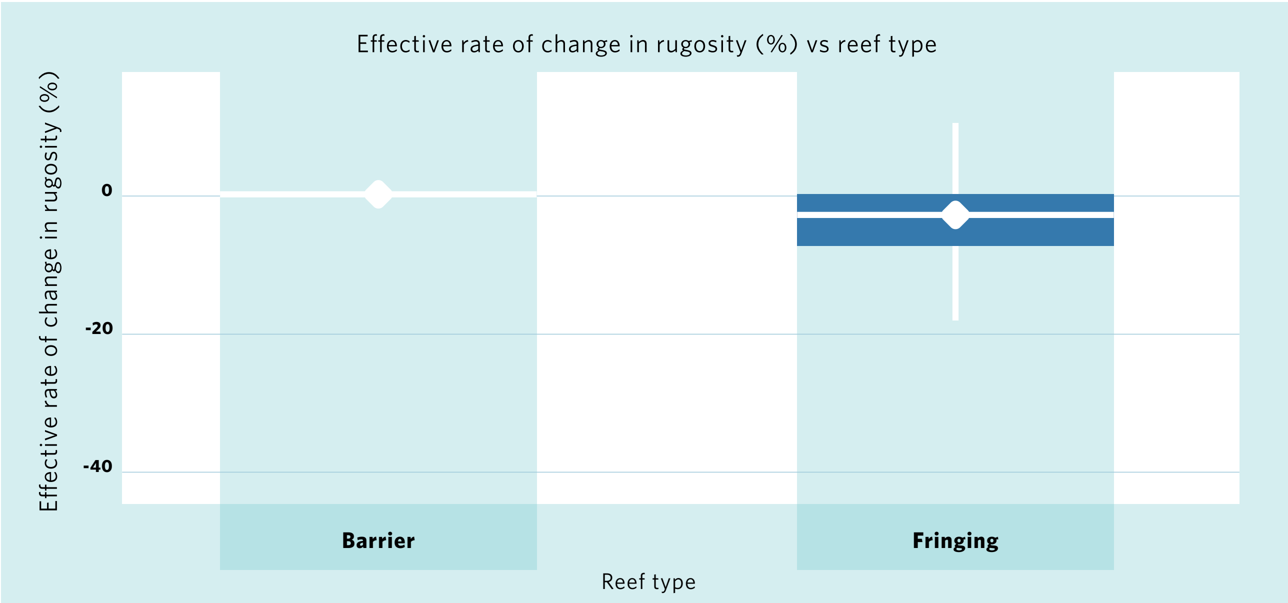


Figura 64. Effective annual rate of change in rugosity by reef type.

3.2.13 Change in Reef Rugosity by Reef Zone

EFFECTIVE ANNUAL RATE

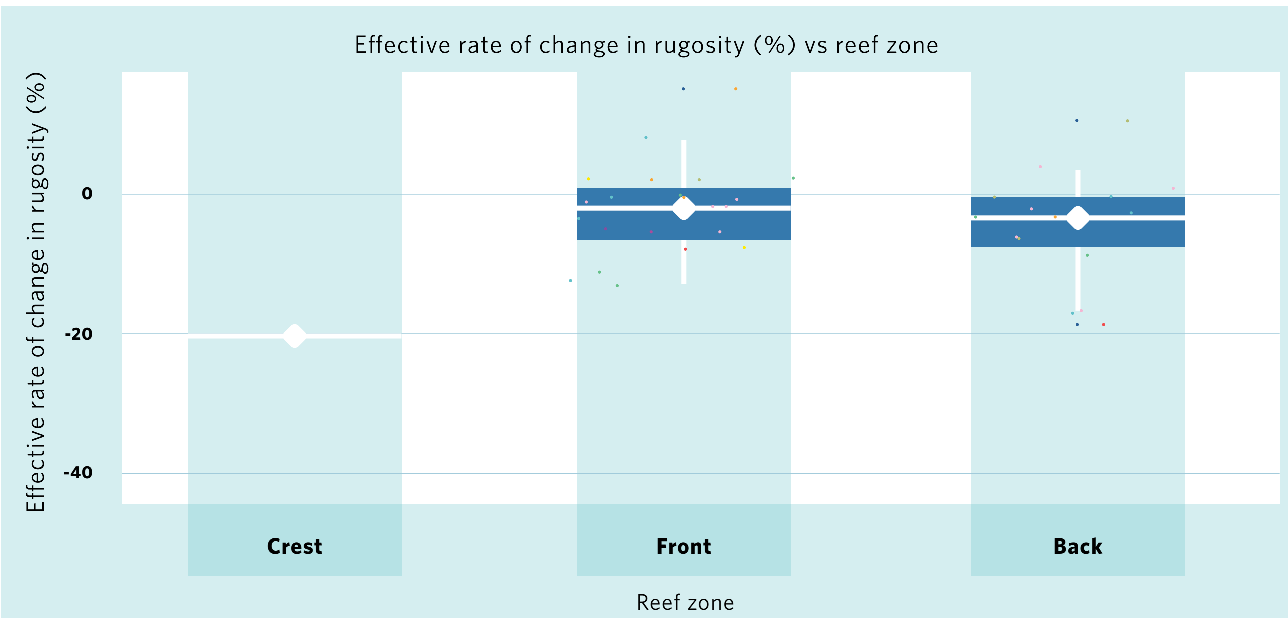


Figura 65. Effective annual rate of change in rugosity by reef zone.

3.2.14 Change in Reef Rugosity due to Mean Depth

EFFECTIVE ANNUAL RATE

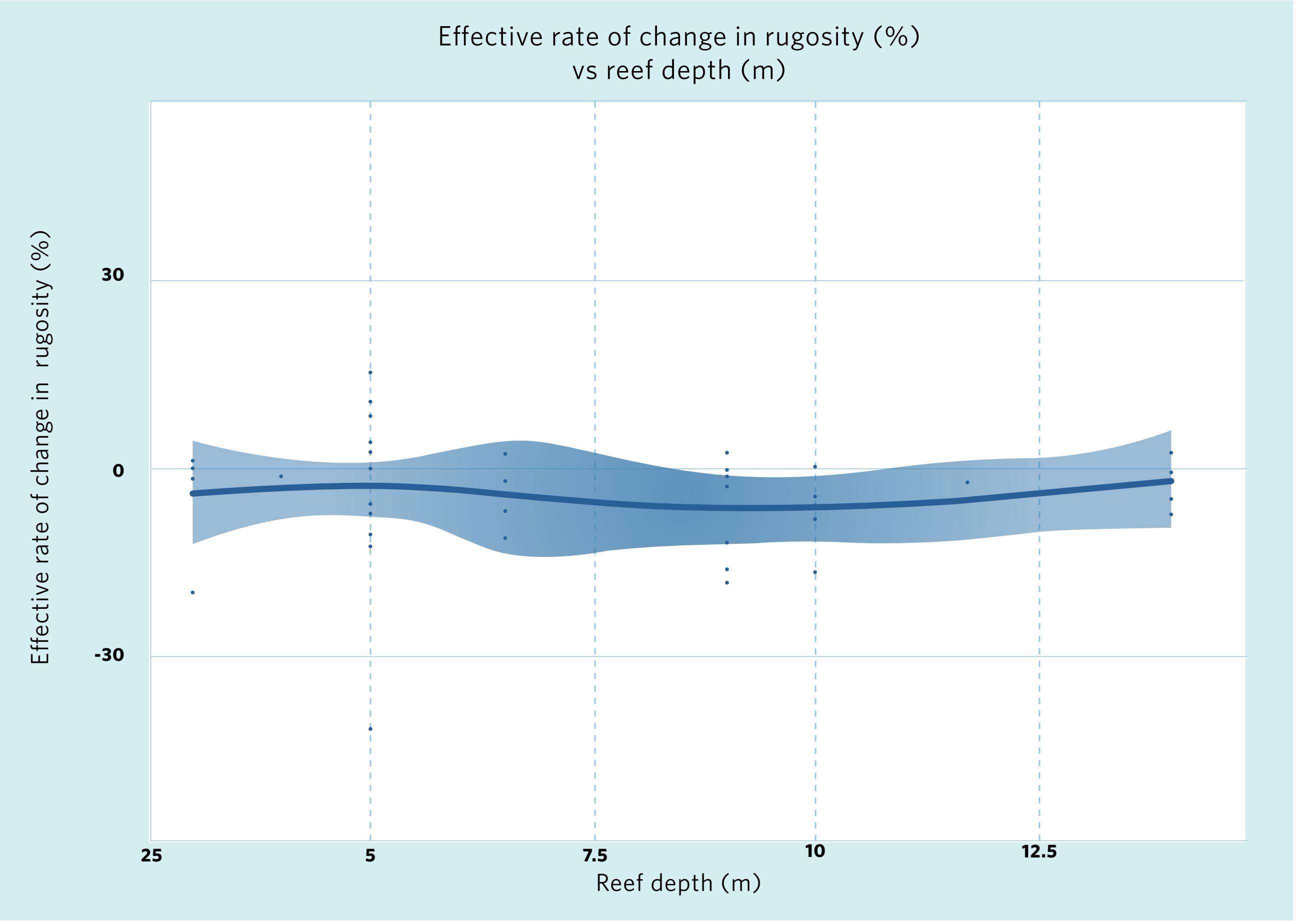


Figura 66. Effective annual rate of change in rugosity by mean depth.

3.2.15 Change in Reef Rugosity by Initial Rugosity Segregated by Exposure

The analysis indicates that windward exposed sites suffered more damage than leeward sites. It also indicates that windward and higher rugosity index sites experience more damage.

EFFECTIVE ANNUAL RATE

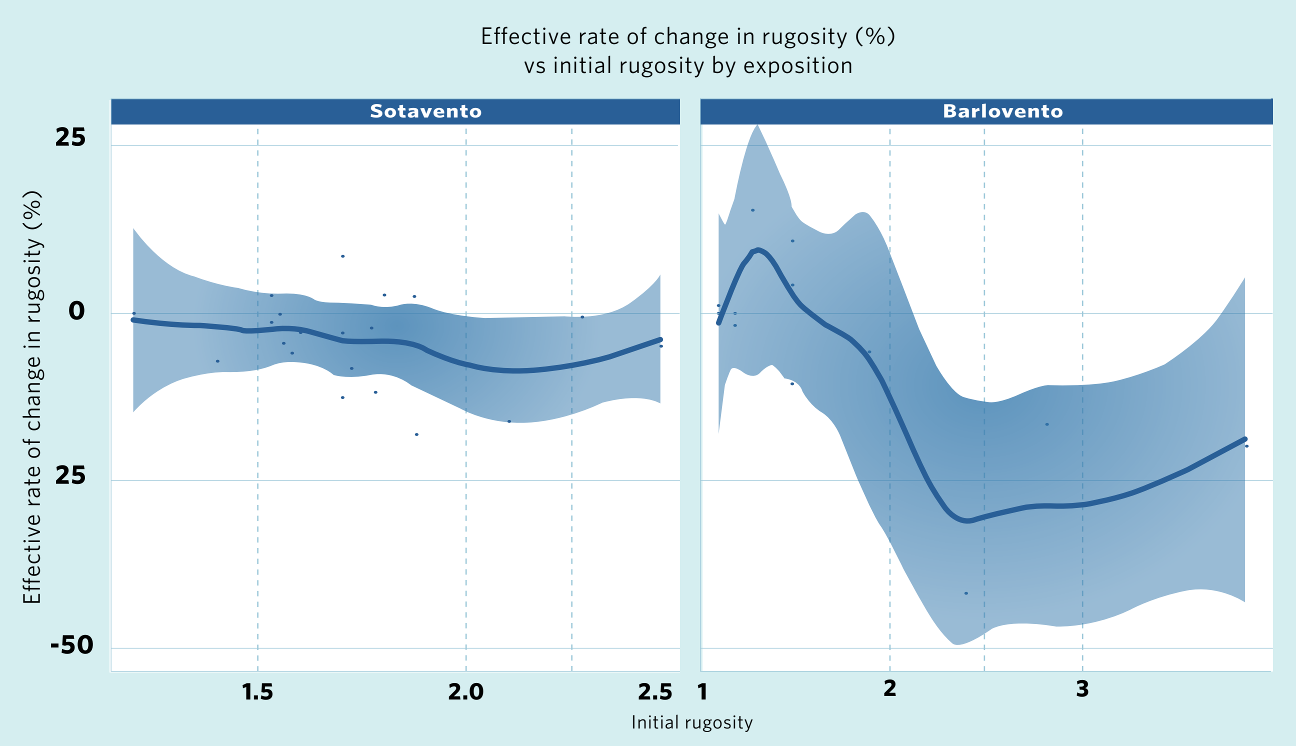


Figura 67. Effective annual rate of change in rugosity per initial rugosity segregated by site exposure.

3.2.16 Change in Reef Rugosity by Mean *Fetch*

EFFECTIVE ANNUAL RATE

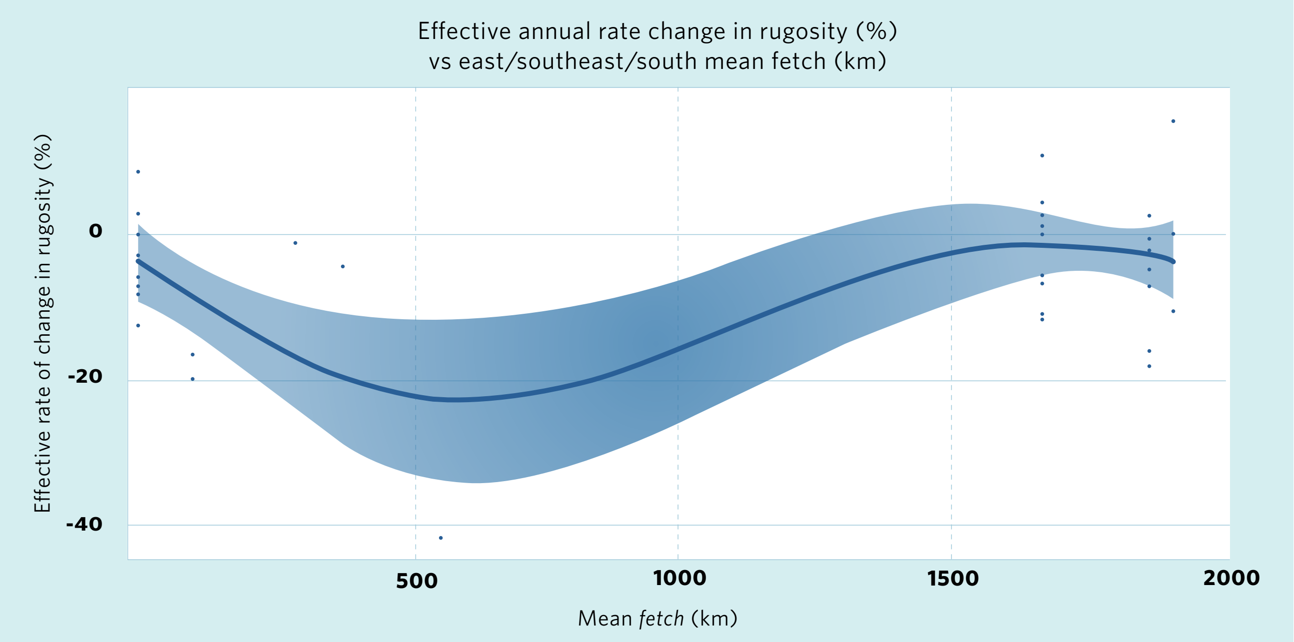


Figura 68. Effective annual rate of change in rugosity per average *fetch*.

3.2.17 Change in Reef Rugosity Due to Central Pressure

EFFECTIVE ANNUAL RATE

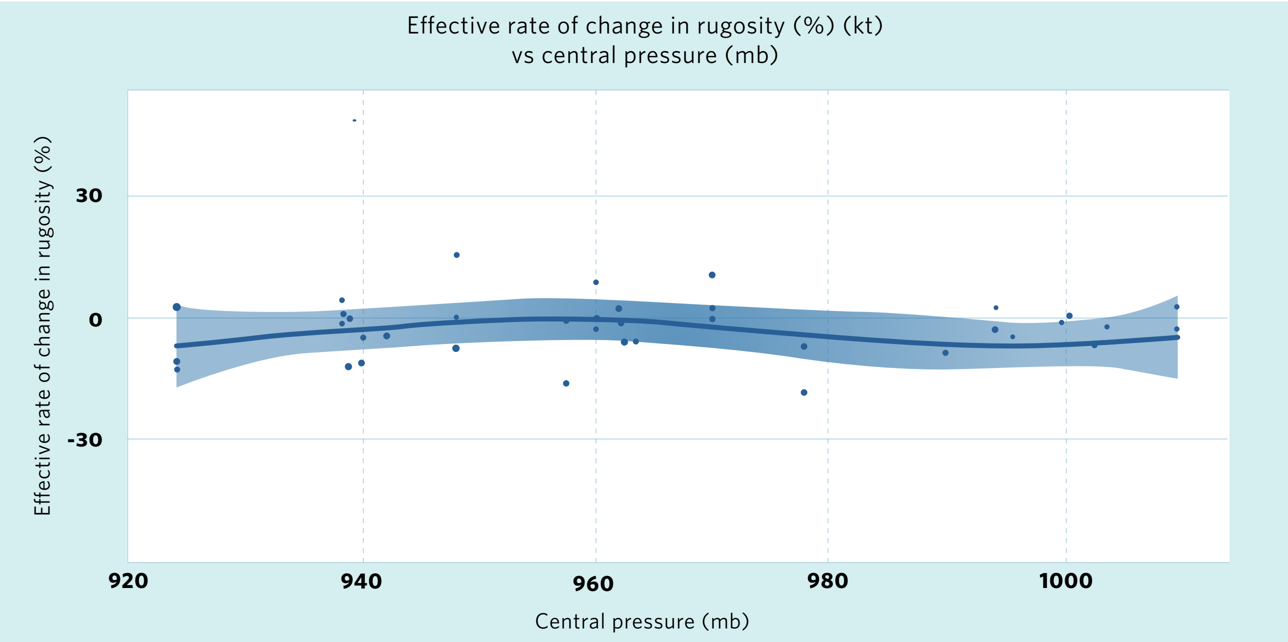


Figura 69. Effective annual rate of change in rugosity by mean central pressure (mb).

3.2.18 Change in Reef Rugosity by Number of *Snapshots*

EFFECTIVE ANNUAL RATE

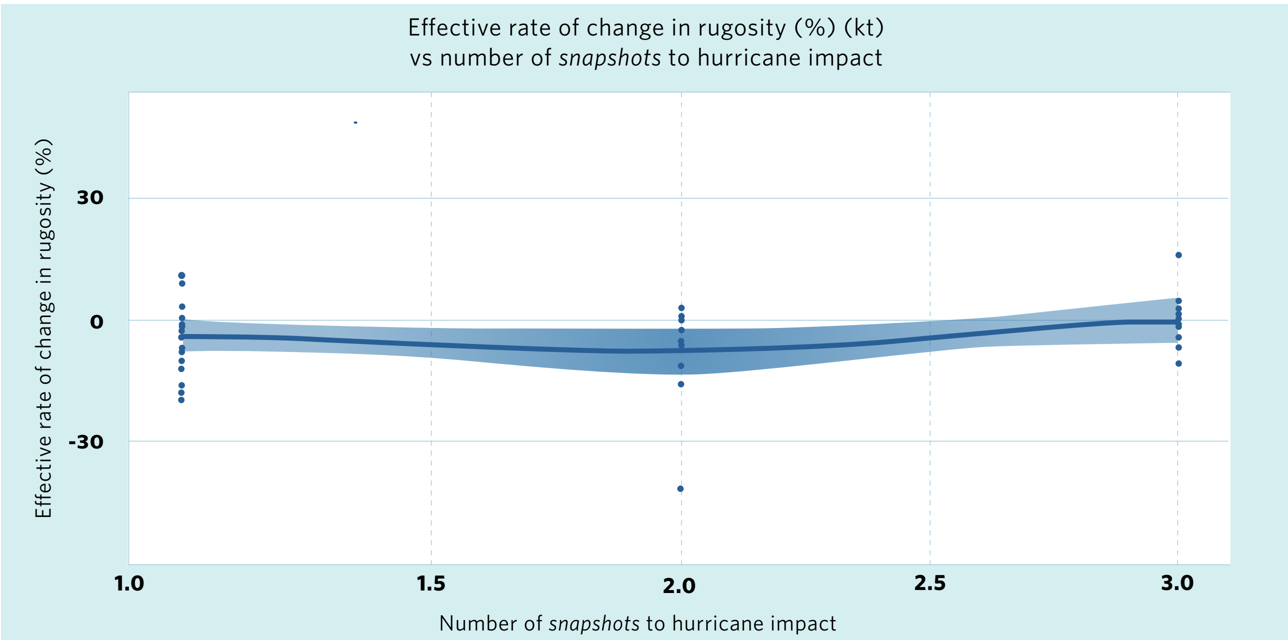


Figura 70. Effective annual rate of change in rugosity per number of *snapshots*.

3.2.19 Change in Reef Rugosity by Minimum Distance from Site

EFFECTIVE ANNUAL RATE

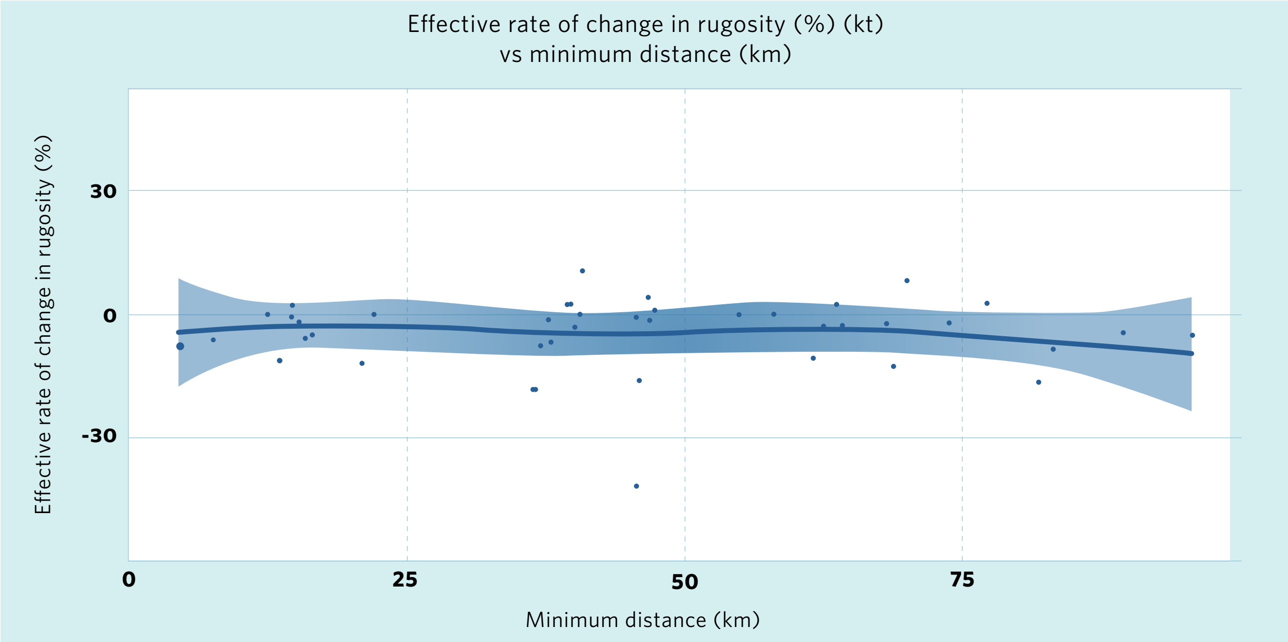


Figura 71. Effective annual rate of change in rugosity by minimum distance to site (km).

3.2.20 Change in Reef Rugosity Due to Storm Surge

EFFECTIVE ANNUAL RATE

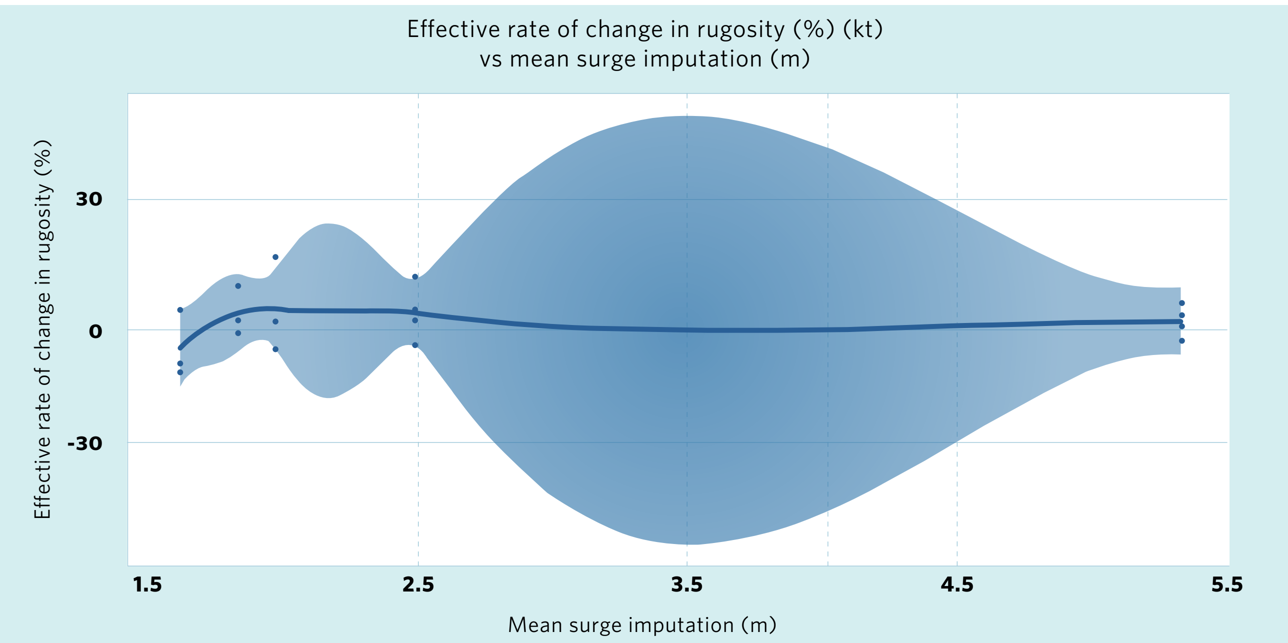


Figura 72. Effective annual rate of change in rugosity per mean surge per imputation (m).

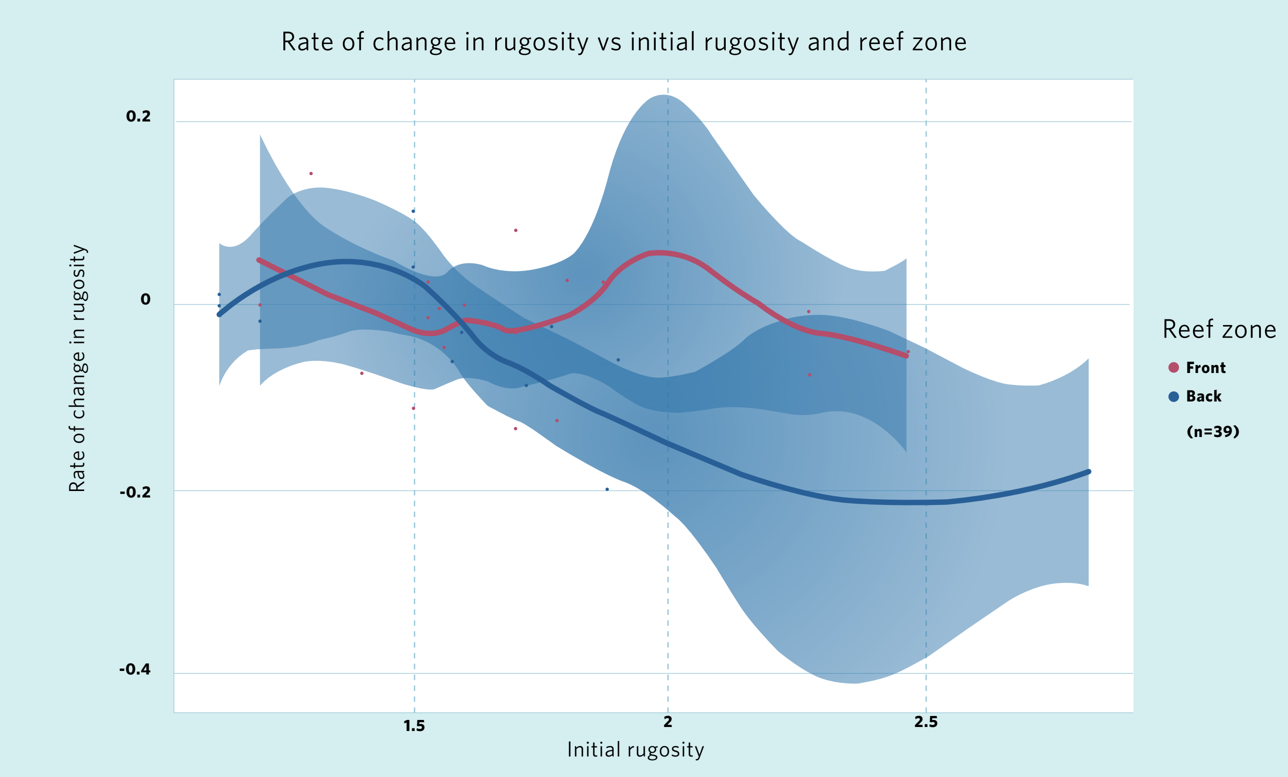


Figura 73. Annual logarithmic rate of change vs. mean rugosity initial sample profiled by reef zone, where the back reef has greater loss after hurricane passage.

3.3 VARIABLES WITH STATISTICAL SIGNIFICANCE

After quantifying the damage caused by hurricanes to reefs and exploring the correlation between damage and the characteristics of hurricanes and reefs, we proceeded to identify the existence of a statistical correlation through inferential analysis. In addition, the effective rate of change was used for the model analysis, since it is easily interpreted as a cumulative percentage change (%) and refers to the initial value (see Table 4).

We selected eleven variables with the highest apparent correlation to facilitate the application of the model:

1. Daily logarithmic rate of change of coral cover (Y).
2. Maximum wind speed at impact kt (categorical).
3. Percent of coral cover initial sample.
4. Interaction between maximum impact wind speed kt, and percentage of coral cover in the initial sample.
5. Number of *snapshots* at impact.
6. Mean central pressure mb.

7. Mean maximum sustained wind kt.
8. Exposure.
9. Average *fetch* km.
10. Interaction between exposure and mean *fetch* km.
11. Difference between final sample and hurricane outflow (in days).

Tabla 4. Linear mixed explanatory model of coral cover. Itntercept=intercept, value=value of , std error=standard error, df=degrees of freedom, t-value=value of t, p-value=value of p to accept or reject the null hypothesis. Statistical correlation exists if the p-value is less than 0.05.

VARIABLE	VALUE	STD. ERROR	DF	T-VALUE	P-VALUE
Percentage of coral coverage initial sample	-0.02	0.01	298.00	-3.90	0.0001
Maximum wind speed at impact kt cat.C: initial sample of coral coverage percentage	-0.02	0.01	298.00	-2.67	0.008
Windward Exposure	0.17	0.07	298.00	2.59	0.0101
Maximum wind speed at impact kt cat.Q: initial sample of coral coverage percentage	-0.02	0.01	298.00	-1.86	0.0642
Maximum wind speed at impact kt cat.L: initial sample of coral coverage percentage	-0.02	0.01	298.00	-1.60	0.1116
Intermediate Exposure	0.21	0.15	298.00	1.43	0.1528
Number of *snapshots* impact	0.03	0.02	298.00	1.23	0.2213
Intermediate Exposure: mean *fetch* km	0.00	0.00	298.00	-1.15	0.2526
Windward exposure: mean *fetch* km	0.00	0.00	298.00	-1.02	0.3078
Medium fetch km	0.00	0.00	298.00	0.98	0.3257
Maximum wind speed at impact kt cat.L	-0.26	0.26	298.00	-0.98	0.3261
Maximum wind speed at impact kt cat.Q	-0.11	0.18	298.00	-0.62	0.5372
Maximum wind speed at impact kt cat.C	-0.05	0.10	298.00	-0.51	0.6071
Mean central pressure mb	0.00	0.01	298.00	-0.43	0.6643
(Itntercep)	3.73	8.94	298.00	0.42	0.677
Mean maximum sustained wind kt	0.00	0.01	298.00	-0.40	0.6865
Difference final sample hurricane output days	0.00	0.00	298.00	-0.08	0.9343

The inferential analysis indicates the variables most correlated with the loss of coral cover after a hurricane (see Table 4). Variables with a p-value of less than 0.05 are statistically significant and are:

1. **Percentage of initial sample coral coverage.**
2. **Windward exposure.**
3. **Maximum wind velocity impact with percentage of coral cover of initial sample.**

The variables included for the final rugosity damage model were:

4. Mean maximum sustained wind kt.
5. Initial sample mean rugosity.
6. Difference final sample hurricane outflow years.
7. Exposure.
8. Interaction between exposure and mean rugosity in the initial sample.
9. Reef zone.

However, after the selection of variables with sufficient data, only the mean rugosity in the initial sample and the reef zone remained. The variable with statistical significance is mean initial rugosity (see Table 5).

Tabla 5. Multiple linear explanatory model. Itntercep= intercept, estimate=estimate, std error=standard error, t-value=t-value, Pr (>|T|) = value to accept or reject the null hypothesis. Statistical correlation exists if the value is less than 0.05.

VARIABLE	ESTIMATE	STD. ERROR	T VALUE	PR(>|T|)
Initial sample average rugosity	-0.094	0.029	-3.216	0.003
(Intercept)	0.144	0.053	2.715	0.011
Back reef zone	-0.038	0.023	-1.648	0.109

4

CONCLUSIONS

Hurricanes are natural phenomena that, depending on their characteristics, can cause damage to coral reefs. In the case of the Caribbean Basin, hurricanes have been identified as contributing to the loss of coral cover since 1980 (Gardner et al., 2003). Studies such as Gardner's in 2005 indicate that reefs that have been impacted by hurricanes have faster rates of coral loss than those that have not been impacted (Gardner et al., 2005).

The analysis presented indicates that wind speed at impact was one of the variables most closely related to the damage that a hurricane can cause as it passes over a reef. Another variable related to damage was the initial condition of the site, since sites with greater coral cover or greater rugosity had more damage than those with little cover and little rugosity. Finally, site exposure was also a significant variable, where sites with less exposure had more damage. Our study provides new information that can help reef managers estimate the damage that a hurricane can cause on a reef. Reefs, which act as protectors of the coast to the action of storms and waves, are currently under constant threat and not only hurricanes cause impact on reefs, threats such as climate change, acidification of the seas, diseases, among others are added and are the cause of its current decline, so knowing the damage a hurricane can cause to reefs can help to be prepared for a possible impact on sites with high coral cover and high rugosity.

5
REFERENCES

Álvarez-Filip, L., Dulvy, N. K., Gill, J. A., Côté, I. M., & Watkinson, A. R. (2009). Flattening of Caribbean coral reefs: region-wide declines in architectural complexity. Biological Sciences, 276 (1669), 3019-3025.

Álvarez-Filip, L., Gill, J. A., Dulvy, N. K., Perry, A. L., Watkinson, A. R., & Côté, I. M. (2011). Drivers of region-wide declines in architectural complexity on Caribbean reefs. Coral Reefs, 30(4), 1051- 1060.

Côté, I. M., Gill, J. A., Gardner, T. A., & Watkinson, A. R. (2005). Measuring coral reef decline through meta-analyses. Philosophical Transactions of the Royal Society of London B: Biological Sciences, 360(1454), 385-395.

Côté, I., Gardner, T., Gill, J., Hutchinson, D., & Watkinson, A. (2006). New approaches to estimating recent ecological changes on coral reefs. In Coral reef conservation. Cambridge University Press.

Dicovskiy-Riobóo, L. M. & Pedroza-Pacheco, M. E. 2017. Modelos lineales generales y mixtos en la caracterización de la variable calificación, ingeniería agroindustrial, Uni-norte. Nexo, 30 (2), 84- 95.

Eddy, T. D., W. W. L. Cheung & Bruno, J. F. 2018. Historical baselines of coral cover on tropical reefs as estimated by expert opinion. PeerJ 6: 01-16. DOI 10.7717/peerj.4308

Gardner, T. A., Cote, I. M., Gill, J. A., Grant, A., & Watkinson, A. R. (2005). Hurricanes and Caribbean coral reefs: impacts, recovery patterns, and role in longterm decline. Ecology, 86(1), 174-184.

Gardner, T. A., Côté, I. M., Gill, J. A., Grant, A., & Watkinson, A. R. (2003). Long-term region-wide declines in Caribbean corals. Science, 301(5635), 958-960.

Graham, N. A. J., & Nash, K. L. (2013). The importance of structural complexity in coral reef ecosystems. Coral Reefs, 32(2), 315-326.

Graft Acquah, H. (2010). Comparison of Akaike information criterion (AIC) and Bayesian information criterion (BIC) in selection of an asymmetric price relationship. Journal of Development and Agricultural Economics, 2(1), 1-6.

Huang, R., K. Yu, Y. Wang, W, Wang, L. Mu & J. Wang. 2018. Method to design a live coral cover sensitive index for multispectral satellite images. Optics express, 26 (10), 374-397.

Hughes, T. P. (1994). Catastrophes, phase shifts, and large-scale degradation of a Caribbean coral reef. Science, 265(5178), 1547-1551.

Healthy Reefs Initiative (2012). Reporte de la Salud Ecológica del Arrecife Mesoamericano. Una Evaluación de la Salud del Ecosistema. https://www.healthyreefs.org/cms/wp-content/uploads/2012/12/Reporte-2012.pdf

InVEST Coastal Vulnerability Model. http://data.naturalcapitalproject.org/invest-releases/documentation/2 2 0/coastal vulnerability.html

Landsea, C. W. & Franklin, J. L. (2013). Atlantic Hurricane Database Uncertainty and Presentation of a New Database Format. Monthly weather review, 141, 3576-3592.

Lang, J. C., Marks, K. W., Kramer, P. A., Kramer, P. R., & Ginsburg, R. N. (2010). AGRRA protocols version 5.4. Atlantic and Gulf Rapid Reef Assessment Program, Florida, USA.

Navarro, E. E. (2020). Efectos de los cambios de cobertura vegetal y de uso de suelo sobre la cobertura de coral en los arrecifes del Caribe Mexicano. Tesis maestría. UNAM

Needham, H.F. & Keim, B. D. (2012). A Storm Surge Database for the U.S. Gulf Coast. International Journal of Climatology, 32 (14), 2108-2123. DOI: 10.1002/joc.2425.

Meza-Padilla, R., Appendini, C.M., Pedrozo-Acuña, A. & González-Villarreal, F. (2015). Evaluación de la marea de tormenta en sitios con escasez de datos: río Pánuco, México. Ribagua, 2, 61-70, DOI: 10.1016/j.riba.2015.09.001

Paddack, M. J., Reynolds, J. D., Aguilar, C., Appeldoorn, R. S., Beets, J., Burkett, E. W., ... & Forrester, G. E. (2009). Recent region-wide declines in Caribbean reef fish abundance. Current Biology, 19(7), 590-595

Porto Tapiquén C. E. (2015). América. Orogénesis Soluciones Geográficas. Porlamar, Basado en capas de Enviromental Systems Research Institute (ESRI). Distribución Gratuita. Venezuela. Descargado desde http://tapiquen-sig.jimdo.com.

R Development Core Team. 2009. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. www.r-project.org

Rogers, A., J. L. Blanchard & P. J. Mumby. (2017). Fisheries productivity under progressive coral reef degradation. Journal of Applied Ecology, 55, 1041–1049.

Ruiz de Alegria-Arzaburu, A., Mariño-Tapia, I., Enriquez, C., Silva, R. & Gonzalez-Leija, M. (2013). The role of fringing coral reefs on beach morphodynamics. Geomorphology, 198, 69-83.

Secaira, F. & César, A. (2017). Importancia de los arrecifes y dunas en la protección de la costa. Serie técnica. El papel de los sistemas naturales en la dinámica costera en el caribe mexicano y el impacto de las actividades humanas en su condición actual. The Nature Conservancy, México

Rohweder, J., Rogala, J. T., Johnson, B. L., Anderson, D., Clark, S., Chamberlin, F., Potter, D. & Runyon, K. (2008). Application of Wind *Fetch* and Wave Models for Habitat Rehabilitation and Enhancement Projects. USGS report. http://www.umesc.usgs.gov/management/dss/wind *fetch* wave models.html

Spalding, M., Burke, L., Wood, S. A., Ashpole, J., Hutchison, J., & Zu Ermgassen, P. (2017). Mapping the global value and distribution of coral reef tourism. Marine Policy, 82, 104-113.

Suchley, A., McField, M. D., & Alvarez-Filip, L. (2016). Rapidly increasing macroalgal cover not related to herbivorous fishes on Mesoamerican reefs. PeerJ, 4, e2084.

Taylor, H. T., Ward, B., Willis, M., & Zaleski, W. (2012). The Saffir-Simpson Hurricane Wind Scale. HYPERLINK "https://www.nhc.noaa.gov/pdf/sshws.pdf" https://www.nhc.noaa.gov/pdf/sshws.pdf

Taylor, M. A., & Alfaro, E. J. (2005). Climate of Central America and the Caribbean. In: J. E. Oliver (editor) Encyclopedia of World Climatology. Netherlands: Springer,p. 183-188.

WWF. 2006. Mejores prácticas de pesca en arrecifes coralinos. Guía para la colecta de información que apoye el Manejo de Pesquerías Basado en Ecosistemas. WWF México/Centroamérica. Pp. 81

APPENDIX

1

IMPACT OF THE RESAMPLING PERIOD ON THE RESULTS.

When the resampling periods are very long (longer than 3 years, for example), coral cover can be influenced by other phenomena or events different from the hurricane, affecting the data and conclusions we can obtain. In this study, we have 72 resamples with resampling periods between 3 and up to 10 years and 382 with shorter periods. To determine whether the inclusion of these 72 resamples influences the results, we generated the results with and without these data. The results show the same trends; therefore, this study used all 454 resamples.

GROSS CHANGE

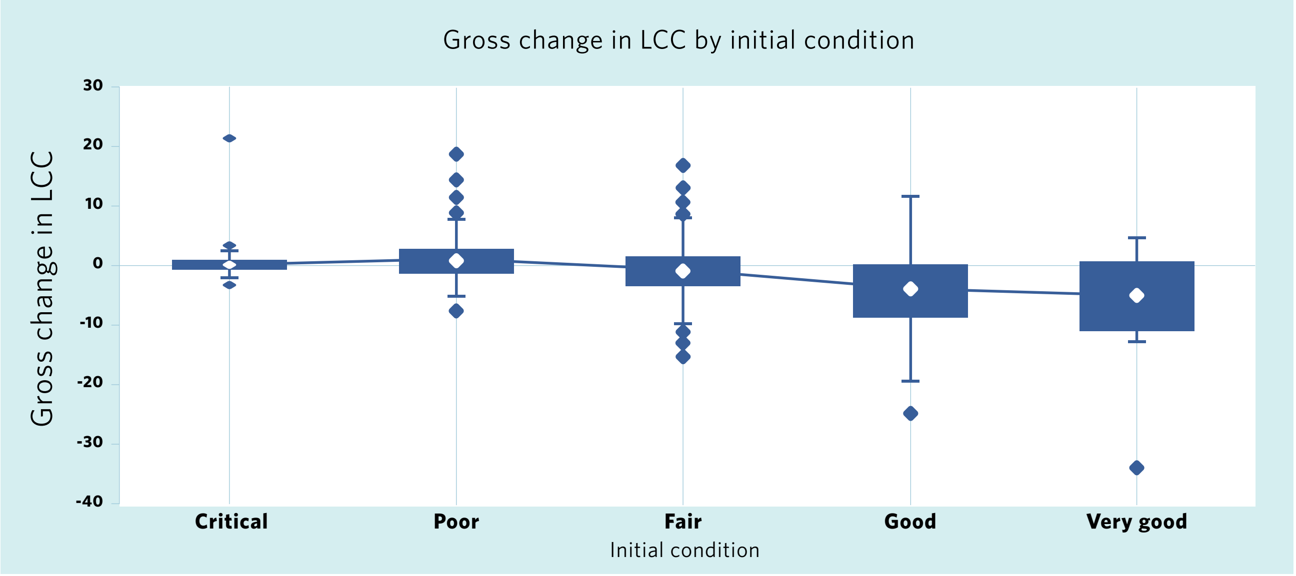


Figura 1. Gross change by initial condition, excluding data with a period between samples of more than 3 years. Number of resamples: 382.

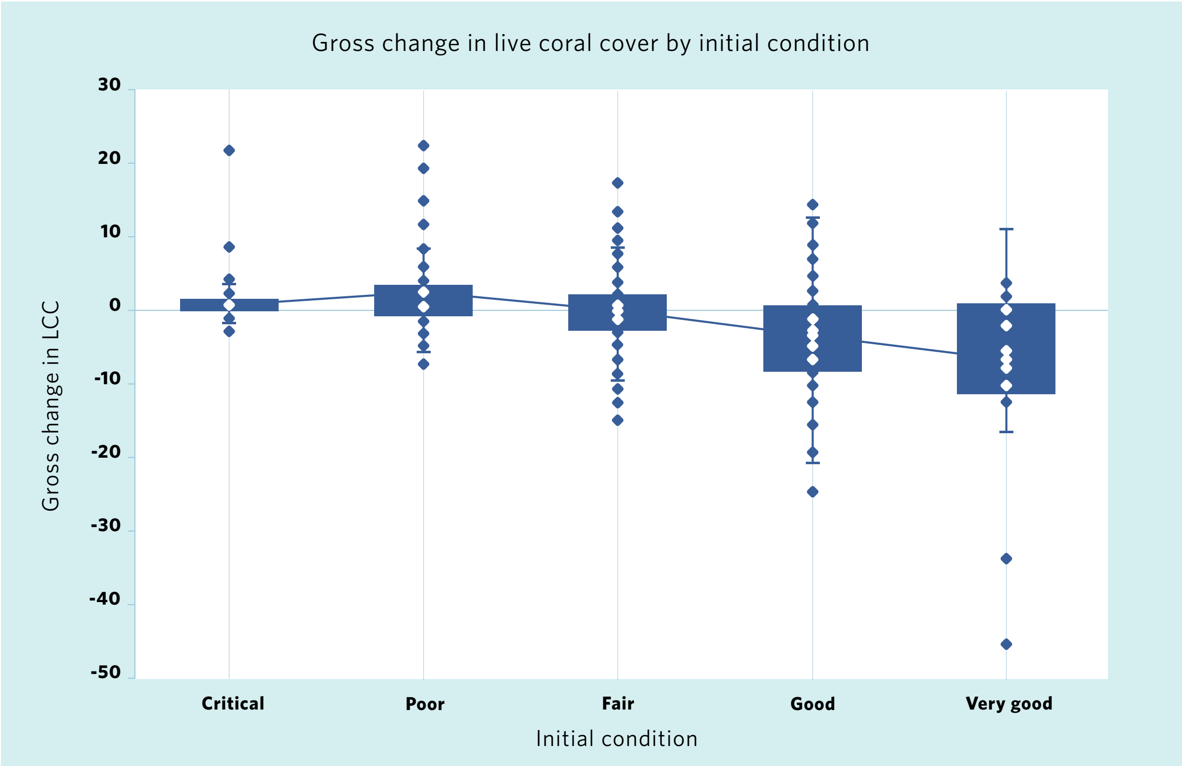


Figura 2. Gross change by initial condition. Number of resamples: 455.

PERCENTAGE OF CHANGE

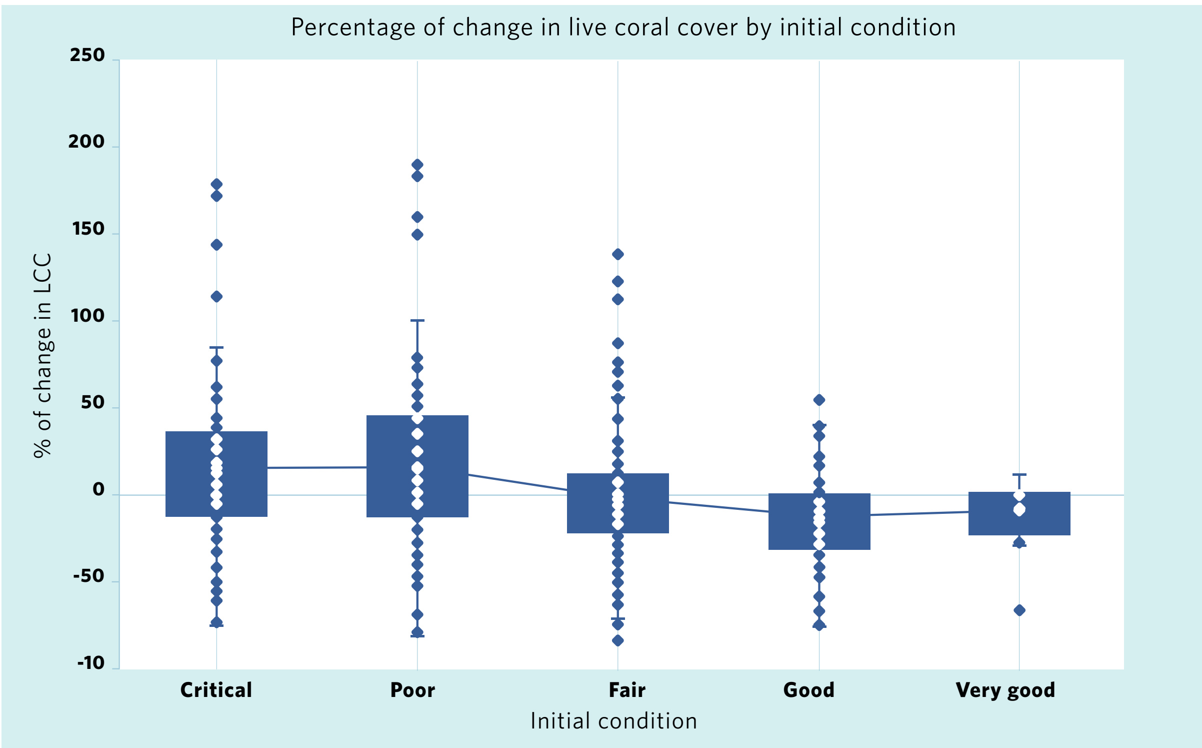


Figura 3. Percent change from initial condition, segregated by initial condition category, excluding data from sites with more than 3 years between samples. Number of resamples: 382.

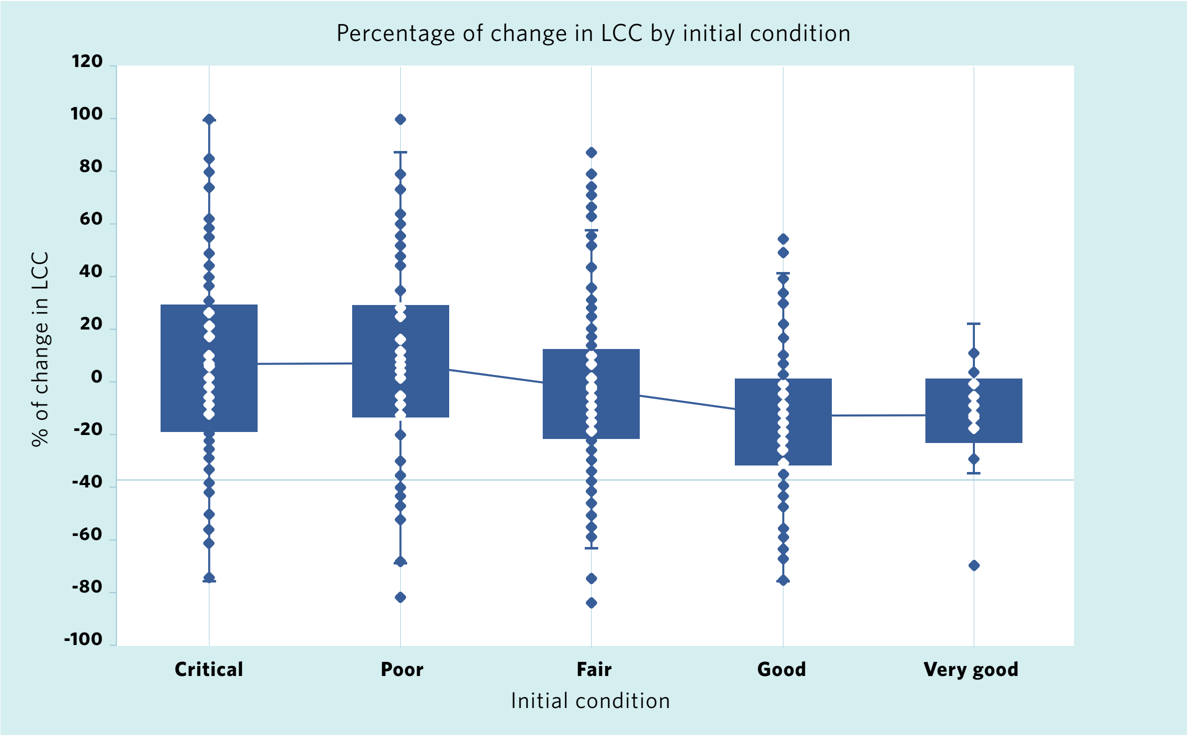


Figura 4. Percent change from initial condition, segregated by initial condition category, including data from sites with more than 3 years between samplings. Number of resamples: 455.

CORAL REEFS DAMAGES CAUSED BY HURRICANES IN THE CARIBBEAN
AND THEIR CORRELATION WITH THE CHARACTERISTICS OF HURRICANES AND REEFS

2020
Mesoamerian Reef Rescue Initiative (RRI)
Coastal Risk and Reslience Initiative, The Nature Conservancy

Esmeralda Pérez Cervantes, Fernando Pardo Urrutia, Lorenzo Álvarez Filip, Fernando Secaira Fajardo, Claudia Ruiz Alvarado, Mariana Alvarez Rocha