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Modelling susceptibility of Abrolhos reefs to coral bleaching

Modelagem da susceptibilidade ao branqueamento nos corais dos recifes de Abrolhos

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ABSTRACT: Coral reefs suffer many threats, including coral bleaching, which occurs mainly in response to environmental variables such as positive temperature anomalies. However, there is a need to explore potential synergies between environmental and anthropogenic variables. The objective of this work is to use multi-criteria analysis to explore associations between environmental and anthropogenic variables in order to estimate in a spatially explicit way the susceptibility of the different Abrolhos reefs in Bahia, Brazil, to coral bleaching. Our results show that from 2001 to 2016 there was a sharp increase in the reef areas with higher susceptibility to bleaching. While in 2001, 20% of the reef area presented low susceptibility to bleaching and 80% showed medium susceptibility, in 2016, 19% of the area showed medium and 81% showed high susceptibility. 2016 presented the highest susceptibility among the years used in the study, suggesting a higher percentage of bleached colonies, which is corroborated by the fact that this year was considered by NASA and NOAA as the hottest year since 1880. Results also show that bleaching pattern is spatially differentiated. The reefs from the coastal arch of Abrolhos present the greater susceptibility to bleaching. Exception is Timbebas reefs which, although located in the coastal arch, are more similar to the outer arch reefs, wich are less susceptible to bleaching.

Keywords: coral reefs; bleaching; modeling; multi-criteria analysis.

RESUMO: Os recifes de coral sofrem muitas ameaças, incluindo o branqueamento de corais, que ocorre principalmente em resposta a variáveis ambientais, como a anomalia positiva de temperatura. Existe, no entanto, a necessidade de explorar potenciais sinergias entre variáveis ambientais e variáveis antropogênicas. O objetivo deste trabalho é utilizar a análise multicritério para explorar associações entre variáveis ambientais e antropogênicas com o objetivo de estimar de forma espacialmente explícita a suscetibilidade dos diferentes recifes de Abrolhos, na Bahia, Brasil, ao branqueamento de corais. Os resultados mostram que, de 2001 a 2016, houve um aumento acentuado nas áreas recifais com maior susceptibilidade ao branqueamento. Enquanto em 2001, 20% da área recifal apresentava baixa suscetibilidade ao branqueamento e 80% apresentava susceptibilidade média, em 2016, 19% da área apresentava média e 81% alta suscetibilidade. 2016 apresentou a maior suscetibilidade entre os anos utilizados no estudo, sugerindo um maior percentual de colônias branqueadas, o que é corroborado pelo fato de este ano ter sido considerado pela NASA e NOAA como o ano mais quente desde 1880. Os resultados também mostram que o padrão de branqueamento é espacialmente diferenciado. Os recifes do arco costeiro de Abrolhos apresentam maior suscetibilidade ao branqueamento. Exceção é feita aos recifes de Timbebas, que, embora localizados no arco costeiro, são mais semelhantes aos recifes do arco externo, que são menos suscetíveis ao branqueamento.

Palavras-chave: recifes de coral; branqueamento; modelagem; análise multicritério.

1. Introduction

In connection with high sea surface temperatures during el Niño, along the summer of 2016, occurred the third global-scale mass bleaching event since it was first recorded in the 80s (Hughes *et al.*, 2017). During this event, on Australia's Great Barrier Reef, more than 60% of reefs bleached with high severity while only 9% did not suffer bleaching (Hughes *et al.*, 2017). In 2017, the Great Barrier Reef was for the second successive year suffering bleaching (Anthony *et al.*, 2017). Hawaiian coral reefs showed record levels of bleaching in 2014-2015 and the southern Maldives reefs experienced more than 70% coral mortality in 2016 (Rodgers *et al.*, 2017; Perry & Morgan, 2017). This event also hit Japan where over 90% of reefs in Ishigaki Island showed bleaching in 2016 (Kayanne *et al.*, 2017). In Brazil, although there is not yet any record on coral mass mortality there is evidence supporting that the percentage of bleached colonies on the Bahia coastal reefs reached values higher than 50% (Leão *et al.* 2008; Leão *et al.*, 2010).

Although it is well established in the literature that thermal anomaly is the most influent contributor to coral bleaching it is important to assess which other contributors may favour susceptibility to bleaching (Mcclanahan *et al.* 2019). The rapid water cooling (Kobluk & Lysenko, 1994), the complex interaction between thermal anomaly and photosynthetically active radiation (Dunne & Brown, 2001), the precipitation and water turbidity (Leão *et al.*, 2010), the exposure to low tides (Fadlallah *et al.*, 1995), low or no wind (Skirving *et al.*, 2006) are factors associated with coral bleaching. The coral bleaching affect in many ways different species and thus susceptibility is highly associated with coral species composition (Loya *et al.*, 2001; Leão *et al.*, 2008; Mónaco *et al.*, 2012). Link synergies between natural and anthropogenic forces are associated by several authors to coral bleaching. From this synergy, anthropogenic causes are responsible for increasing the frequency and intensifying bleaching events (Westmacott *et al.*, 2000; Allemand *et al.*, 2004; Castro & Zilberberg, 2016; Garrido *et al.*, 2016).

When trying to remove the oxidative stress source caused by environmental perturbations that deregulate the production of reactive oxygen species the coral expels the zooxanthellae (Marangoni *et al.*, 2016). With the elimination of zooxanthellae and their pigments degradation, coral loses their usual color and show the whitish color of the calcium carbonate skeleton (Douglas, 2003; Marangoni *et al.*, 2016). This occurs as a result of the braek down of the symbiosis relationships between the photosynthesizing microalgae and the coral. As an outcome corals will die if not recolonized by other clades more tolerant to the rise of the water temperature (Douglas, 2003; Marshall & Schuttenberg, 2006; Freitas *et al.*, 2012; Garrido *et al.*, 2016).

There is a consensus in the literature that corals tend to support a thermal anomaly of 1 degree Celsius of mean sea surface temperature in the summer. Exposure above 1 degree of thermal anomaly for a couple of weeks results in the occurrence of a bleaching event (Goreau & Hayes, 1994; Hoegh-Guldberg, 1999; Marshall & Schuttenberg, 2006; Garrido *et al.*, 2016). In Brazil, however, there are records of coral bleaching even when thermal anomaly is below 1 degree Celsius (Krug *et al.*, 2013).

Coral reefs are particularly important due to its productivity, biodiversity and complexity (Connell, 1978; Villaça, 2009). Due to the impacts of bleaching on life on Earth there is a call for continuous monitoring for better target policy making. Although marine ecosystems are crucial for life on Earth, until recently, Brazil had only 1,5% of the marine protected area (MMA, 2015). Currently, Brazil has 182 marine protected areas (26,45% of sea area), despite the two largest Brazilian marine conservation units (APA São Pedro e São Paulo and APA de Trindade e Martim Vaz) were only created in 2018 (MMA, 2019).

Spatially explicit modelling has been used by Hughes *et al.* (2017) which modelled three mass bleaching events in Australia from data acquired through diving and aerial survey. This study found that the 2016 event was so intense that the effect of protected areas was null. In Abrolhos there has been occurring monitoring on the coral response to bleaching events from field estimates of the percentage of bleached coral colonies (Ferreira & Maida, 2006; Leão *et al.*, 2008; Kikuchi *et al.*, 2010). Krug *et al.* (2013) using Bayesian networks estimates bleaching intensity in seven different reef regions in Bahia. Lisboa *et al*. (2018) used a similar approach to model bleaching in Abrolhos reefs and produced a model that allowed a good estimation of bleaching with at least four months in advance. However, to our knowledge, there is not yet a comprehensive study spatially differentiating susceptibility to coral bleaching in Abrolhos complex. In order to contribute to fill in this gap this study innovatively uses spatially explicit multi criteria analysis for differentiate susceptibility of Abrolhos reefs to coral bleaching.

Abrolhos, mainly the coastal arch, suffers continuous anthropogenic impacts such as urban development, tourism and pollution (Kikuchi *et al.*, 2010). Therefore, it becomes evident the importance of directing greater attention and efforts to the development of simulations in this area and, thus, to guide actions that diminish the anthropogenic impacts. Abrolhos was in 2019 place of a conservation vs. development disputes and this spatially explicit work can help at assessing the role of both environmental and antropogenic variables into susceptibility to bleaching. There are however lack of data to build data driven spatially explicit models for example using weights of evidence (Bonham-Carter, 1994) we based our approach on expert knowledge for assigning scores and weights to variables. We also conducted sensivity analysis of the estimates. In order to fulfill the data gap it is important periodic monitoring of the reef environment in order to develop strategies and for actions that aim at minimizing chronic stress conditions for enhancing the resilience of corals to climate change. Therefore, investment in new forms of continuous reef monitoring can contribute to the survival of this mature, productive and biodiverse ecosystem.

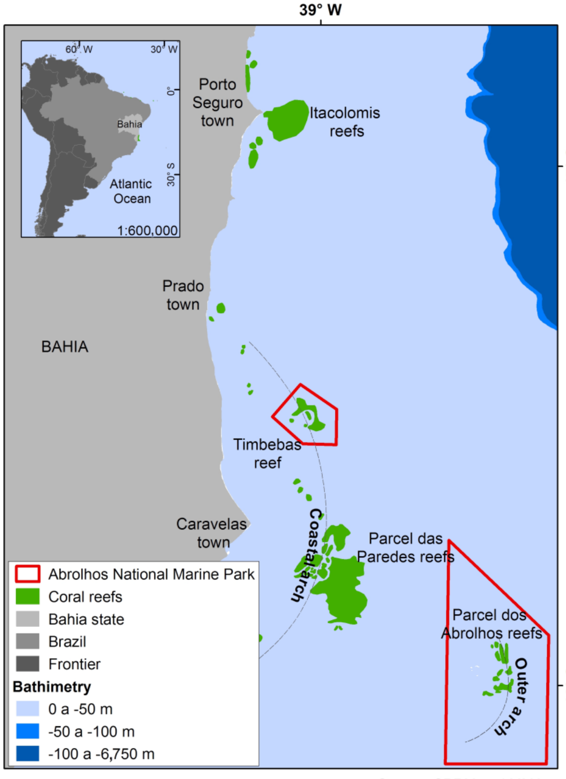
2. Material and methods

2.1. Study area

The Abrolhos bank has an area of approximately 46.000km² distributed in 409 km of shoreline from the municipality of Prado (BA) to the mouth of the Doce river (ES) (Marchioro *et al.*, 2005). While most of the Brazilian continental shelf has irregular and reduced widths (~ 50km), the Abrolhos bank consists of an expansion of this platform that reaches approximately 200km in the vicinity of Caravelas municipality (Leão, 1999). The Abrolhos reef complex covers an area of 6.000km² (Figure 1) (Leão, 1999; Ferreira & Gonçalves, 1999).

Inserted in the limits of the Abrolhos bank, is the first National Marine Park in Brazil, which was created by Decree 88,218 on 1983, includes the Timbebas reefs, the volcanic islands of Siriba, Sueste, Redonda and Guarita and Parcel dos Abrolhos reefs (Brasil, 1983; Ibama, 1991). Between Abrolhos and Royal Charlotte banks are located the Itacolomis reefs characterized by high richness of coral species and for presenting their tops exposed during periods of low tides (Castro & Segal, 2001). The climate of the eastern Brazilian coast is tropical humid and the sea surface temperature varies from 24°C in winter to 28°C in summer (Kelmo *et al.*, 2003; Leão *et al.*, 2003; Leão *et al.*, 2010).

Abrolhos coral reefs are formed by coral pinnacles known as “chapeirões” (Ferreira & Gonçalves, 1999; Leão *et al.*, 2003). These “chapeirões”, not found in any other reef in the world, present a mushroom shape that can reach up to 25m high and 50m wide (Leão *et al.*, 2003). Abrolhos reefs are spatially arranged in two arches oriented almost parallel to the coastline: the coastal arch and the outer arch (Leão, 1999). The Coastal Arch, distant



Source: CPRM and MMA
Geographic coordinate system
Datum SIRGAS 2000

FIGURE 1 – Location map of the study area.

approximately 10 to 20km from the coastline, is composed by isolated coral pinnacles and bank reefs formed by fusion of "chapeirões" (Leão, 1999; Leão *et al.*, 2003). The outer arch, located approximately 70km from the coastline, consists of numerous giant and isolated "chapeirões" located at depths greater than 20m (Leão, 1999; Leão *et al.*, 2016). The Abrolhos archipelago, located about 5km west of the Parcel dos Abrolhos, is constituted of five volcanic islands that are bordered by incipient fringing reefs (Leão *et al.*, 2003).

In Brazil there is low diversity of coral species with high number of endemism when compared for example with to Caribbean (Leão *et al.*, 2016). There are currently five species of endemic stony corals (*Mussismilia brasiliensis, Mussismilia hispida, Mussismilia harttii, Mussismilia leptophylla and Siderastrea stellata*) and three hydrocorals (*Millepora braziliensis, Millepora nítida and Millepora laboreli*), major reef-building coral species in Brazil (Castro & Zilberberg, 2016). The high endemism of corals and hydrocorals are an important feature of Abrolhos reefs (Leão, 1999).

2.2. Selection of variables, conceptual model and stages of modeling

The literature review highlights that coral bleaching events can be associated to the exposure of corals to a set of environmental and anthropogenic variables. *In situ* and laboratory experiments that show the influence of these variables on the triggering of coral bleaching are presented in Table 1.

From these were selected eight variables shown in Table 2 with their respective units of measure, spatial resolution and data source.

According to the literature, thermal anomaly / rising sea surface temperature is the variable that better explains bleaching. This happens because coral reefs are highly sensitive to changes in sea temperature (Machado *et al.*, 2016). Excessive photosynthetically active radiation is also associated with coral bleaching, and its effect combined with increased seawater temperature has been reported as the cause of bleaching events (Dunne & Brown, 2001; Freitas *et al.*, 2012; Winter *et al.*, 2016). Low or no wind conditions favor coral bleaching as there is no vertical mixing of the water column which has been surface heated by solar energy (Skirving *et al.*, 2006).

Also incorporated into the model are anthropogenic exposure variables that increase the susceptibility to coral bleaching, since, as mentioned in the literature, they reduce the resistance of these to environmental disturbances. The anthropogenic variables considered in the model are distances: from reefs to urban areas, to waterways, to harbor and presence of marine protected areas. The urban areas were considered because disposal of untreated waste from cities in the coastal region unbalances the reef ecosystem and reduces its resilience to environmental disturbances (Horta *et al.*, 2016; Leão *et al.*, 2016). Navigation makes reef ecosystems susceptible to chronic and acute contamination by oil caused by small leaks in the vessel, tank washing and dumping of waste at sea (Lopes, 2007; Sousa *et al.*, 2013). The oil transport near Abrolhos region threatens sensitive environments such as the Abrolhos reef complex reducing the ability of organisms to survive other environmental disturbances (Lopes, 2007; Jablonski, 2008). The increase of terrigenous sedimentation in the proximity of Abrolhos coastal reefs in the last decades indicates that anthropogenic forcing such as dredging can negatively influence the Abrolhos reefs (Silva *et al.*, 2013). Pollock *et al.* (2014) related dredging operations with coral bleaching in Australia and suggested that if the energy used for self-cleaning of corals is not supplied, bleaching may even evolve to coral mortality. The presence of marine protected areas benefit coral reefs as access and activities are regulated within the limits of the marine protected areas (Vila-Nova & Ferreira, 2016). In the Abrolhos National Marine Park, fishing is prohibited and, therefore, stocks of herbivorous fish that control the proliferation

TABLE 1 – Relation of variables used *in* situ and laboratory experiments in studies on coral bleaching.

Scale	Variables	Data type	Source
National scale	Thermal anomaly, photosynthetically active radiation, Wind magnitude, UV radiation and chlorophyll	Consultation with coral reefs experts and literature (Expert driven), Spatial Principal Component Analysis and Parametric Fuzzy relations in combination with Analytical Hierarchical Process (Data driven).	Maina *et al.* (2008)
National scale	Thermal anomaly, Chlorophyll a and protected areas	It relates the severity of bleaching with the variation of water surface temperature, protected areas and water quality (Data driven).	Hughes *et al.* (2017)
Regional scale	Thermal anomaly, Maximum temperature, Wind speeds, K490, rain precipitation and ENSO proxies.	Bayesian networks (Data driven) with Specialist knowledge (Expert driven)	Krug *et al.* (2013)
Regional scale	Urban areas	Field monitoring of coral vitality indexes (Data driven)	Kikuchi *et al.* (2010)
Regional scale	Wind	Hydrodynamic model to evaluate the thermal capacitance of the region from the stability level of the water column.	Skirving *et al.* (2006)
Local scale	Presence of Marine protected area	In situ experiments to analyze the effect of herbivorous fish on coral resilience to bleaching events (Data driven)	Hughes *et al.* (2006); Mumby & Harborne (2010); Mellin *et al.* (2016)
Local scale	Specific susceptibility	Measurement of the tissue thickness of different species and Field monitoring based on the number of bleached colonies and the intensity of bleaching in each species (Data driven)	Loya *et al.* (2001); Mónaco *et al.* (2012)
Local scale	Oil pollution	In situ research on the chronic effect of oil pollution with consequent reduction of coral cover and juvenile coral (Data driven).	Bak (1987)
Laboratory experiment	Oil pollution	Simulation of chronic oil pollution in tanks that concluded that oil affects the corals' reproduction and recolonization (Data driven)	Rinkevich & Loya (1979)
Laboratory experiment	Temperature and photosynthetically active radiation	Monitoring the response of corals at different temperatures and photosynthetically active radiation (Data driven)	Lesser & Farrell (2004); Winter *et al.* (2016)

TABLE 2 – Variables considered in modeling.

Variable	Unit of measure	Spatial resolution	Source
Coral bleaching (dependent variable)	%	-	Kikuchi *et al.*
Sea surface temperature	°C	25km	NOAA (2016 a)
Sea surface thermal anomaly	°C	25km	NOAA (2016 c)
Photosynthetically active radiation	einstein.m^{-2}.day^{-1}	9km	NASA (2016a, b)
Wind magnitude	m.s^{-1}	≅200km	NOAA (2016 b)
Urban áreas	-	-	IBGE (2010)
Waterways	-	-	ANTAQ (2013b)
Harbor	-	-	ANTAQ (2013a)
Marine protected areas	-	-	MMA (2012)

TABLE 3 – Percentage of coral bleaching (dependent variable) in each reef recorded in the study by Kikuchi *et al*. (2010).

% bleaching	Mean	Std. deviation
Lixa 2001	3.8	4.1
Lixa 2002	2.8	3.6
Lixa 2003	17.5	-
Paredes 2001	11.0	8.1
Paredes 2002	3.4	4.2
Timbebas 2001	3.4	2.3
Timbebas 2002	4.4	4.5
Timbebas 2003	11.8	-
Parcel dos Abrolhos 2001	5.0	4.4
Parcel dos Abrolhos 2002	7.5	4.1
Parcel dos Abrolhos 2003	8.2	-
Santa Bárbara 2001	0.3	0.6
Santa Bárbara 2002	6.1	0.6
Santa Bárbara 2005	24.5	5.4
Redonda 2001	0.7	-
Redonda 2002	4.0	-
Siriba 2005	24.7	-
Sueste 2001	1.1	-
Itacolomis 2005	10.4	5.9

of algae that compete with corals for space can be preserved (Vila-Nova & Ferreira, 2016).

As a dependent variable was used the percentage of coral bleaching recorded in the study by Kikuchi *et al.* (2010) (Table 3).

It is known that other variables such as tourism pressure, diseases and specific species susceptibility are important variables but not yet available. Those may be incorporated into the model in the future. It is important to note that published coral bleaching data of Abrolhos reefs are limited. Currently, there are data only up to 2005 published by Kikuchi *et al.* (2010) that was used in this work. At the time this work was conducted, data collected in the 2010 and 2016 events were under revision and cross verification. Despite the high cost involved in diving expeditions with scientific goals and the need for training of the team involved in this type of research, it is of fundamental importance the continuity of this monitoring in order to follow the behavior of Abrolhos reefs in anticipation of the climate changes for the coming decades.

Based on the above mentioned variables, the spatial distribution of the susceptibility of Abrolhos corals to bleaching events was performed using the multicriteria analysis method that assigns scores and weights to the variables. Using the data available our model was calibrated using the years 2001 and 2003 seeking to obtain as a result a bleaching susceptibility map compatible with data obtained in the field by Kikuchi *et al.* (2010). Subsequently, the reef susceptibility simulation was performed for the summer of 2016. The 2016 estimates were not so far validated as there are not yet published data on percentage of bleaching.

We used DINAMICA EGO that is a modeling platform for creating environmental models that allows dynamic modeling incorporating iterations, transition matrices, feedback, regionalization and bifurcation of processes (Soares-Filho *et al.*, 2013).

The raster files for each variable were constructed for the summer of each year used in the study in the DINAMICA EGO software. It is important to note that for the construction of the rasters referring to the summer of each year, the three months previous to the field sampling were considered. For the year 2016 (February, March and April), while for the other years were the summer months (January, February and March).

For building the rasters of maximum sea surface temperature and for the maximum photosynthetically active radiation we used the highest pixel value among the daily range. For the minimum wind magnitude we used the smallest pixel value of the monthly.

The persistence of temperatures above the climatological average was included in the model as the thermal anomaly variable accumulated in periods of five or more consecutive days (Adapted from Krug *et al.*, 2013). The sum of the values of thermal anomaly was performed, pixel by pixel, and then was generated the thermal anomaly map accumulated in the summer of a given year. Although there are several measures for predicting coral bleaching, such as Degree Heating Weeks (DHW), Degree Heating Months (DHM), etc. they were not spatially explicit at the scale we needed and therefore we developed this metric -number of days above 1 degree Celsius of historical mean (adapted from Krug *et al.*, 2013) at the resolution of our pixel.

In DINAMICA EGO software was calculated the Euclidean distances, in meters, from the reefs to waterways, urban areas and Caravelas harbor. These maps were used in the modeling of all years used in the study, with the exception of the map of distance to the Caravelas harbor that was considered in the modeling only from the year of its implementation in 2003.

Then, the spatial correlation analysis was performed in order to assess whether or not variables used were spatially independent. We consulted the literature and two co-authors of this paper assigned weights and scores to the variables considered in the model. The weights were assigned by experts at the Universidade Federal da Bahia, who have been developing research on coral bleaching in Abrolhos since 2000. Although we consulted only two experts there was little variability on the weights and scores and those generally agreed with the specialized literature.

Finally, the multicriteria analysis model was then constructed in DINAMICA EGO as shown in Figure 2. In DINAMICA EGO, maps were uploaded for each environmental variable in the summer of a given year, maps of distances and the map of marine protected areas. Next, scores were assigned for each class of each variable and weights for each variable. Finally, the sum of the already weighted variables that resulted in the susceptibility map of Abrolhos reefs to bleaching were carried out for each year used in the study.

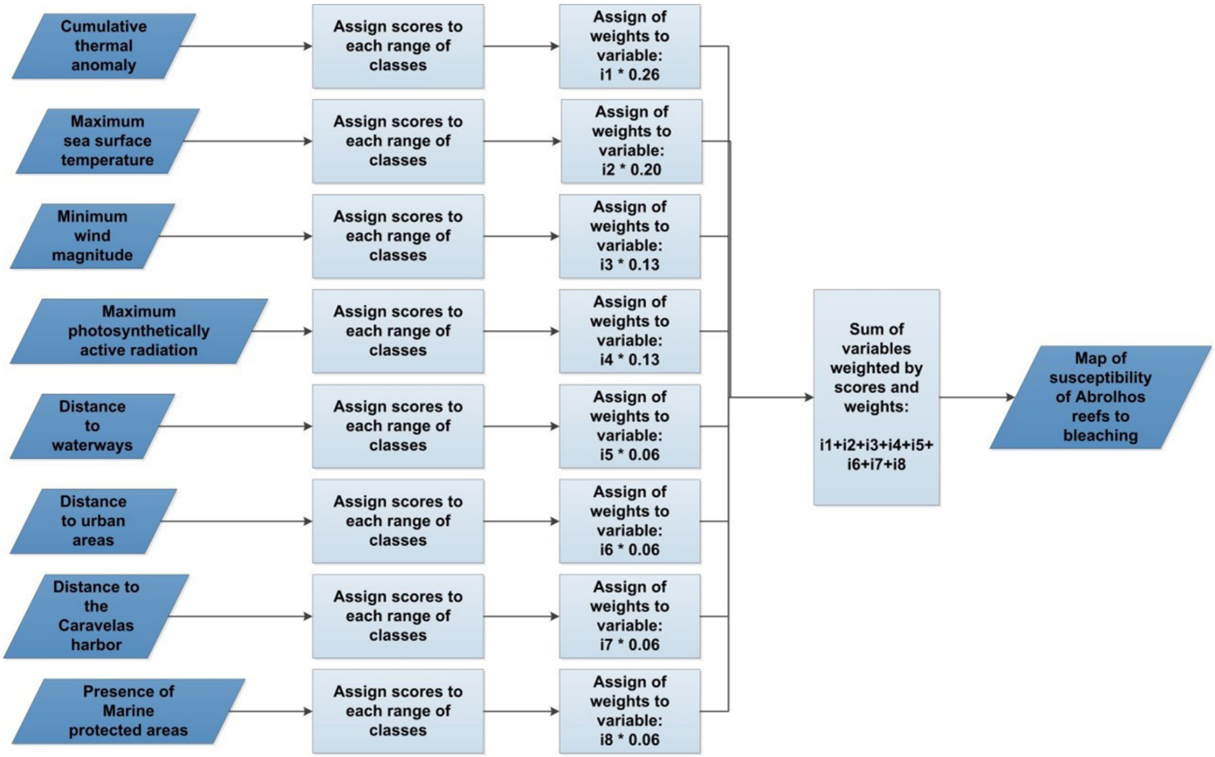


FIGURE 2 – Multicriteria analysis of the susceptibility of coral reefs to bleaching: variables, scores and weights.

2.3. Statistical analyses

The Kruskal Wallis test was used with significance level α = 0.05 in order to verify if the dependent variable (intensity of coral bleaching) and the independent environmental variables (thermal anomaly, maximum sea surface temperature, maximum photosynthetically active radiation and minimum wind magnitude) showed significant differences among the years used in the study.

3. Results

It is well known that environmental variables are key explain coral bleaching events. There is, however, less evidence on the associations and synergies between natural and anthropogenic forcings. In this work we aim at exploring the effects of both environmental and anthropogenic variables for estimating susceptibility to coral bleaching. In order to do so we developed a spatially explicit model to assess the susceptibility to bleaching of different Abrolhos reefs incorporating environmental (climatic) and local (anthropogenic) variables. Although the model does not can be considered predictive (its results are not on the same scale observations), they do demonstrate the same trend of data obtained in situ and therefore can be used for exploring associations amongst environmental and antropogenic variables across different years.

3.1. Results of the independent variables built in DINAMICA EGO

The first outputs of our analysis were the rasters created for being used as input variables. Figures 3, 4, 5 and 6 show the input rasters of each independent environmental variable (accumulated thermal anomaly, maximum sea surface temperature, maximum photosynthetically active radiation and minimum

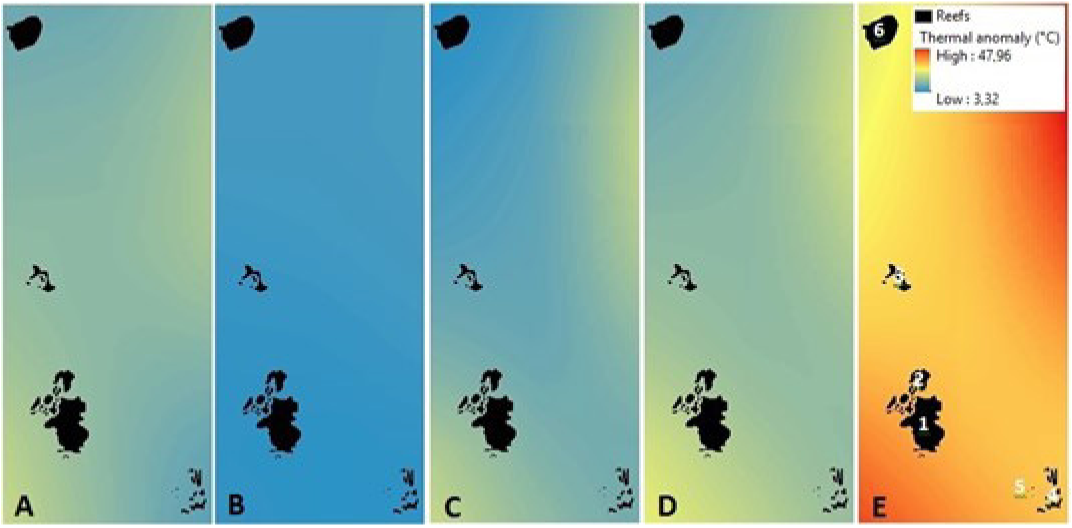


FIGURE 3 – Accumulated thermal anomaly (°C) in the summers of 2001 (a), 2002 (b), 2003 (c), 2005 (d) and 2016 (e). Parcel das Paredes reefs (1), Lixa reef (2), Timbebas reefs (3), Parcel dos Abrolhos reefs (4), Abrolhos archipelago (5) and Itacolomis reefs (6).

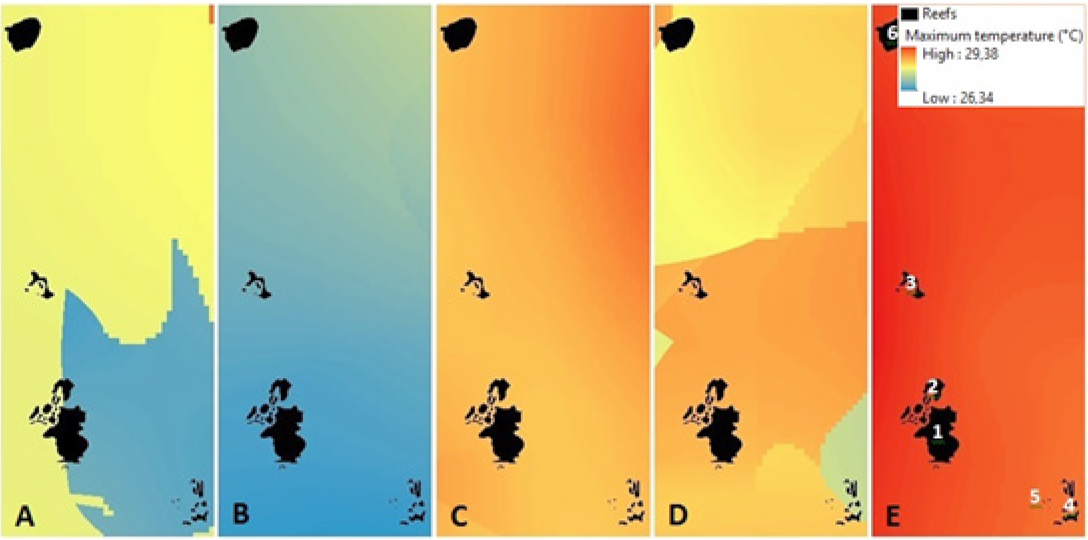


FIGURE 4 – Maximum sea surface temperature (°C) in the summers of 2001 (a), 2002 (b), 2003 (c), 2005 (d) and 2016 (e). Parcel das Paredes reefs (1), Lixa reef (2), Timbebas reefs (3), Parcel dos Abrolhos reefs (4), Abrolhos archipelago (5) and Itacolomis reefs (6).

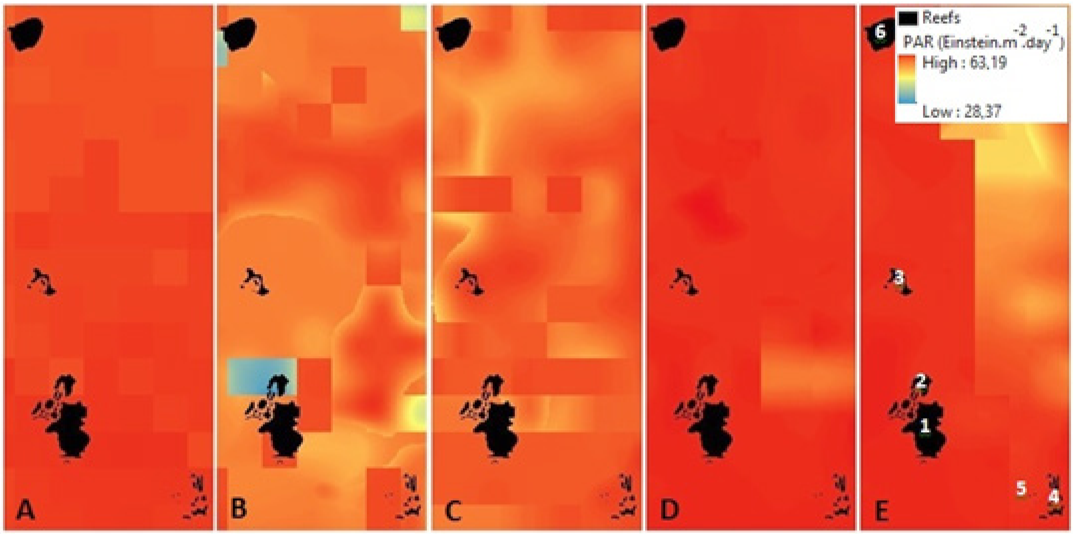


FIGURE 5 – Maximum photosynthetically active radiation (einstein.m^{-2}.day^{-1}) in the summers of 2001 (a), 2002 (b), 2003 (c), 2005 (d) and 2016 (e). Parcel das Paredes reefs (1), Lixa reef (2), Timbebas reefs (3), Parcel dos Abrolhos reefs (4), Abrolhos archipelago (5) and Itacolomis reefs (6).

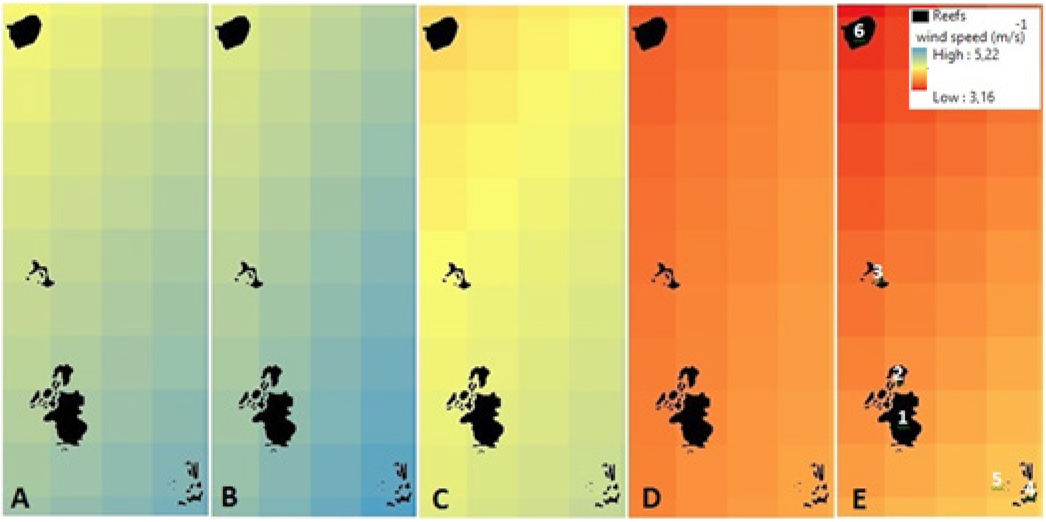


FIGURE 6 – Minimum wind magnitude (m.s^{-1}) in the summers of 2001 (a), 2002 (b), 2003 (c), 2005 (d) and 2016 (e). Parcel das Paredes reefs (1), Lixa reef (2), Timbebas reefs (3), Parcel dos Abrolhos reefs (4), Abrolhos archipelago (5) and Itacolomis reefs (6). Note that the high values (in blue) correspond to lower susceptiblity to bleaching.

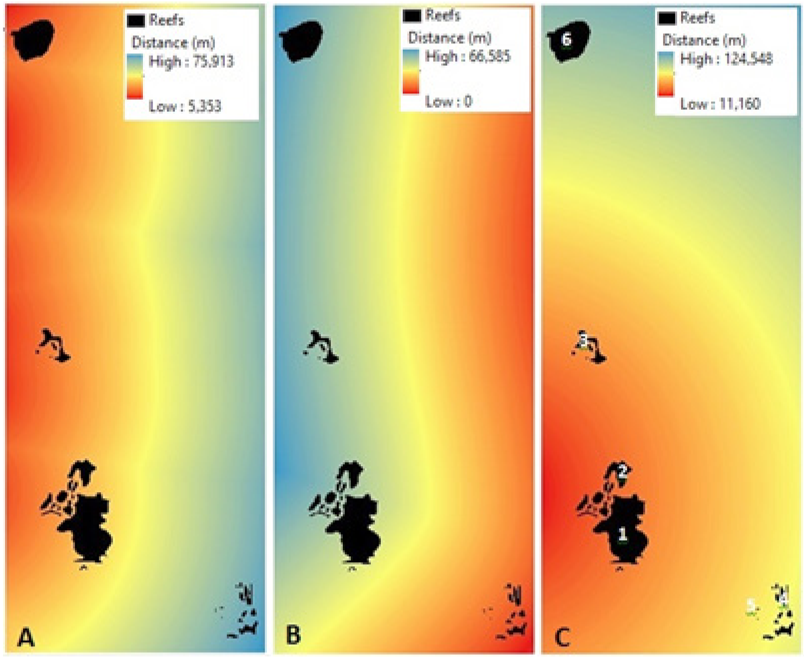


FIGURE 7 – Distances (m) to urban areas (a), waterways (b) and Caravelas harbor (c). Parcel das Paredes reefs (1), Lixa reef (2), Timbebas reefs (3), Parcel dos Abrolhos reefs (4), Abrolhos archipelago (5) and Itacolomis reefs (6).

wind magnitude) for the years 2001, 2002, 2003, 2005 and 2016. The color of the legends in the figures range from bluish (likely associated to lower bleaching intensity) to reddish (likely associated to higher bleaching). As highlighted in the methods section.

The independent anthropogenic variables (distances to urban areas, waterways and Caravelas harbor) are shown in Figure 7.

The mean values of the variables (accumulated thermal anomaly, maximum sea surface temperature, maximum photosynthetically active radiation and minimum wind magnitude) in each reef in the

TABLE 4 – Values of independent environmental variables (accumulated thermal anomaly, maximum sea surface temperature (SST), maximum photosynthetically active radiation (PAR) and minimum wind magnitude) were calculated for each reef in 2001, 2002, 2003, 2005 and 2016.

Reefs	**Variable**	**2001**	**2002**	**2003**	**2005**	**2016**
Lixa	Maximum thermal anomaly (°C)	13.32	4.00	10.17	14.88	31.98
Paredes	Maximum thermal anomaly (°C)	13.70	3.85	11.71	16.38	33.57
Timbebas	Maximum thermal anomaly (°C)	7.85	3.66	9.56	13.41	29.29
Parcel dos Abrolhos	Maximum thermal anomaly (°C)	12.63	4.46	7.67	12.83	31.17
Santa Bárbara	Maximum thermal anomaly (°C)	8.55	3.64	9.83	13.89	31.57
Redonda	Maximum thermal anomaly (°C)	8.68	3.63	9.91	14.04	31.72
Siriba	Maximum thermal anomaly (°C)	8.42	3.62	9.87	13.98	31.72
Sueste	Maximum thermal anomaly (°C)	8.68	3.63	9.91	14.04	31.71
Itacolomis	Maximum thermal anomaly (°C)	9.15	5.37	3.68	8.13	24.20
Lixa	Maximum SST (°C)	27.02	26.48	28.32	28.46	29.18
Paredes	Maximum SST (°C)	27.07	26.45	28.33	28.40	29.18
Timbebas	Maximum SST (°C)	26.53	26.40	28.33	27.66	29.27
Parcel dos Abrolhos	Maximum SST (°C)	27.73	26.67	28.32	28.50	28.91
Santa Bárbara	Maximum SST (°C)	26.56	26.40	28.30	28.20	28.94
Redonda	Maximum SST (°C)	26.56	26.40	28.29	28.20	28.95
Siriba	Maximum SST (°C)	26.56	26.39	28.29	28.21	28.95
Sueste	Maximum SST (°C)	26.56	26.40	28.29	28.20	28.94

Itacolomis	Maximum SST (°C)	27.77	26.92	28.36	28.02	29.18
Lixa	Maximum PAR (einstein.m^{-2}.day^{-1})	60.64	32.19	59.45	61.98	62.10
Paredes	Maximum PAR (einstein.m^{-2}.day^{-1})	61.74	56.83	57.77	62.44	62.42
Timbebas	Maximum PAR (einstein.m^{-2}.day^{-1})	61.84	59.48	61.02	62.49	62.20
Parcel dos Abrolhos	Maximum PAR (einstein.m^{-2}.day^{-1})	61.10	56.71	61.21	62.14	62.38
Santa Bárbara	Maximum PAR (einstein.m^{-2}.day^{-1})	61.95	60.77	61.23	62.38	62.14
Redonda	Maximum PAR (einstein.m^{-2}.day^{-1})	61.86	60.75	61.05	62.36	62.10
Siriba	Maximum PAR (einstein.m^{-2}.day^{-1})	61.87	60.76	61.18	62.41	62.13
Sueste	Maximum PAR (einstein.m^{-2}.day^{-1})	61.85	60.75	61.09	62.37	62.21
Itacolomis	Maximum PAR (einstein.m^{-2}.day^{-1})	60.05	55.76	56.62	61.91	62.04
Lixa	Minimum Wind (m.s^{-1})	4.66	4.79	4.32	3.60	3.63
Paredes	Minimum Wind (m.s^{-1})	4.71	4.83	4.34	3.60	3.68
Timbebas	Minimum Wind (m.s^{-1})	4.93	5.09	4.51	3.74	3.47
Parcel dos Abrolhos	Minimum Wind (m.s^{-1})	4.50	4.62	4.20	3.51	3.91
Santa Bárbara	Minimum Wind (m.s^{-1})	4.92	5.08	4.50	3.74	3.89
Redonda	Minimum Wind (m.s^{-1})	4.92	5.08	4.50	3.74	3.89
Siriba	Minimum Wind (m.s^{-1})	4.92	5.08	4.50	3.74	3.89
Sueste	Minimum Wind (m.s^{-1})	4.92	5.08	4.50	3.74	3.89
Itacolomis	Minimum Wind (m.s^{-1})	4.27	4.40	4.02	3.41	3.22

TABLE 5 – Mean values of independent anthropogenic variables (distance to the urban areas, waterways and harbor) were calculated for each reef. The variable distance to the harbor was only considered from the year 2003 (year of implementation of the harbor).

Reefs	**Variable**	**Mean (meters)**
Lixa	Urban area	28,179
Paredes	Urban area	29,525
Timbebas	Urban area	18,928
Parcel dos Abrolhos	Urban area	68,495
Santa Bárbara	Urban area	63,221
Redonda	Urban area	62,161
Siriba	Urban area	62,522
Sueste	Urban area	64,066
Itacolomis	Urban area	15,048
Lixa	Waterways	50,204
Paredes	Waterways	45,709
Timbebas	Waterways	51,324
Parcel dos Abrolhos	Waterways	6,744
Santa Bárbara	Waterways	11,526
Redonda	Waterways	12,347
Siriba	Waterways	11,850
Sueste	Waterways	10,222
Itacolomis	Waterways	59,225
Lixa	Harbor	27,750
Paredes	Harbor	28,995
Timbebas	Harbor	38,284
Parcel dos Abrolhos	Harbor	67,938
Santa Bárbara	Harbor	62,662
Redonda	Harbor	61,601
Siriba	Harbor	61,961
Sueste	Harbor	63,505
Itacolomis	Harbor	98,954

summers of 2001, 2002, 2003, 2005 and 2016 are shown in Table 4.

The mean values of the variables (distances to urban areas, waterways and Caravelas harbor) in each reef are shown in Table 5.

3.2. Results of the temporal variability of the data

The intensity of coral bleaching is influenced by the year of occurrence (Kruskall-Wallis, $H(3) = 15.326$, $p = 0.002$). The box plot of the dependent and independent variables is shown in Figure 8. The variables thermal anomaly (Kruskall-Wallis, $H(4) = 37.007$, $p= 0.000$), maximum sea surface temperature (Kruskall-Wallis, $H(4) = 39.262$, $p= 0.000$), maximum photosynthetically active radiation (Kruskall-Wallis, $H(4) = 35.865$, $p= 0.000$) and minimum wind magnitude (Kruskall-Wallis, $H(4) = 36.728$, $p= 0.000$) are also influenced by the year of occurrence.

3.3. Results of consultation with specialists

The scores and weights obtained from consultation of two experts and the literature are presented in Figure 9.The highest weights were attributed to

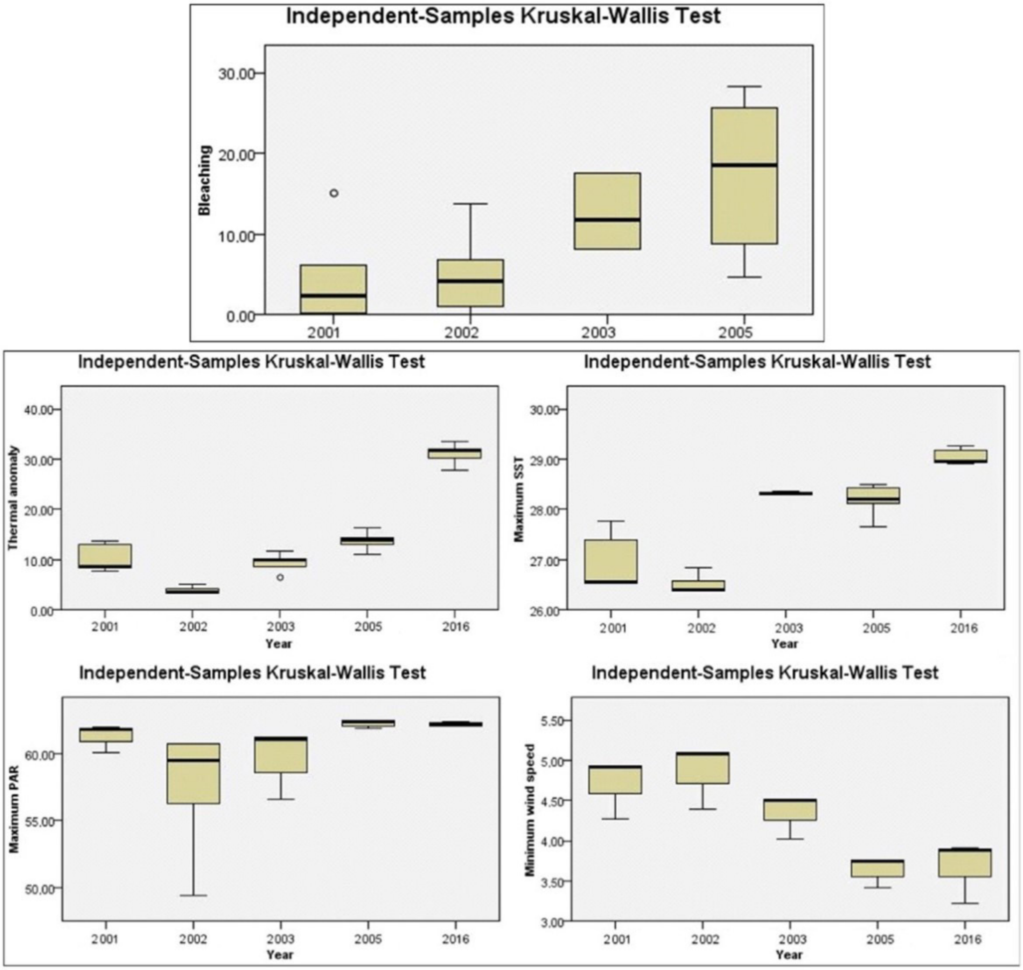


FIGURE 8 – Box plot of bleaching dependent variable (top) and box plot of the independent environmental variables (bottom). Thermal anomaly (°C); maximum sea surface temperature (°C); maximum photosynthetically active radiation (einstein.m^{-2}.day^{-1}) and minimum wind speed (m.s^{-1}).

the variables thermal sea surface anomaly (0.26) and maximum sea surface temperature (0.20). Followed by the minimum magnitude of the wind and maximum photosynthetically active radiation (0.13 for both). Anthropic variables, although increasing the vulnerability of corals, they do not act directly in

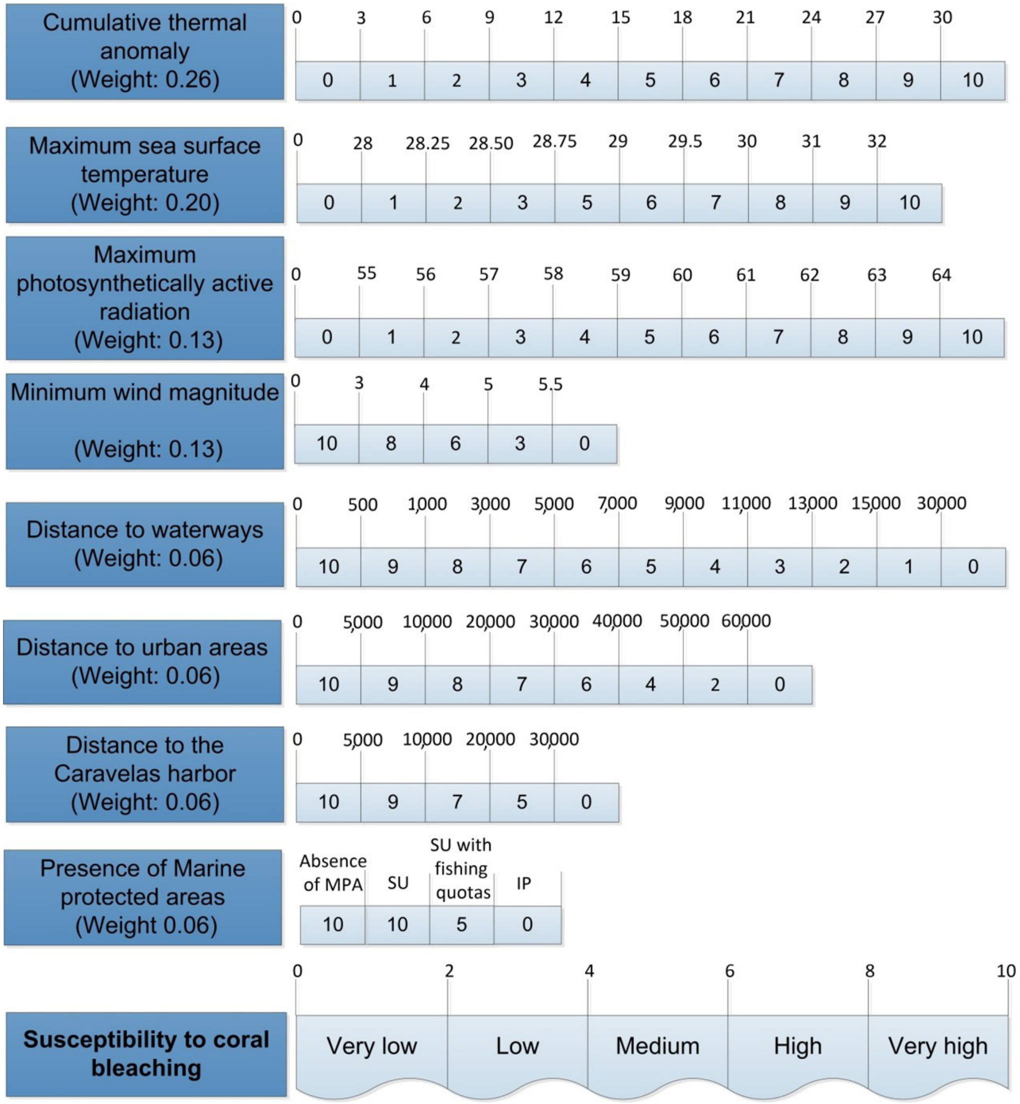


FIGURE 9 – Scores and weights assigned to variables. The variable distance to the Caravelas harbor was used in the modeling since the year 2003, year of implementation of the harbor. MPA = Marine protected area; SU = Sustainable use conservation unit; IP = Integral protection conservation unit. Accumulated thermal anomaly (°C); maximum sea surface temperature (°C); maximum photosynthetically active radiation (einstein.m^{-2}.day^{-1}); minimum wind magnitude (m.s^{-1}) and distances to waterways, urban areas and Caravelas harbor (m).

the triggering of coral bleaching, and thus received the lowest weight (0.06) as they present less influence in the phenomenon. The scores for each class of variables range from 0 (Lower influence) to 10 (Higher influence). Finally, a susceptibility scale ranging from 0 (very low) to 10 (very high) was suggested.

3.4. Results of sensibility analysis

Sensibility analysis was performed in relation to the weights attributed to each explanatory variable. Models were generated to show the effect of the removal (weight of 0%) and the allocation of 5, 25, 50 and 75% of the total weight of the model to each variable. The sensitivity variation of each variable obtained from the spatial correlation matrix between each generated model and the model used in the study is shown in Figure 10.

The sensitivity analysis showed that the model is insensitive to the variation of the weights of the variable wind in both cases, year of weak (2003) and strong (2005) bleaching due to the absence of spatial variation of this variable. In years of lower sea surface temperatures as in 2003, the absence of spatial variation also made the model insensitive to this variable. However, influenced the model when the temporal variation of the phenomenon is analyzed (Kruskall-Wallis, H (4) = 39.262, p = 0.000 for the maximum sea surface temperature and Kruskall-Wallis, H (4) = 36.728, p = 0.000 for the minimum magnitude of the wind).

The model presents low sensitivity in relation to the accumulated thermal anomaly variable. This indicates a lower level of uncertainty in relation to this parameter, corroborating the high weights in this model and in several others in the specialized literature (Maina *et al.*, 2008; Krug *et al.*, 2013; Hugues *et al.*, 2017). The model presented greater sensitivity in relation to the anthropic variables, mainly marine protected areas and waterways. Therefore, we opted for a more conservative approach with lower weights attributed to the anthropic variables that present the greater uncertainties of the model. It was also taken into account that the anthropic variables do not act directly in the triggering of coral bleaching, but present a secondary

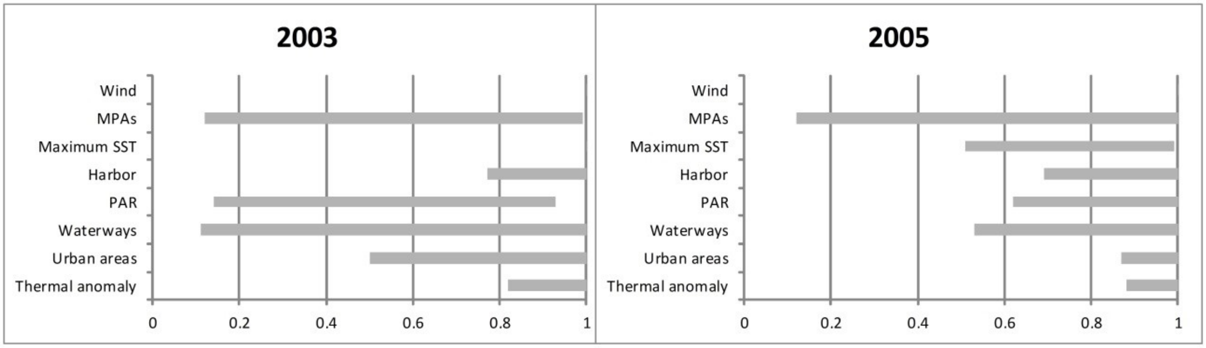


FIGURE 10 – Sensitivity analysis in year of weak bleaching (2003) and strong bleaching (2005).

role in increasing the vulnerability of corals to the phenomenon.

3.5. Comparison of the levels of susceptibility presented for each year used in the study

The area of Abrolhos reefs under conditions of very low, low, medium and high susceptibility

TABLE 6 – Comparison of the levels of susceptibility in each year used in the study.

Year	Very low		Low		Medium		High	
	Area (km^2)	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**
2001	-	-	34	20	140	80	-	-
2002	31	18	143	82	-	-	-	-
2003	-	-	131	75	44	25	-	-
2005	-	-	17	10	158	90	-	-
2016	-	-	-	-	32	19	142	81

Total area = 175km2. No reef was classified as very high susceptibility in the years used in the study. The reef area shown in the table does not necessarily is completely covered by corals, and may present other covers such as macroalgae, turf algae and coralline algae.

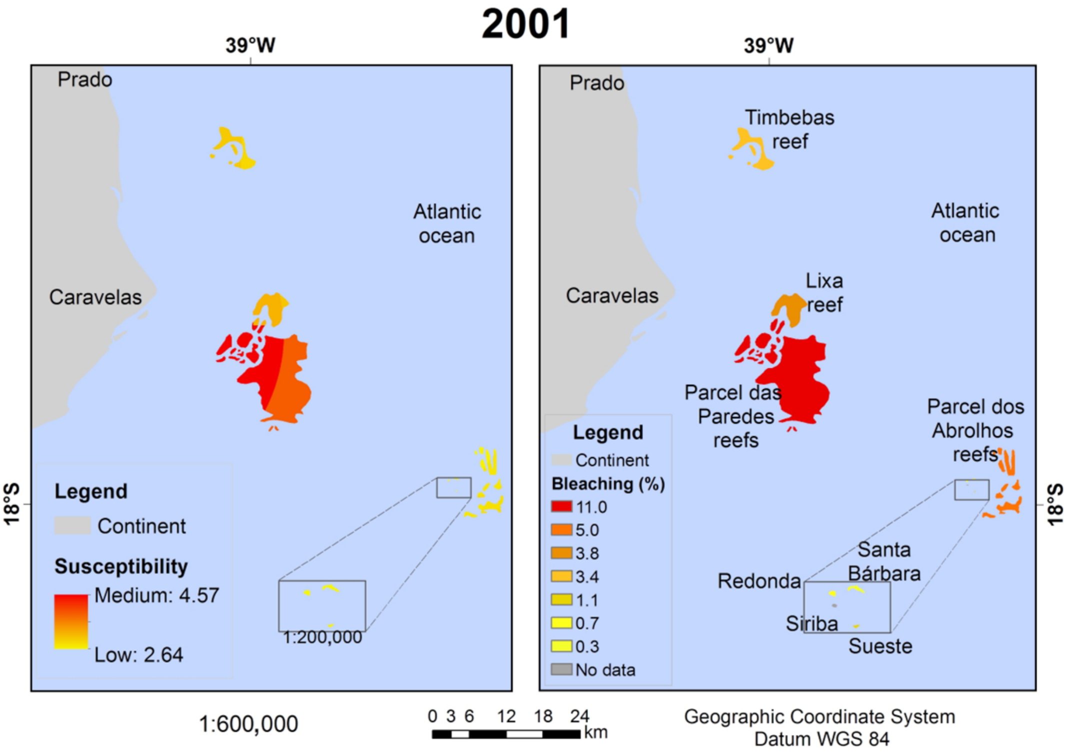


FIGURE 11 – Simulation of reef susceptibility to bleaching (left) and spatialization of field data (right) for 2001.

to coral bleaching in each year used in the study is presented in Table 6.

In 2001 the model shows that 20% of the reef area was under low and 80% of medium susceptibility to coral bleaching (Table 6). The results of the multicriteria analysis for the year 2001 are shown in Figure 11.

The simulation done for the year 2001 agrees with the field data, evidencing that the Parcel das Paredes reefs (coastal arch) present the highest susceptibility and the highest bleaching value as sampled in the field by Kikuchi *et al.* (2010). The variable accumulated thermal anomaly presented spatial differentiation and, consequently, different scores attributed to reefs of the coastal arch and outer arch. Therefore, the higher values of thermal anomaly in the coastal arch reefs in 2001, together with the effect of the anthropogenic variables, contributed to the greater susceptibility in these reefs. The Timbebas reefs, although presenting values of thermal anomaly and proximity to urban areas more similar to the other coastal arch reefs, shows lower susceptibility than these.

The year 2002 was the year with the lowest susceptibility, being very low in 18% of the area and low in 82% (Table 6). The field data of Kikuchi *et al.*

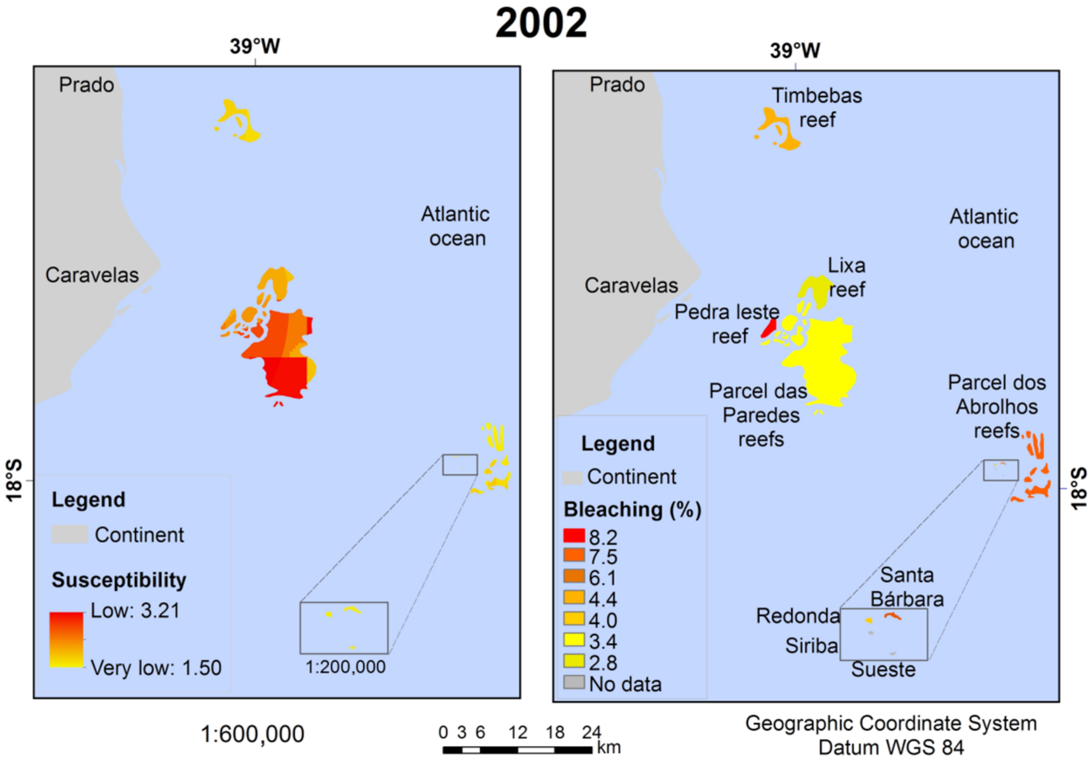


FIGURE 12 – Simulation of reef susceptibility to bleaching (left) and spatialization of field data (right) for 2002.

(2010) also presented low levels of coral bleaching (varying between 2.8 and 8.2% in the summer of 2002). It is likely that the reduced susceptibility presented in this year is associated to lower thermal anomaly. The simulation for the year 2002 (Figure 12) did not present a similar susceptibility pattern to the field data by Kikuchi *et al.* (2010).

This result, similarly to other years studied, shows a pattern of higher susceptibility to bleaching in the coastal reefs. On the contrary the pattern is of lower values of susceptibility in the Timbebas reefs and outer arch reefs. However, field data reveal lower coral bleaching percentages in the Lixa and Paredes reefs (coastal arch). Unlike Paredes and Lixa reefs, the Pedra Leste reef that was sampled only in the year 2002, presented the highest percentage of bleaching (8.2%). This reef, belonging to the Parcel das Paredes, is the closest to the continent and therefore likely influenced by proximity to the urban area. The sea surface thermal anomaly is widely disseminated by the scientific community as the main determinant of coral bleaching during global events (Dunne & Brown, 2001; Leão *et al.*, 2008; Marangoni *et al.*, 2016; Winter *et al.*, 2016). However, in the summer of 2002 Abrolhos presented a very low thermal anomaly if compared with records of other years. In addition to this, in 2002 there wasn't sufficient spatial variation of thermal anomaly among the Abrolhos reefs. Likely due to the absence of spatial variation of thermal anomaly among reefs the model did not show the real spatial distribution of corals susceptibility that summer. The only environmental variables that presented spatial variability among the reefs in 2002 and, therefore, influence on the susceptibility pattern, were the wind magnitude and the photosynthetically active radiation, besides the anthropic variables.

The spatial variation of coral bleaching among the reefs was very low (between 2.8 and 8.2% while in 2001 was between 0.3 to 11%). The estimated bleaching percentages was similar among reefs (less than 6 % variation) and it may not indicate a well-defined pattern as in other years. This can be caused either by a random variation or is reflecting the absence of other explanatory variables in this model. The level of susceptibility presented by the model for this year was low (maximum of 3.21) which is expected for a year with a reduced percentage of bleached colonies sampled in the field.

In 2003, 75% of the area presented low and 25% medium susceptibility (Table 6). The simulation made for the year 2003 (Figure 13) agrees with field data, evidencing that the Parcel das Paredes and Lixa reefs (coastal arch), again, presented the greatest susceptibilities. Among the reefs sampled in the field by Kikuchi *et al.* (2010), the Lixa reef presented the highest value of bleaching (17.5%).

The variables maximum photosynthetically active radiation and, mainly, the accumulated thermal anomaly, together with the antropic variables were responsible for the spatial variability of the susceptibility among the Abrolhos reefs. Timbebas reefs, similarly to the results of 2001, presented both susceptibility and bleaching (11.8%) more similar to the outer arch reefs (8.2%). The pattern of higher susceptibility to bleaching on coastal arch reefs and smaller in the outer arch is kept. Again, exception is made to Timbebas reefs that despite being located closer to the cost kept lower susceptibiliy in the 2003 simulation (similarly to 2001). Possibly, the protection conferred by the Abrolhos National Marine Park to the Timbebas reefs and the condition of thermal anomaly (7.67°C) lower than the coastal arch reefs (10.7°C in Lixa reef and

11.71°C in Parcel das Paredes reefs) favored the lowest susceptibility and bleaching percentage in Timbebas reefs in the summer of 2003.

In 2005, the reef area under conditions of medium susceptibility reached 90%, and only 10% presented lower susceptibility (Table 6). The spatialization of bleaching susceptibility for the year 2005 (Figure 14) shows, again, higher values for the coastal reefs and lower to the outer arch and Timbebas reefs. Although the Timbebas reefs have been classified with medium susceptibility, they are lower values than in the Parcel das Paredes.

In 2005, only the fringing reefs of the Abrolhos archipelago (outer arch) and the Itacolomis reefs, which are located in the coastal region of Porto Seguro town, were sampled in the field by Kikuchi *et al.* (2010). As recorded in the field, the modeling presented lower susceptibility in the Itacolomis reefs and higher in the Abrolhos archipelago. It was decided to model the susceptibility of this year due to the repetition of the susceptibility pattern in the Abrolhos reef complex. However, since no coastal arch reefs were sampled, it is not possible to compare the field data with the simulation of coastal arch reefs susceptibility. The environmental variables that presented spatial variation and defined the bleaching susceptibility in 2005 were mainly the thermal anomaly and the maximum sea surface

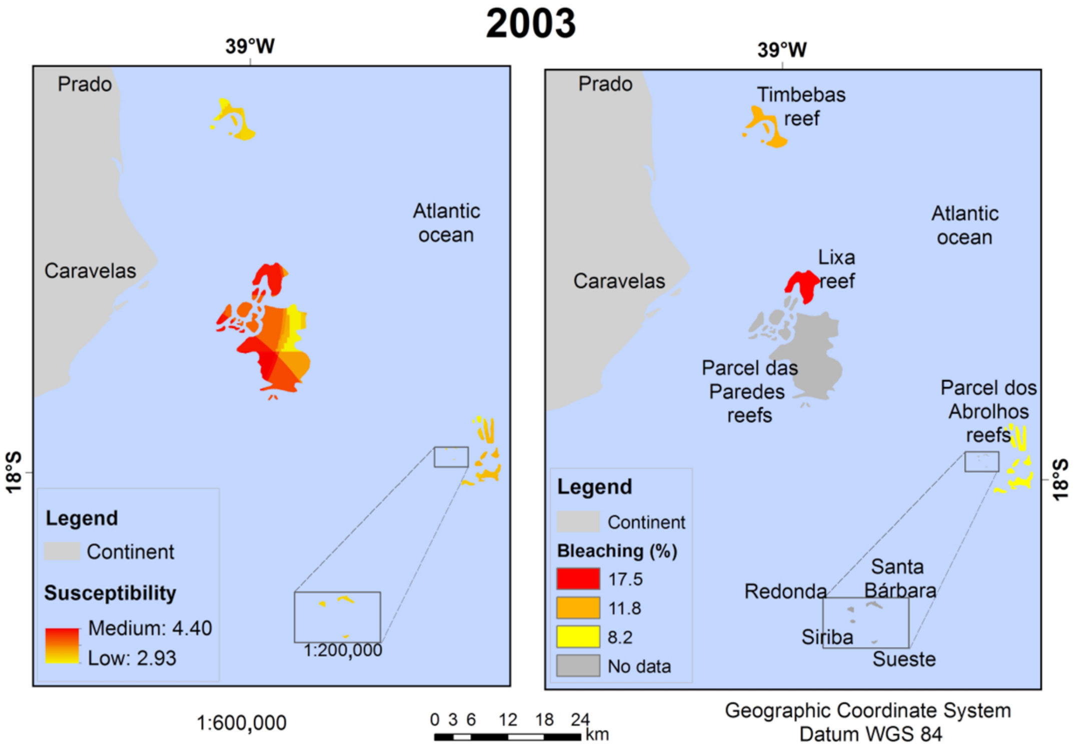


FIGURE 13 – Simulation of reef susceptibility to bleaching (left) and spatialization of field data (right) for 2003.

temperature, besides the anthropic variables. The maximum sea surface temperature was higher in the archipelago than in the Itacolomis reef. The thermal anomaly and the maximum photosynthetically active radiation also favored the lower susceptibility in the Itacolomis reefs.

The simulation performed for the year 2016 presented 19% of the area with medium susceptibility and 81% with high susceptibility (Table 6). 2016 presented the highest levels of susceptibility among the years used in the study, suggesting a higher percentage of bleached colonies. As in 2001 and 2003, the Timbebas reefs and the outer arch (Parcel dos Abrolhos and Abrolhos Archipelago) presented lower levels of susceptibility than the Parcel das Paredes that reached susceptibility of 7.07 in 2016 (Figure 15).

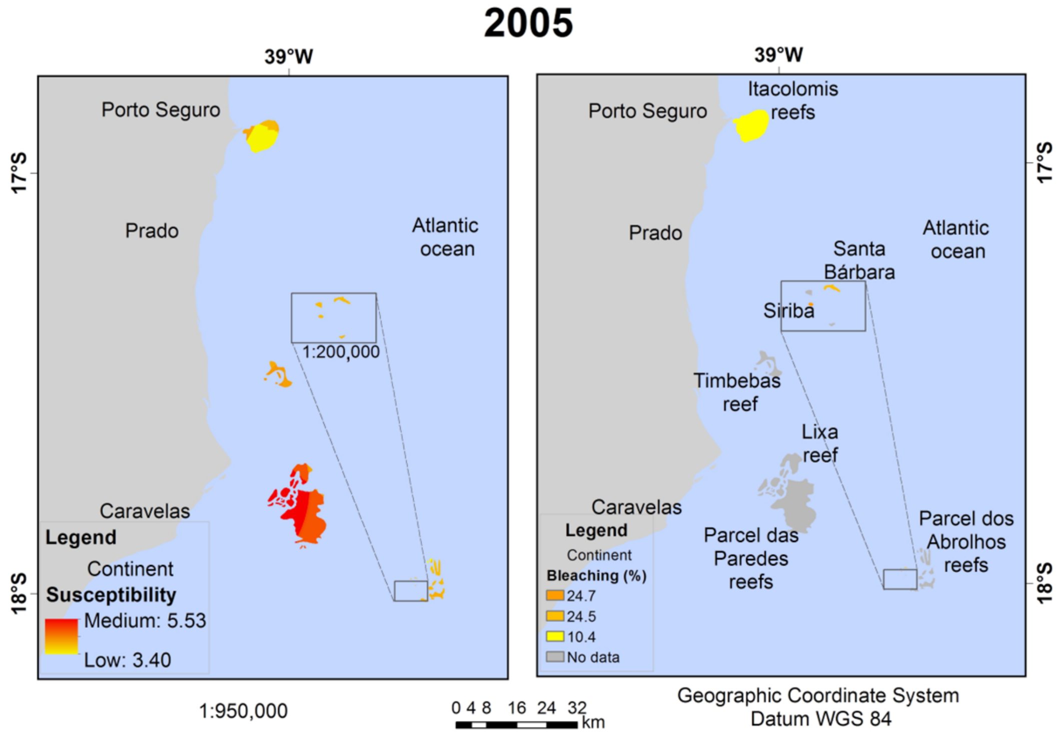


FIGURE 14 – Simulation of reef susceptibility to bleaching (left) and spatialization of field data (right) for 2005.

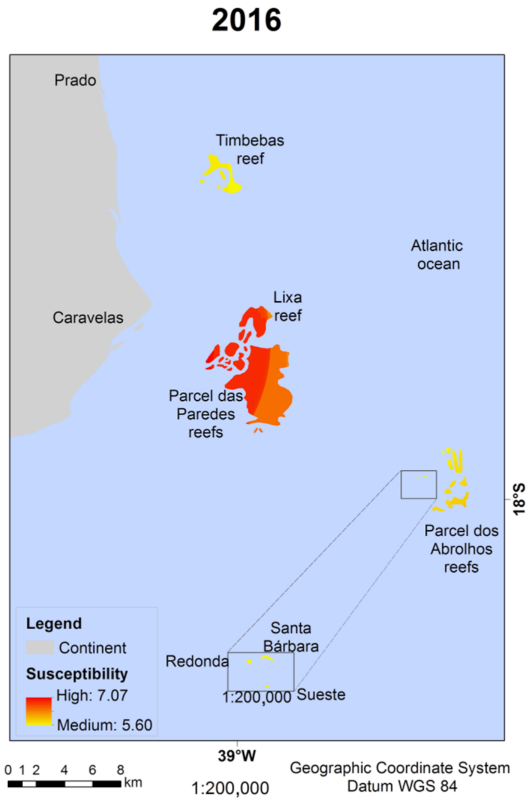


FIGURE 15 - Simulation of reefs susceptibility to bleaching in 2016. No field work data is available.

4. Discussion

The synergism between natural and anthropogenic forcing has often been related to the coral bleaching phenomenon, with anthropic forcing being responsible for increasing the frequency and intensity of bleaching events (Westmacott *et al.*, 2000; Allemand *et al.*, 2004; Castro & Zilberberg, 2016; Garrido *et al.*, 2016). Aiming to contemplate the effects of this synergy, the proposed model identified Abrolhos reef areas that are more susceptible to coral bleaching phenomena incorporating global (climatic) and local (anthropogenic) forcings.

Local anthropogenic stressors such as proximity to urban areas, waterways, harbors, tourism, and overfishing make reefs more fragile to environmental disturbances by diminishing the resilience of the environment. However, the creation of marine protected areas is a management measure that seeks to preserve the state of equilibrium of the environment, favoring the maintenance of ecosystem resilience. Studies on the reefs of the Great Barrier Reef and the Caribbean indicate that reefs inserted in protected marine areas present higher rates of resistance and resilience to environmental disturbances (Mumby & Harborn, 2010; Mellin *et al.*, 2016). Therefore, the presence of the integral protection conservation unit (Abrolhos National Marine Park) may be protecting the Timbebas reefs, Parcel dos Abrolhos and archipelago reefs making these environments healthier with the prohibition of fishing, control of tourism and boat traffic and improvement in water quality.

It is important to emphasize that this is a management measure in order to decrease local stressors and thus increase the resistance and resilience of the reef ecosystem when compared to a more degraded reef. However, this measure does not protect corals from the direct effects induced by the climate (Hughes *et al.*, 2003; Knowlton & Jackson, 2008), that is, the management does not prevent the bleaching that is triggered mainly by thermal anomalies. However, it may result in fewer affected coral colonies than fragile environments suffering from climatic and anthropogenic disturbances (Mellin *et al.*, 2016). An example of this is the study by Hughes *et al.* (2017) conducted on Australia's Great Barrier Reef in 2016 which revealed that the effect of marine protected areas was canceled by the strong coral bleaching event that occurred in 2016 in Australia. This is the reason why our study can contribute to policy making bringing empirical results that can shed light on the discussion of the concession of natural resources exploitation in Abrolhos. Our results show that Timbebas reefs protected by Marine Protected areas present lower susceptibility to bleaching even in the presence of anthropogenic variables in its vicinity. Although we acknowledge limitations of our approach (namely the coarse resolution of some variables) and the lack of data to build a data driven spatially explicit model (for example using weights of evidence Bonham-Carter 1994) we do believe this expert driven approach (including the sensivity analysis) fulfilled the goals of this work. We also aknowledge that other variables such as tourism pressure, diseases and specific species susceptibility are important variables but not yet available. Those may be incorporated into the model in the future.

The coral bleaching events recorded so far in Brazil were always less intense than in regions such as the Caribbean and North Atlantic (Leão *et al.*, 2008; Leão *et al.*, 2016) and, unlike the high coral mortality rates in these regions, Brazilian corals so far have always recovered after bleaching events. The high turbidity of Brazilian waters that reduces the intensity of the radiation reaching the corals and the lower intensity of the thermal anomalies, probably, favored the lower impact of these events on the corals (Kikuchi *et al.*, 2010; Leão *et al.*, 2016). Therefore, due to the lower intensity of the bleaching phenomenon in Brazil, it is possible that protected marine areas may be favoring the resilience of protected reefs by providing an ecosystem more similar to their steady state when compared to a degraded reef.

The model shows that the spatial pattern of susceptibility to coral bleaching in the Abrolhos reef complex is greater in coastal arch reefs than in outer arch reefs, with the exception of the Timbebas reefs. This spatial pattern of susceptibility to bleaching agrees with the field data of Kikuchi *et al.* (2010) in the years 2001 and 2003. The spatial pattern is mainly due to higher thermal anomalies in these reefs than in the outer arch reefs as shown in Table 4 and by the anthropogenic variables as shown in Table 5. Several experiments and modeling (Maina *et al.*, 2008; Krug *et al.*, 2013; Hughes *et al.*, 2017; Lisboa *et al*., 2018) have shown thermal anomalies as the main direct cause of bleaching in coral tissues. In the years 2001, 2003, 2005 and 2016, the accumulated thermal anomaly was markedly higher in coastal arch reefs than in outer arch reefs. In 2002, the model did not present the real spatial distribution of coral susceptibility to bleaching. The model is based, mainly, on the influence of water temperature on the triggering of coral bleaching. In that year, Abrolhos presented very low accumulated thermal anomaly (between 3.62°C and 4.46°C) when compared to records from other years, hampering the simulation of the real susceptibility in 2002.

Parcel das Paredes reefs presented the highest levels of susceptibility in all simulations conducted in this study. Despite shortage of available field data, those are frequently the reefs of the Abrolhos reef complex with the highest percentages of bleached coral colonies. In addition to the fishing exploration carried out in Parcel das Paredes reefs, other local stressors such as proximity to urban areas, presence of tourists and boats and sedimentation contribute to the fragility of these reefs.

The temporal variation of bleaching susceptibility seems to be explained by intensity of environmental variables (thermal anomaly (Kruskall-Wallis, $H(4) = 37.007$, $p = 0.000$); maximum sea surface temperature (Kruskall-Wallis, $H(4) = 39.262$, $p = 0.000$); maximum photosynthetically active radiation (Kruskall-Wallis, $H(4) = 35.865$, $p = 0.000$) and minimum wind magnitude (Kruskall-Wallis, $H(4) = 36.728$, $p = 0.000$), with a clear difference among the years (2001, 2002 and 2003) who presented low percentage of bleaching (less than 20%) and the years (2005 and 2016) that presented high percentage of bleaching.

There is a marked intensification of accumulated thermal anomaly and maximum sea surface temperature among the years with the least susceptibility to bleaching (2001, 2002 and 2003) and the years of greatest susceptibility (2005 and 2016). The highest values of accumulated thermal anomaly (33.57°C) and maximum sea surface temperature (29.27°C) wich favored bleaching events were recorded in 2016 during the third global coral bleaching event. The lower magnitudes of the wind, which also favor the coral bleaching process, were also recorded in 2005 (3.41 $m.s^{-1}$) and 2016 (3.22$m.s^{-1}$). The photosynthetically active radiation presented little temporal variation, being slightly higher in the years 2005 and 2016.

The proposed scale of susceptibility indicated that 2002 was the year in which Abrolhos reefs were less susceptible to coral bleaching with 82% of the reef area presenting low susceptibility to bleaching. The low susceptibility in this year is mainly explained by the lower sea surface temperatures that occurred in 2002. In 2016, during the third global coral bleaching event, 81% of the Abrolhos reef area presented high susceptibility, mainly due to the intensity of the thermal anomalies of the water superior to the other years used in the study. The higher levels of susceptibility among the years used in the study suggest a higher percentage of bleached colonies, which is corroborated by the fact that this year was considered by NASA and NOAA as the hottest year since 1880 (NASA, 2017).

Abrolhos reefs have favorable characteristics against of climate change, as they are historically more resistant than other major reefs in the world. In addition, the reefs indicated by the model as less susceptible to bleaching are protected by Abrolhos National Marine Park (Timbebas, Abrolhos archipelago and Parcel dos Abrolhos reefs) that may be making them more resilient to environmental disturbances such as coral bleaching. These reefs were also frequently influenced by the lower thermal anomalies when compared to the other reefs of the Abrolhos reef complex. Therefore, since the management of local anthropogenic forcing does not alter the climate change scenario, but may increase the resistance and resilience of corals, improving the efficiency of Abrolhos National Marine Park is fundamental. This result builts in favor of maintenance of the protected status instead of supporting resource concessions as was raised in 2019. The improvement of the efficiency of marine protected areas stimulating sustainable tourism activities, environmental education, controlling of illegal fishing and deforestation as well as planned coastal occupation are measures that must be considered by decision makers in order to guarantee the conservation of reef environments.

5. Conclusion

Coral reefs suffer many threats, including coral bleaching, which occurs mainly in response to environmental variables such as positive temperature anomalies. However, there is a need to explore potential synergies between environmental and anthropogenic variables. Given the estimates of average ocean temperature rise for the year 2100, the importance of reducing anthropogenic impacts on coral reefs is evident. Because of the proven synergistic relationship between global and local forcing reducing anthropogenic pressure can favor the resistance and resilience of these marine ecosystems to coral bleaching events. This work inovativelly used both environmental and antropogenic variables for modeling susceptibility of Abrolhos reefs to coral bleaching.

The model proved to be effective in spatially differentiating coral susceptibility to bleaching in years in which sea surface thermal anomaly was high and presented spatial variation across the reefs. In years with low thermal anomaly and little spatial variation across the reefs such 2002, the model did not faithfully estimated bleaching. Further work is required for exploring which other set of variables better explain susceptibility to bleaching in this situation. However, the model correctly estimated the lowest susceptibility to coral bleaching in this year.

One of the major problems in need to overcome is to find data available to faithfully estimate susceptibility to bleaching. Bleaching data are scarce and satellite images do not have appropriate resolution to model susceptibility to bleaching in relatively small reef areas such as Abrolhos. As soon as more field data are published, it will be possible to carry out the validation of the model and, thus, to develop simulations of future scenarios. Despite the data constraints this work is innovative in spatially differentiate susceptibility of bleaching within a reef complex.

The inclusion of variables such as specific susceptibility of different coral species, intensity of tourism, occurrence of diseases, among others, may improve the efficiency of the proposed model. This research calls for investment in new forms of continuous reef monitoring and development of simulations of possible future scenarios in this area. These can guide actions that diminish the anthropogenic impacts and increase the resilience of Abrolhos corals to global environmental change.

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