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Spatial modelling of *Acropora muricata* and *Porites lutea* distribution using environmental descriptors across Lakshadweep–Chagos Archipelago

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ABSTRACT

Globally, climatic and anthropogenic forcings are causing the catastrophic decline of coral reef ecosystems, which sustain a plethora of marine life and support the livelihoods of several millions of people. Lakshadweep–Maldives–Chagos archipelago (LMC) forms one of the largest chains of atoll systems in the world, and due to remoteness from the mainland, its islands boast a unique set of flora and fauna. The coral reefs of these tropical islands are highly vulnerable to stressors such as climate change, overfishing, monsoon runoff, and ocean acidification. To understand and manage these sensitive ecosystems, knowledge about the existing coral cover and distribution patterns are essential. In the present study, habitat modelling of the two corals *Acropora muricata* (Linnaeus, 1758) and *Porites lutea* (Milne Edwards & Haime, 1851) were carried out using the Maximum Entropy (MaxEnt) model to predict the probability of occurrence using remotely sensed environmental variables as predictors. The average test AUC values of 0.980 and 0.974, respectively, for *A. muricata* and *P. lutea* as estimated by MaxEnt shows that the model performance for both the species is outstanding. The average uncertainty (standard deviation) was about 0.012 and 0.021 respectively. It is found that the bathymetry is the variable having the highest contribution followed by Calcite and Phosphate for the distribution of both the species. The results of this study throw light on the probable occurrence of coral reefs in many of the hitherto unknown areas, especially the submerged banks and seamounts in the region. Much of these areas are less explored and have strategic positional advantages in increasing the ecosystem connectivity of the region. Furthermore, the relationship between coral distribution and the environmental variables as predicted by this study will be valuable in future conservation activities and designing marine protected areas.

1. Introduction

Globally, coral reefs are one of the most productive and diverse marine ecosystems, and they support 0.5 million species approximately (Spalding et al., 2001). Yet, they are highly sensitive to climatic change, anthropogenic stressors (Paulay, 1997; McClanahan et al., 2007; Wild et al., 2011) and are currently experiencing large-scale transformations (Bruno and Selig, 2007; Paddack et al., 2009). Extensive bleaching episodes reveal that coral reefs are expected to be one of the first ecosystems damaged by climate change (Hayes and Goreau, 1991). As a response to this crisis, governments around the world have developed various reef conservation initiatives (Mora et al., 2003; Bellwood et al., 2004; Hughes et al., 2017). There are numerous coral reef survey programmes which evaluate the reef status worldwide to facilitate proper monitoring. Reef Check and Coral Watch falls into those global categories of initiatives while the monitoring at regional level is catered by programmes like CORDIO (Coral Reef Degradation in the Indian Ocean) (Obura et al., 2008), CARICOMP (Caribbean Coastal Marine Productivity Program) and AGRRA (Atlantic and Gulf Rapid Reef Assessment). The data obtained from such sources assist efforts like GCRMN that provide reports on global status of coral reefs in every two years from 1998–2008 (Wilkinson, 1998, 2000, 2002, 2004). However, high spatial variability of the occurrence of different corals limits our conservation efforts (Foo and Asner, 2019). Proper knowledge on the current extent of coral reefs is essential to understand the actual impact of stressors and undertake any conservation interventions, including protection and resilience-based management.

The LMC Archipelago is one of the largest atoll reef systems of the world (Wilkinson, 2000). They are true atolls, formed on the peaks of the underwater Lakshadweep–Chagos volcanic ridges

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and spread across the geopolitically separate clusters viz., Lakshadweep (Laccadive), Maldives and Chagos islands (Woodroffe, 2008). The WWF categorized this region as a vulnerable marine priority ecoregion after considering its species richness, endemic species, unusual higher taxa, unusual ecological or evolutionary phenomena, and the global rarity of habitats (Olson and Dinerstein, 1998). At the same time, this area is predicted as highly vulnerable and will face frequent catastrophic bleaching events shortly (Vivekanandan et al., 2009).

The LMC ridge has numerous atolls, submerged reefs and seamounts, and there is a high chance of identifying coral reefs in addition to what is currently known. Even though published information on coral diversity and taxonomy from the LMC region are plenty (Shepard and Wells, 1988; Pillai and Jasmine, 1989; Rajasuriya et al., 2004; Kench et al., 2005; Benzoni and Pichon, 2007; Jeyabaskaran, 2009; Sheppard et al., 2012; Jaleel, 2013; Sreenath et al., 2015), those devoted to their spatial distribution are scanty. The remoteness of the islands, the large spread, higher cost involved, and the submerged banks make it difficult for studying the extent of the reefs in this region. In such instances, species distribution models (SDM) comes in handy (Davies et al., 2008; Tittensor et al., 2009; Krigsman et al., 2012; Huff et al., 2013; Guinotte and Davies, 2014). Earlier, the range of coral reef distribution at restricted geographic areas were investigated by few researchers with the aid of methods based on satellite imagery (Bahuguna and Nayak, 1994, 1998); (DOD & SAC, 1997). The statistical tools like SDMs serve to predict the hitherto unknown habitats of different species based on their relationship with the environmental variables of known occurrences (Tittensor et al., 2009; Guisan et al., 2013; Rengstorf et al., 2013; Franklin et al., 2013; Freeman et al., 2013). The present work aims to predict the spatial distribution of two commonly occurring corals in the region, the *P. lutea* (Milne Edwards and Haime, 1851) and *Acropora muricata* (Linnaeus, 1758) across the LMC Archipelago using a Maximum Entropy model. The resultant models are produced as probability coverage maps for the study area. We hope that studies like this can trigger in situ investigations for reef communities in the region which is characterized by large numbers of submerged mounts and related topography. Further, as seamounts are known to attract benthopelagic species for feeding and spawning, often facilitated by the presence of patchy coral communities (Althaus et al., 2009) prediction and further validation of the existence of such sites can improve the conservation efforts in the region.

2. Methods

2.1. Study area

LMC Archipelago covering the coordinates 65° E, 15°N, 75°E, 5°S (Fig. 1) forms the study area. The ridge is composed of three main segments *viz*., Laccadive Islands (Lakshadweep) in the north, Maldives islands in the middle and Chagos islands down south. Lakshadweep is a group of twelve atolls named Kavaratti, Kalpeni, Agatti, Chetlat, Bitra, Kiltan, Kadmat, Amini, Bangaram, Suheli, Minicoy, Androth and three reefs named Baliapani, Cheriapani, Perumal Par and five submerged banks named Bassas de Pedro, Sessostris, Coradivh, Investigator Bank, & Elikalpeni Bank in the Lakshadweep Sea. The Maldives with a double chain of 22 atoll coral reefs extends from Ihavandhippolhu in the north to Addu atoll on 0.65° S latitude. It has 1200 reefs (Kench, 2012). They are unique in terms of their biodiversity, reef structure and evolutionary mode (Kench, 2011). Chagos islands are part of British Indian Ocean Territory and have seven atolls and 50 islands. A dozen more are submerged to a depth of six to twenty-five metres (Sheppard et al., 2012). This area is selected for the study as it had a higher incidence of corals and several underexplored benthic features that seem suitable for coral growth.

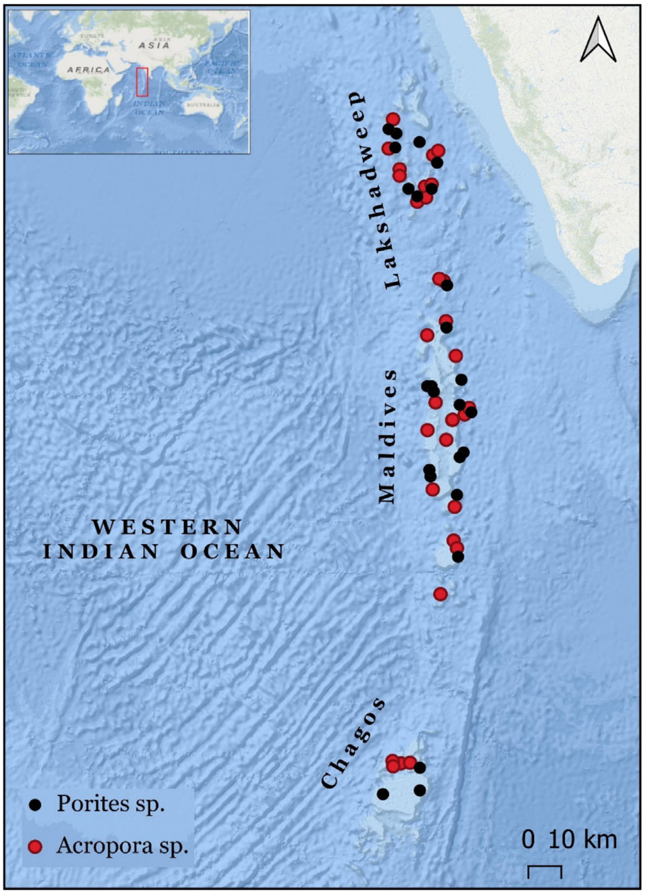


Fig. 1. Map of the Lakshadweep–Chagos archipelago with occurrence points of *A. muricata* and *P. lutea*.

2.2. Data on hard corals occurrence and environmental variables

Two of the dominant coral species in the LMC region, *viz. A. muricata* and *P. lutea* were selected for the study. Presence-only data of their current distribution were collected and compiled from the Global Biodiversity Information Facility (GBIF) database. As the collinearity among variables may overfit the model and mislead further research, we performed the Pearson' correlation analysis for avoiding the correlated variables (Supplementary data). The Jackknife analysis (Pearson et al., 2007) is used to quantify the contribution of each environmental parameter on the distribution of hard corals in the current study area. The 13 environmental covariates selected were Mean Sea Surface Temperature (SSTmean), Maximum sea surface temperature, (SSTmax), Sea Surface Salinity (SSS), Chlorophyll-a, Bathymetry, Ocean current, Photosynthetically Active Radiation (PAR), Euphotic depth, Calcite, Phosphate, Nitrate, Diffusion attenuation coefficient and distance from the shore. The remotely sensed annual climatology data of SSTmean and SSTmax were derived from MODIS-Aqua (Moderate Resolution Imaging Spectroradiometer (EOS PM) satellite) with a spatial resolution of 2 arc-minutes, provided by NASA (https://oceancolor.gsfc.nasa.gov/). SSS data of Simple Ocean Data Assimilation ocean/sea-ice reanalysis (SODA) (Carton et al., 2018) of 14 arc-minute were utilized. The gridded bathymetric data of 30 arc-seconds were obtained from GEBCO (General Bathymetric Chart of the Ocean) Global ocean & land terrain models hosted by the British Oceanographic Data Centre (BODC). The chlorophyll-a data at two arc-minute spatial resolution was taken from the Ocean colour web database. Ocean current data of 5 arc-minute

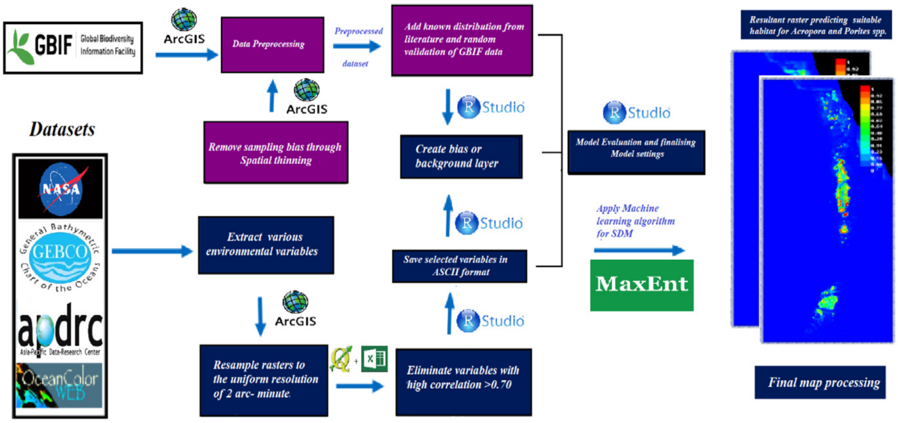


Fig. 2. Schematic representation of methodology.

spatial resolution was taken from HYCOM Global (Bleck, 2002). The monthly climatology data of Photosynthetically Active Radiation (par) (5 arc-minute spatial resolution) was taken from Bio-Oracle (Tyberghein et al., 2012). The gridded data of euphotic depth with a resolution of 2 arc-minute was taken from Globcolour (http://globcolour.info) database. The Calcite, Phosphate, Nitrate, Diffusion attenuation coefficient (kd) and distance from the shore data with a spatial resolution of 5 arc-minute were collected from GMED (Global Marine Environment Datasets, version 2.0) (Basher et al., 2018). Using ArcMap (version 10.0), each variable was reprojected to GCS_WGS_1984 coordinate system, clipped to the same extent and were resampled using advanced spatial technique tool like Inverse Distance Weighting (IDW) interpolation to get the uniform resolution of 2 arc-minute (Peterson et al., 2011). The rasters were finally converted into ASCII using conversion tools in ArcMap (Fig. 2).

2.3. Predicting hard coral distributions

Maximum Entropy (MaxEnt) model, a technique that uses the presence-only data to predict the distribution of a species employed in Maximum Entropy modelling software Version 3.4.1 (Phillips et al., 2006) was used to predict the hard-coral distribution. MaxEnt is a machine learning method for modelling the geographic distribution of species as a function of the predictor environmental variables at a grid. To reduce the bias in the samples, a background raster was created using ArcGIS and used in the model. To develop the SDM, we utilized the maxEnt function included in the R version 1.1–4 of the dismo package (Hijmans et al., 2017). The model settings were finalized using ENMeval function of the ENMeval package (Muscarella et al., 2014), which provides species-specific configurations for model selection, such as a combination of feature classes like L, LQ, H, LQH, LQHP, LQHPT (L - linear, Q - quadratic, H - hinge, P - product, & T - threshold) with regularization multiplier (ranging from 0 to 4) values. Various models compared during the iteration process to identify the best model with the lowest value of Akaike's Information Criterion corrected for small sample sizes (AICc). (Muscarella et al., 2014). The regularization multiplier (ß) function helps to prevent the overfitting of data (Phillips, 2008). The sub-sampling method was used for the replication as it did not encourage the inclusion of noise variables and was proven to produce a stable model (Meinshausen and Bühlmann, 2006, 2010). The occurrence points will continuously split into training and testing subsets. The random training percentage was kept at 75%, whereas 25% of the occurrence data were utilized for testing the model, which reduce the bias when using the single set of points from the entire model results.

The area under the curve (AUC) describes the accuracy of the model (Fielding and Bell, 1997; Phillips et al., 2006), especially those using presence-only data (Stockwell and Peters, 1999). But the value of AUC could be lowered for the species having wide distribution due to the increase in their commission. (Lobo et al., 2008). The AUC provides a general view about the distribution of species based on the environmental conditions. So, it cannot be considered as the best measure of model performance (Velasco and González-Salazar, 2019). The value of sensitivity vs. 1-specificity, between 0 and -1 indicates that the model performance was no better than random, while values close to 1.0 indicate better model performance or predictability (Lobo et al., 2008).

3. Results

3.1. Model outputs and environmental predictors

3.1.1. Model evaluation

The sensitivity vs. 1-specificity graph (Fig. 3) represents the area under the Receiver Operating Characteristic (ROC) curve or AUC. The average test AUC values of 0.980 and 0.974, respectively, for *A. muricata* and *P. lutea*, as estimated by MaxEnt shows that the model performance for both the species is outstanding. The average uncertainty (standard deviation) was about 0.012 and 0.021, for *A. muricata* and *P. lutea* respectively.

3.1.2. The contribution of predictor variables

MaxEnt shows the contribution of each predictor variable to the model through the jackknife of regularized training analysis (Fig. 4) and percentage contribution tables (Tables 1 and 2). Among the predictors (Tables 1 and 2), bathymetry showed the highest percentage contribution of 72.4% and 74.3% for *A. muricata* and *P. lutea* respectively, emphasizing the role of bathymetry in the distribution of hard corals. The next variable having major contribution is Calcite with 9.9 & 9.8%, followed by phosphate (7.4 & 7.2%). SSTmax and ocean currents (0 & 0% respectively) became the least influencing parameters in this model for *A. muricata* whereas, for *P. lutea*, it was the distance from the shore and ocean current (0.4 & 0.0% respectively). The Jackknife of regularized training shows the influence of each variable on the *A. muricata* distribution as well as provide the total predictor performance when this particular variable is removed. While considering the contribution of each variable separately, the bathymetry, calcite, and euphotic depth has major roles while the salinity had a minor influence on the distribution of *A. muricata*. In the case of *P. lutea,* bathymetry, calcite, euphotic depth, chlorophyll-a, and distance from shore have a higher contribution whereas ocean currents and nitrate have the least influence.

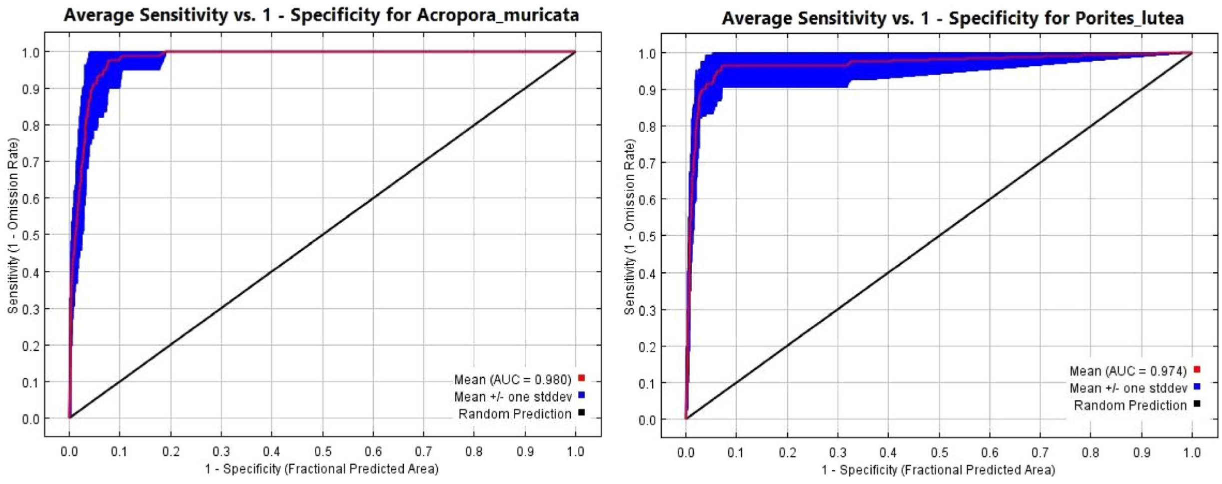
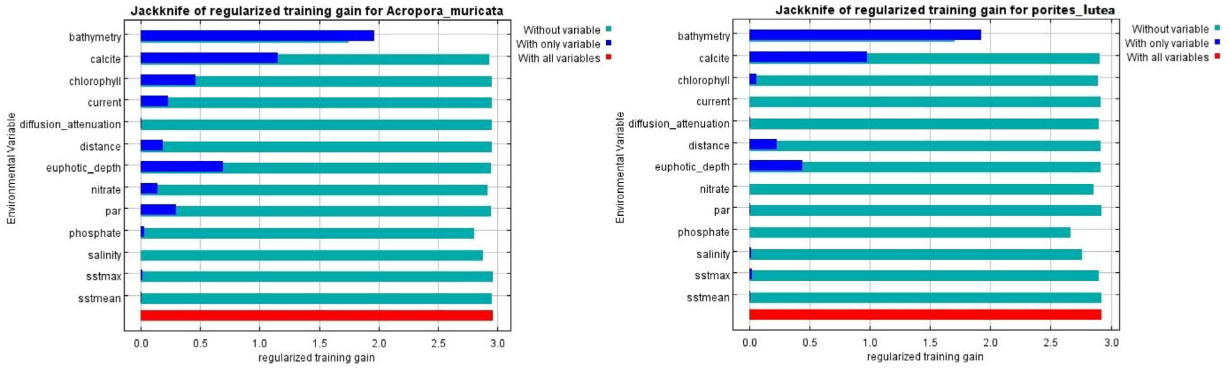


Fig. 3. The Average Sensitivity vs. 1 - specificity graph of the model output showing mean AUC of model replicas as well as mean standard deviation (blue).



(a) (b)

Fig. 4. Jackknife analysis for *A. muricata* and *P. lutea* showing the regularized training gain when a single variable was used to develop the model (blue bars) or excluded from the modelling process (Turquoise bars). This process of inclusion and exclusion isolates the contribution of each predictor variable from the other variables and describes whether a particular variable improves or degrades the performance of a model. The red bar represents the regularized training gain when all variables are considered together.

Table 1
The relative contribution of Variables of *A. muricata*.

Variable	Percent contribution	Permutation importance
bathymetry	72.4	83.7
Calcite	9.9	3.5
phosphate	7.4	1.9
chlorophyll	3.8	0.6
diffusion_attenuation	3.3	0.3
Sstmean	3	0.1
Salinity	2.5	1.6
Nitrate	2.3	0.9
Par	0.7	0.2
Distance	0.7	0.2
euphotic_depth	0.5	0.4
Current	0	0.2
Sstmax	0	0

Table 2
The relative contribution of Variables of P. lutea.

Variable	Percent contribution	Permutation importance
bathymetry	74.3	86.4
Calcite	9.8	0.8
phosphate	7.2	1.6
Salinity	7.1	1.7
Sstmean	3.6	0
diffusion_attenuation	2.9	2.7
Sstmax	2.7	0.7
euphotic_depth	2.4	0
par	2.1	0.1
Nitrate	1.8	0.5
chlorophyll	0.5	0.4
Distance	0.4	0
Ocean current	0	0

3.2. The predicted distribution of the coral species studied

The predicted distribution maps were created by spatially averaging the 10 model replicates for both species. Habitat suitability ranging from high to low for *A. muricata* and *P. lutea* were represented in the maps by colour coding progressing from red to yellow. The red shade implies maximum suitability for coral distribution, whereas yellow represents the least. In addition to the well-studied reef systems of the British Indian Ocean Territory (Chagos), the five southern submerged banks show low to high abundance of *A. muricata* along with the Wight bank and Pitt bank (Fig. 5). These mounts have their peaks at depths ranging from 7 to 53 m. The submerged mounts including Colvocoresses reef, Blenheim reef, Solomon Islands, and Victory bank located between the Chagos bank and Speakers bank are also predicted to be highly suitable for *A. muricata.* However, there are prominent variations in the predicted distribution of *P. lutea* (Fig. 6) in these

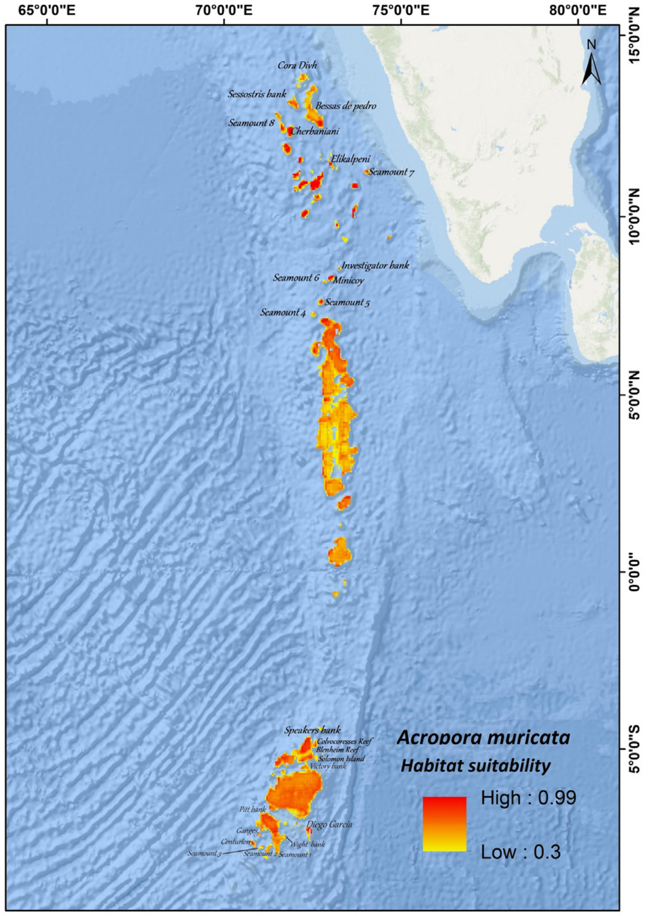


Fig. 5. The map shows the predicted probability of occurrence of *A. muricata* along Chagos Lakshadweep Archipelago.

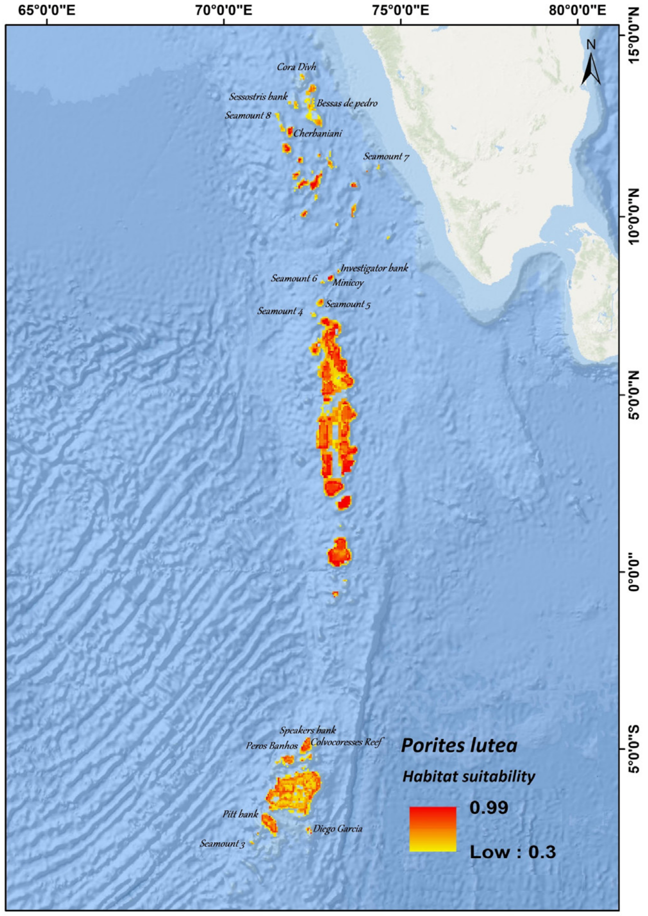


Fig. 6. The map shows the predicted probability of occurrence of *P.lutea* along Chagos Lakshadweep Archipelago.

regions. It has medium to high suitability (50%–90%) in Wight bank, Pitti bank, Blenheim reef, Salomon Islands, Victory bank, and Speakers bank. Though the Maldives have a higher percentage (75%–99%) of suitability for *P. lutea*, the total expanse of suitable areas were relatively less than that for *A. muricata* which has more suitable areas in these well-explored reefs. Remarkably, the northern islands of Maldives are predicted to have a better *A. muricata* presence with 70 to 90% probability than the rest of Maldives. Low to high abundance is predicted for *A. muricata* in three of the submerged banks including Investigator bank (10° 55' 22.4" S, 98° 20' 33.1" E) situated near Minicoy island. These mounts have their minimum depths ranging from 8 to 85 m. In Lakshadweep group of islands, the seamounts named Bessas de Pedro, Cora Divh and Sessostris bank show lesser suitability for *P. lutea* (40%–50%) but for *A. muricata* more incidence (60%–90%) is predicted in these regions. An unnamed seamount situated to the northwest of Cherbaniani island is also predicted to have greater suitability for A. *muricata*. The Elikalpeni bank, at a depth of 10 m, and an unnamed seamount in its proximity shows higher suitability for *P. lutea* (50%–70%) and *A. muricata*. These mounts have minimum depths ranging from 10 to 35 m. The rest of the Lakshadweep islands are found to be highly suitable for both species.

4. Discussion

The LMC ridge has several seamounts and submerged banks that are difficult to access due to their oceanic nature. The bottom relief of the Lakshadweep–Chagos region is highly undulated with numerous volcanic seamounts on the ridge. The present study unveils a greater probability of coral distribution in these hitherto unexplored seamounts and the less-studied Wight bank in Chagos. Chagos has a sublittoral photic zone of about 60,000 km^2, where the extent of active reef area has been uncertain and 95% of which has not been fully explored (Dumbraveanu and Sheppard, 1999). Yesson et al. (2012) mapped the global distribution of cold-water octocorals using bathymetry and satellite data. They suggest that more than 65,000 square kilometres of British Indian Ocean Territory is suitable for at least one of the octocoral suborder species of concern (Alcyoniina, Calcaxonia, Holaxonia, Scleraxonia, Sessiliflorae, Stolonifera and Subselliflorae) and about 10,000 square kilometres are seemed to be suitable for all suborders. Our model assessed the occurrence possibilities of two species of corals and the environmental parameters that can influence their distribution in these regions:

Bathymetry

It is evident from the results that the most important variable which influences the distribution of both *A. muricata* and *P. lutea* is their depth of occurrence or bathymetry (Tables 1 and 2). It is a well known fact that the hard corals are mostly found in the photic zone as the symbiotic zooxanthellae need solar radiation for photosynthesis and hence the depth of occurrence must have a major influence on its distribution. The abundance of zooxanthellate scleractinian corals diminish with depth past 20–40 m, depending upon the clearness of the water (Muscatine and Porter, 1977). However, the deepest zooxanthellate scleractinian corals were discovered at around 100 m underneath the tropical waters (Englebert et al., 2014). The recovery of reefs in the Chagos after the 1998 bleaching event was higher than anywhere else in the Indian Ocean (Sheppard et al., 2012). This phenomenon can be validly correlated to the presence of corals under varying depths in the surrounding submerged banks where the bleaching event had a minor or no impact at all, which in turn might act as a source of coral larvae to re-establish in the bleached zones.

Nutrients

The scleractinian larvae which are dispersed by way of ocean currents to suitable areas, colonize and establish reefs based on the availability of nutrients like calcite and phosphate. These two nutrients were among the important variables influencing the occurrence of corals as indicated by our model output. Phosphate is a nutrient that is required for the growth and development of corals (Rosset et al., 2017), even though it has both positive and negative effects. In our study, the value of phosphate across the study area ranged from 0.01686 to 0.3562 mgL^{-1}. The average concentration of phosphate in the natural reef ecosystem is reported from 0.01 mgL^{-1} (Kleypas et al., 1999) to 0.266 mgL^{-1} (Cruz-Piñón et al., 2003). The influx of effluents from coastal areas increases the concentration of nutrients like phosphate in the coastal waters and may thereby decline the coral growth. The increased concentration of phosphate seems to affect the growth rate, skeleton density, mortality, and zooxanthellae density of the corals (Dunn et al., 2012).

SST and SSS

When compared to the established knowledge that SST and SSS have a profound influence on the coral distribution (Ferreira et al., 2013; Tierney et al., 2015; Lenderink, 2016; Pretet et al., 2014), our model has shown a comparatively lower contribution of these variables. This can be attributed to the fact that the study area is distributed in the same belt of the tropics and does not have a wide gradient of SST and SSS.

Chagos is the largest no-take pristine region in the world with more than 550,000 km^2 area covered by a group of 55 low lying isolated islands (Hamylton and East, 2012). Diego Garcia, the southernmost inhabited atoll in Chagos is one among the world top five 'most vulnerable' military installations and is also highly susceptible to climate change (Sheppard et al., 2017). One of the reasons for its scientific importance is the lack of population and human impacts, though the alterations happening on the reefs usually have a direct link with environmental predictors (Sheppard et al., 2012). The predicted distribution in this study shows more presence of coral reefs along the submerged seamounts of Chagos due to its elevation and environmental suitability. Sheppard et al. (2013) emphasized the importance of Chagos coral reefs to act as a genetic linkage by permitting the transport of marine species such as coral larvae between Western Indian Ocean and Indo-Pacific province through the equatorial current and south equatorial counter current. Hence, the knowledge of a wide area of coral distribution will enhance the understanding about the role of these reefs in coral connectivity.

At the Maldives, the present study indicates a considerably wider range of habitat suitability for *A. muricata* and *P. lutea*. Apart from the unexplored seamounts and submerged banks, distribution is also predicted in much wider areas in the other atolls than what is currently known to us. Though several isolated efforts are being done to survey the reefs, overall explorations on the coral coverage from the entire Maldives is less. Raghuraman et al. (2013) have reported that Maldives reefs have exhibited high variability in recovery after the 1998 bleaching in which the western atoll recovered faster than eastern with a coral cover less than 10% to above 8%. *Acropora,* which was the highly impacted genus during 1988 bleaching dominated in a survey in 2006 (Raghuraman et al., 2013).

The inhabited islands of Lakshadweep have been taxonomically explored for the presence of hard corals since the 1950s (Pillai, 1971,a,b, 1972, 1977, 1983). Lakshadweep consists of 12 atolls with 36 islands/islets, three reefs, and six submerged banks. The Lakshadweep islands comprise about 37 genera with 103 species of corals. The results of the current study give a considerable indication that the coral reefs are present in previously unexplored and unknown areas like the submerged banks of Cora Divh Bank, Bassas de Pedro Bank, Sesostris Bank lying in the northern latitudes and the low elevation seamounts sparsely distributed among other major islands. The presence of coral reefs in the northern seamounts were previously predicted using satellite image-based studies (Bahuguna and Nayak, 1998), which have emphasized the chances of occurrence of deepwater coral reefs in the region. Further explorations are yet to be performed at these locations.

Laccadive-Chagos ridge system is considered as a zone of transition between oceanic crust in the west and continental crust in the east. This study reveals the possibilities of *A. muricata* presence in previously unknown geographical areas like Cora Divh Bank, Bassas de Pedro Bank, Sesostris Bank, Investigator bank, Wight bank in addition to several unexplored seamounts. There are 47 marine protected areas (MPA) (one in Lakshadweep, 42 in the Maldives and entire Chagos have been proclaimed as a single MPA) (Sivakumar et al., 2014; Yesson, 2012) in the region. Baa atoll of Maldives is a UNESCO Man And Biosphere (MAB) reserve since 2009 (Payri et al., 2012). The present attempt is the first of its kind to predict hard coral distribution using modelling techniques in Lakshadweep Chagos Archipelago. MaxEnt method employed in the present study has successfully predicted a variety of species' occurrence (Jackson and Robertson, 2010; Papes and Gaubert, 2007; Saatchi et al., 2008; Mingyang et al., 2008; Suárez-Seoane et al., 2008; Carroll, 2010). As the coral reefs are very sensitive as well as an important source of ecosystem services, the distribution data will have remarkable applications. On the global scale, only 3.6% of the world ocean is considered as marine protected area and studies found only 2% of that have fully restricted access.

The Convention on Biological diversity put a baby step to secure a healthier ocean by protecting 10% of the global ocean by 2020 (Aichi Biodiversity Target 11). Here comes the importance of knowledge about unknown distributions of marine flora and fauna which helps to improve conservation efficiency. It is advisable to survey the less explored ecosystems identified herewith and consider them while enhancing the area under protection abiding by the Aichi Targets. Besides, these identified reefs might be playing an important role in the coral connectivity of the region. Lozano et al. (2013) emphasized the importance of considering such connectivity as a significant factor while selecting areas for MPA which in turn helps in making policy decisions as well as for marine spatial planning. While the technology has expanded human reach to the outskirts of the solar system, the potential of occurrence of such valuable and vulnerable ecosystems at a stone's throw must not be overlooked.

During a time when UN General Assembly has announced 2021–30 as the UN Decade for Ocean Science for Sustainable Development and a healthy and resilient ocean, in which the mapping of marine ecosystems are envisaged as one of its societal outcome (Ryabinin et al., 2019), many of the sensitive ecosystems such as coral reefs are yet to be explored and understood. Thus studies attempting at throwing lights on yet to discover reef systems gain significance in regional as well as global scale while undertaking connectivity studies and resilience-based policy initiatives.

Limitation of the study

The distribution model in this study is developed using limited number of available remotely sensed variables. As some of the predicted areas of occurrence are of higher depths than the current records, care should be taken to confirm this by performing underwater exploratory surveys before initiating any management actions.

CRediT authorship contribution statement

Anakha M.: Collection of data, Analysis of data, Presentation. **Sreenath K.R.:** Conceiving the idea, Guidance through the work. **Joshi K.K.:** Statistical Analysis, Helped in interpreting the results. **Shelton P.:** GIS mapping expert who has assisted in the final mapping. **Nameer P.O.:** Expertise in SDM, Guided through the MaxEnt modelling.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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