Herbivores on the plate: the growing fishing pressure on parrotfish

Natália Carvalho Roos

Natal,
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APRESENTAÇÃO

Os recursos pesqueiros marinhos possuem grande importância econômica, social e ecológica, pois além de comporem parte relevante da dieta proteica da população, ainda são responsáveis pela renda de inúmeras pessoas ligadas direta e indiretamente ao setor pesqueiro em todo o mundo (Diegues, 2000; Gasalla, 2004).

Grande parte dos bens e serviços marinhos essenciais para as populações costeiras do mundo advêm dos ambientais recifais. Porém, o aumento no número de embarcações, a diversificação das artes de pesca e as melhorias das tecnologias de captura, somado ao aumento populacional e à maior demanda por pescado nas últimas décadas (FAO, 2006) tornaram estes ecossistemas uns dos mais afetados pela ação humana, os quais sofrerem efeitos em cadeia com a perda de funções ecológicas essenciais (Hughes, 1994; Bellwood et al., 2004).

Uma série de processos-chave já foram identificados como fundamentais para a estruturação dos ambientes recifes, como predação, herbivoria e recrutamento de peixes, invertebrados e corais (Caley et al., 1996; Bellwood, et al., 2004; Dulvy et al., 2004). Muitos peixes desempenham vários destes processos, como por exemplo, os budiões (Labridae: Scarini), que estão entre o grupo de peixes herbívoros mais dominantes dos ambientes recifais tropicais e subtropicais do mundo, tanto em termos de abundância como de biomassa (Choat e Randall, 1986; Francini-Filho e Moura, 2008). Este grupo de peixes herbívoros controlam o crescimento de algas, mantendo a resiliência e diversidade dos recifes de corais (Hughes, 1994; Mumby et al., 2007).

Infelizmente, a pesca de peixes herbívoros cresceu nas últimas décadas em todo o mundo, e a explotação de grupos funcionais como os budiões vem causando mudanças significativas nos ecossistemas recifais (Lokrantz et al., 2010). Um dos principais motivos para o aumento da procura destes peixes é a depleção dos estoques de peixes de níveis tróficos mais altos, como os das famílias Epinephelidae e Lutjanidae, que levam ao aumento da procura de peixes de níveis tróficos mais baixos, como os budiões. Este processo é chamado de *fishing down marine food webs* (Pauly et al., 1998).

No Brasil, apesar da pesca direcionada aos budiões ser relativamente recente, várias espécies deste grupo veem sendo amplamente explotadas, como é o caso do gênero *Sparisoma*. A espécie *Scarus trispinosus*, endêmica e considerada o maior scarídeo brasileiro, é atualmente classificada como Ameaçada de Extinção pela IUCN, na categoria em “em perigo” (Ferreira et al., 2010). Além disso, dados recentemente publicados na Lista Nacional Oficial de Espécies da Fauna Ameaçadas de Extinção (Portaria nº 445 de 17 de dezembro de 2014), incluíram cinco espécies de scarídeos das quais quatro são alvos de pesca, e destas, três fazem parte do presente estudo: *Sparisoma axillare* e
S. frondosum, classificadas como “Vulneráveis”, e Scarus trispinosus, classificada como “Em Perigo de Extinção”.

Dessa forma, entender como a pesca afeta as populações de peixes é fundamental para desenvolver estratégias de manejo pesqueiro que visem minimizar os efeitos da pesca, tanto a curto prazo, como a diminuição dos estoques, quanto a longo prazo, como mudanças na história de vida das espécies (McClanahan e Mangi, 2004; Mangi e Roberts, 2006; Campell e Pardede, 2006).

Além disso, entender a distribuição espacial das espécies marinhos é fundamental para a identificação de habitats essenciais (Manderson et al., 2002; Leite e Gasalla, 2013) e para o estabelecimento de áreas marinhos protegidas (Jones, 2002), como estratégias efetivas de manejo pesqueiro. Para os peixes recifais, isto possui uma importância particular devido à natureza fragmentada dos ambientes em que vivem (Saul, 2013).

Desta forma, os objetivos deste trabalho foram: (i) identificar habitats essenciais das espécies de budião no Brasil e desenvolver cenários espaciais probabilísticos e (ii) avaliar a seletividade e a pressão dos aparelhos de pesca sobre as espécies de budiões capturadas na APA dos Recifes de Corais do Rio Grande do Norte. Para isso, essa dissertação foi dividida em dois capítulos:

CAPÍTULO 1 – Modelando a distribuição espacial dos budiões (Labridae: Scarini) ao longo da costa brasileira.

Resumo

Os budiões (Labridae: Scarini) são peixes recifais herbívoros que desempenham papéis funcionais críticos em ambientes recifais, prevenindo o crescimento excessivo de algas e favorecendo o estabelecimento de corais. Alguns estudos sugerem que a pesca comercial está explotando grandes quantidades de budiões dos recifes brasileiros, causando mudanças significativas na estrutura das comunidades bentônicas. Especificamente, três espécies, Scarus trispinosus (Valenciennes, 1840), Sparisoma frondosum (Agassiz, 1831) e Sparisoma axillare (Steindachner, 1878) têm sido intensivamente capturadas na costa nordeste brasileiro. Apesar do interesse econômico e ecológico, pouco se sabe sobre o que afeta a ocorrência dessas espécies. Neste estudo, modelos hierárquicos Bayesionos espaço-temporais são utilizados para mapear a distribuição destas três espécies ao longo da costa do Brasil. Desembarques de três tipos de aparelhos de pesca (redes, arpão e linha) foram amostrados durante um ano, dos quais foram registrados abundância e informações geográficas das operações de pesca. Os resultados mostraram que habitats associados a águas mais quentes e profundas em baixas latitudes possuem maior probabilidade de ocorrência das três espécies. A produção primária mostrou-se positivamente relacionada apenas com S. trispinosus, que por sua vez é mais comum em áreas costeiras do S. axillare e S. frondosum. Finalmente, a variável pescador, tratada como um efeito aleatório, também mostrou ser um importante componente na captura das espécies, destacando a importância da associação entre o planejamento espacial marinho com o manejo pesqueiro para estas espécies ecologicamente importantes e vulneráveis.
CAPÍTULO 2 – Efeitos da seletividade dos aparelhos de pesca em espécies ameaçadas de budiões (Labridae: Scarini),

Resumo

Os efeitos da seletividade dos aparelhos de pesca na captura de budiões (Labridae: Scarini) foram avaliados dentro de uma Área de Proteção Ambiental no nordeste do Brasil. Alguns estudos sugerem que a pesca comercial está explotando grandes quantidades de budiões dos recifes brasileiros, causando mudanças significativas na estrutura das comunidades bentônicas. Especificamente, três espécies, Scarus trispinosus (Valenciennes, 1840), Sparisoma frondosum (Agassiz, 1831) e Sparisoma axillare (Steindachner, 1878) têm sido intensivamente capturadas na costa nordeste do Brasil. Apesar do interesse econômico e ecológico, poucos estudos avaliaram os efeitos da pesca sobre os budiões no Brasil. Neste estudo, os efeitos de diferentes tipos de aparelhos de pesca sobre a composição da captura, tamanhos e seletividade são examinados para estas três espécies. Desembarques de três tipos de aparelhos (redes, arpão e linha) foram amostrados durante um ano, e informações sobre cada operação de pesca e a frequência de tamanhos dos peixes capturados foram registradas. Os resultados mostram que as redes são os aparelhos menos seletivos, capturando uma grande proporção de indivíduos imaturos de S. trispinosus. Linha obteve o menor valor de captura por unidade de esforço (CPUE), capturando todos os indivíduos de S. axillare e S. frondosum acima do tamanho de primeira maturação. O arpão é o único aparelho de pesca que captura uma maior proporção de indivíduos maduros de S. trispinosus, mas necessita controles de manejo para evitar a captura de indivíduos imaturos bem como dos maiores indivíduos. Por este motivo, um slot de captura para este aparelho é sugerido. Este estudo também sugere outras medidas de manejo a fim de alcançar a sustentabilidade da pesca de budiões e evitar a sobrepesca bem como mudanças nas características de história de vida das espécies capturadas.

REFERÊNCIAS BIBLIOGRÁFICAS


Modeling sensitive parrotfish (Labridae: Scarini) habitats along the Brazilian coast.
Modeling sensitive parrotfish (Labridae: Scarini) habitats along the Brazilian coast.

Abstract

In coral reef environments, there is an increasing concern over parrotfish (Labridae: Scarini) due to their rising exploitation by commercial small-scale fisheries, which is leading to significant changes in the reefs’ community structure. Three species, Scarus trispinosus (Valenciennes, 1840), Sparisoma frondosum (Agassiz, 1831) and Sparisoma axillare (Steindachner, 1878), currently labeled as threatened, have been intensively targeted in Brazil, mostly on the northeastern coast. Despite their economic importance, ecological interest and worrisome conservation status, not much is known about which variables determine their occurrence. In this study, we adopted a hierarchical Bayesian spatial-temporal approach to map the distribution of these three species along the Brazilian coast, using landing data from three different gears (gillnets, spear guns, and handlines) and environmental variables (bathymetry, shore distance, seabed slope, Sea Surface Temperature and Net Primary Productivity). Our results identify sensitive habitats for parrotfish along the Brazilian coast that would be more suitable to the implementation of spatial-temporal closure measures, which along with the social component fishers could benefit the management and conservation of these species.

Keywords: Bayesian models, coral reef species, conservation, small-scale fishery, fisheries management.
Introduction

An ecosystem approach to reef fisheries should include the study of current and expected fishing impacts on exploited habitats in order to prepare efficient strategies for the conservation of the marine environment and, in particular, of its living resources. The approach should also include careful marine spatial planning of reef use to ensure the protection of the relevant habitats of key species (Katsanevakis et al. 2011). Therefore, it is a requirement to have a solid knowledge of species-environment relationships and to identify priority areas for conservation or management using a robust analysis based on the available information. In this regard, habitat and species mapping are important tools for conservation programs because they provide a clear picture of the distribution and the extent of these marine resources and their key species and thus facilitate management (Pennino et al. 2013).

Key species are the species that play important functional roles with significant consequences in the food web, including the persistence of other species (Bond 1994). They are not restricted to one level of the food chain, including predators and herbivores alike (Mills et al. 1993). In fisheries, top predators, some of which are considered key species, tend to get most of the attention, first from fishers and then consequently from researchers (Myers and Worm 2003; but see cases where fisheries start at lower trophic levels, especially in places where the targets are highly valued invertebrates; Tewfik and Béné, 2004). Usually other large-bodied species at lower trophic levels, such as reef herbivores, become new targets (Bender et al. 2014) when apex predatory fish species become economically unfeasible (Pauly et al. 1998).

It is then important to understand the consequences of not having this type of species in the environment anymore, especially if they are also key species, and to address management solutions for their exploitation. Herbivores play an important functional role in the ecosystem, especially in reef environments, and their role can be easily disrupted if their numbers go slightly down (Cheal et al. 2010), which is achievable even by relatively low fishing pressure. The overfishing of herbivores,
a more extreme situation, has been shown to simultaneously impact multiple ecosystem functions (Bellwood et al. 2012), resulting in several negative consequences for coral reef ecosystems (Lokrantz et al. 2009), including phase shifts and loss of resilience (Hughes et al. 2007; Mumby et al. 2007).

Parrotfish (Labridae: Scarini) are among the most notable and dominant group of herbivore fish in tropical and subtropical reef habitats around the world both in numbers of individual fish and in biomass (Choat and Randall, 1986; Francini-Filho and Moura 2008). This group of fish is classified into three functional groups, excavators, scrapers, and grazers (Streelman et al. 2002; Francini-Filho et al. 2008), and plays key functional roles in coral reef ecosystems (Hughes 1994; Bellwood et al. 2003). As consumers of benthic algae, parrotfish directly affect the structure and composition of benthic communities through the top-down control of macroalgae, which supports coral survival, growth, and recruitment (Mumby et al. 2006).

Fishing pressure on parrotfish has grown in the last decades around the world (Edwards et al. 2014). This increasing exploitation has taken place mainly in areas of decreasing catches of top predators (Ferreira and Gonçalves 1999), such as the Caribbean (Hughes 1994) and the southwestern Atlantic (Francini-Filho and Moura 2008; Bender et al. 2014). In Brazil, parrotfish have also been increasingly exploited (Francini-Filho et al. 2008) with many of them already showing signs of depletion (Bender et al. 2014). Some are emblematic species, such as *Scarus trispinosus* (Valenciennes, 1840), which in addition to being the largest Brazilian parrotfish is also an endemic species (Padovani-Ferreira et al. 2012). These large-bodied and long-living fish have become a favorite spearfishing target in the last decade, which explains its sharp population decline along the Brazilian coast (Floeter et al. 2006; Francini-Filho et al. 2008; Bender et al. 2014). The same fate has occurred with other large-bodied parrotfish in Brazil, such as the *Scarus zelindae*, *Sparisoma amplum*, *Sparisoma axillare*, and *Sparisoma frondosum* (Francini-Filho et al. 2008). Four out of these five species have recently been classified as vulnerable, including *Sparisoma axillare* and *S. frondosum*, while *Scarus trispinosus* has been listed as endangered in Brazil. Therefore, the economic interest in
their exploitation associated with the recent conservation concerns highlight the need to have basic information on parrotfish to guide conservation and management actions.

Our study aimed to identify sensitive habitats for three parrotfish species, the greenback parrotfish (Scarus trispinosus, Valenciennes, 1840), the agassiz’s parrotfish (Sparisoma frondosum, Agassiz, 1831), and the gray parrotfish (Sparisoma axillare, Steindachner, 1878), along the Brazilian coast and to develop probabilistic spatial scenarios as effective tools to support decision making within the conservation framework. Therefore, we analyzed data on the presence of these parrotfish in commercial fish landings in the Brazilian northeast. Using the hierarchical Bayesian spatial-temporal models with a Species Distribution Model approach (models containing biotic or accessibility predictors and/or being spatially limited) (Soberon and Peterson 2005; Soberón 2010), we predicted the presence of these species for the entire Brazilian coast.

Because S. axillare and S. frondosum are browser/scaper species (Ferreira and Gonçalves 2006) that have strategies that allow the use of different types of habitats (Ferreira and Gonçalves 1999), we expected them to be distributed along a wide area of the Brazilian coast. On the other hand, we expected a narrower distribution of Scarus trispinosus, which is an excavator (Ferreira and Gonçalves 2006) and hence requires more specific food items. This approach underlines the importance of having marine-protected areas that consider not only species diversity but also functional biodiversity, reducing overall fish assemblage vulnerability (Parravicini et al. 2014). Also, the approach applied in this study improves the understanding of species distribution and demonstrates the biological needs for the management of any biologically and economically important reef species under some sort of threat.
Material and Methods

Study area

Parrotfish were sampled in fish landings with fishing activities that took place up to three miles offshore within a Regional Protected Reef Area, hereafter referred to as APARC (from Portuguese, Área de Proteção Ambiental dos Recifes de Corais, see Fig.1). This protected area was established in 2001 in the northern part of the oriental coast of the Rio Grande do Norte state, Brazil (5°00’–5°30’S – 35°10’–35°30W). The entire area covers 180.000 ha and is characterized by complex rocky reefs formed by various types of benthic environments (rhodolith, prairies of phanerogams, corals, algae, and sandy fund) (Amaral et al. 2005).

Figure 1: Map of the study area and sampling locations.

The small-scale fishing activities in this area have a high heterogeneity of gear and targets and are performed by about 700 fishers. Most of these fishers use small sail vessels (4-6m) that are also powered by small engines. These vessels employ various types of fishing gears, but bottom-set panel
gill nets with stretched mesh sizes that range from 30 to 60 mm (knot-to-knot), handlines, and spear guns are primarily used.

The fishing gear changes throughout the year according to the seasonality of the main target species. Red snapper (*Lutjanus analis*), dog snapper (*Lutjanus jacu*), black grouper (*Mycteroperca bonaci*), king mackerel (*Acanthocybium solandri*), Spanish mackerel (*Scomberomorus brasiliensis*), and Atlantic little tunny (*Euthynnus alleteratus*) are caught year-round mainly using handlines. Gillnets are primarily used to catch ballyhoo (*Hemiramphus brasiliensis*), manjuba (*Anchoviella lepidentostole*), lane snapper (*Lutjanus synagris*), and yellowtail snapper (*Ocyurus chrysurus*), usually from December to April. Octopus (*Octopus insularis*) is also targeted yearlong, although usually between December and May, by free divers using a long hook.

**Data sampling**

Parrotfish landings were registered monthly in the Maracajaú and the Rio do Fogo harbors from September 2013 to August 2014. These locations were previously identified as the most frequent places for parrotfish fishing. The sampling was performed for two consecutive days (from approximately 10:00 am to 4:00 pm) in each place every month. Harbor observers recorded information about fishing grounds, fishing gear, crew size, date, duration of the fishing operation, and the species caught.

Fishers provided information regarding the fishing grounds using a geo-referred spatial grid (1°x1°) of the area. The latitude and longitude of each fishing operation was extracted *a posteriori* using the “Feature to Points” tools of the ArcGis 10.2.2 version (ESRI, 2014, link: http://www.esri.com/).

Fishing trips that resulted in no parrotfish being caught were not available in the original dataset because only fishery operations that landed parrotfish were sampled. In order to generate a presence/absence dataset, pseudo-absences were chosen at random for the entire area, considering
both expert and bibliographic knowledge (Bonaldo et al. 2006; Francini-Filho et al. 2008; Francini-Filho and Moura 2008) of the habitat range of the species. Such information was used to restrain the areas in which to generate these absences. We generated the set of pseudo-absences 100 times using the \textit{srswor} function (simple random sampling without replacement) from the “\textit{Sampling}” package in R (R Development Team 2014). In each case, the number of generated pseudo-absences was the same as the number of real presences. Pseudo-absences were then combined with real presences into a single presence-absence dataset to be used in a binomial model.

Although the generation of pseudo-absence datasets is an open hot research topic, (\textit{e.g.} Hastie and Fithian 2013), subjected to some debate, we preferred to use such a binomial distribution with a Bayesian spatial model instead of a less accurate model that allows the use of presence-only data (\textit{e.g.} BIOCLIM, DOMAIN). The advantage of using a Bayesian approach, instead of other models, is, among other advantages mentioned in the next section, the capacity to include a spatial effect to deal with spatial autocorrelation. Spatial autocorrelation should be taken into account in the species distribution models, even if the data were collected in a standardized sampling, since the observations are often close to each other and, therefore, subjected to similar environmental features.

\textit{Environmental variables}

Potential fixed-effects have been considered for each of the models for each species (the modeling approach is described in the modeling section). As environmental variables, we included bathymetry (mean depth of each fishing operation), distance to shore (\textit{km.}), slope of the seabed (\textit{m.}), monthly mean of Sea Surface Temperature (SST in °C), and monthly mean of Net Primary Productivity (NPP in \textit{mg m}^{-3}).

The sea surface temperature (SST) was extracted from NODS_WOA94 long-term monthly mean climatology provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (at http://www.esrl.noaa.gov/psd/).
The variable net primary productivity (NPP) was retrieved from 920x1680 global grids of NPP and calculated as a function of chlorophyll, available light, and photosynthetic efficiency using the entire SeaWIFS chlorophyll record on the Ocean Productivity website (http://www.science.oregonstate.edu/ocean.productivity/index.php).

The bathymetry was retrieved from the NOAA-NGDC ETOPO1 Global Relief Model (Amante and Eakins 2009), a 1 arc-minute global relief model of Earth’s surface that integrates land topography and ocean bathymetry. In addition, fishers provided the bathymetry information at the moment of the landing sampling. When the data differed between the NOAA and the fishers’ information, a mean of the two datasets was used. We opted for the mean because we did not know a priori which of the two datasets was a more reliable source of data. However, only 15 points out of 54 differed between the datasets and this difference was only about 4-5 meters.

The distance to the coast and slope information were derived from the bathymetry map using the Near (World Equidistant Cylindrical coordinate system) and Slope Spatial Analyst tools of ArcGis 9.2 (ESRI Inc., 2008; Redlands, California, USA).

The remaining potential source of variation on the species occurrence dataset could be due to the fishers sampled, who could have been sampled by us multiple times if they happened to land more than once during the sampling year. The individual behavior of fishers caused by random aspects, such as experience, age, and social needs, and/or unobserved gear characteristics could have caused some of the variation in the data. Ignoring such non-independence of the data may lead to an invalid statistical inference. To remove any bias caused by fishers-specific differences in the fishing operation, a fisher effect was included. This variable was included as a random effect because there was no interest in knowing the specific nature of the observed fishers.

Environmental variables were standardized and collinearity between explanatory environmental variables was checked using a draftsman’s plot and the Pearson correlation index. The variables were not highly correlated ($r < 0.5$), so all variables were considered in further analyses.
**Modeling species occurrence**

Spatial distribution models use the range of sampled environments and the same general time frame of the sampling to predict quantities of interest at un-sampled locations based on measured values at nearby sampled locations. Many spatial distribution model algorithms can be used to predict the spatial distribution of species; however, these algorithms do not always provide accurate results if they are run using traditional prediction methods (frequentist inference) because there is often a large amount of variability in the measurements of response and environmental variables. To solve this problem, we used the hierarchical Bayesian spatial-temporal models.

Bayesian methods have several advantages over traditional ones and are increasingly used in fisheries (Colloca et al. 2009, Muñoz et al. 2013, Pennino et al. 2014). In fact, they provide a more realistic and accurate estimation of uncertainty due to the possibility of using both the observed data and the model parameters as random variables (Banerjee et al. 2004). Bayesian methods also allow for the incorporation of the spatial component as a random-effect term, thereby reducing its influence on estimates of the effects of geographical variables (Gelfand and Silander 2006). Specifically, by treating the spatial effect as a variable of interest, hierarchical Bayesian spatial models can identify additional covariates that may improve the model fit or the existence of area effects that may affect the density of recruits.

We used the hierarchical Bayesian spatial-temporal approach, specifically a point-reference spatial model, to estimate the probability of occurrence of the three parrotfish caught at the sample site (*Sparisoma* axillare, *S. frondosum* and *Scarus trispinosus*). These models are highly suitable for cases (as presented here) in which data are observed at continuous locations occurring within a defined spatial domain. These models can also be considered to be a spatial extension of Generalized Linear Models (GLMs) because the modeling process describes the variability in the response variable as a function of the explanatory variables with the addition of a stochastic spatial effect to model the residual spatial autocorrelation.
Specifically, once we have generated the presence-pseudo-absence dataset, the response variable $Z_{ij}$ is a binary variable that represents the presence (1) or absence (0) of the species in each fishing location identified in the fishing landings. Consequently, the conditional distribution of the data is $Z_{ij} \sim \text{Ber}(\pi_{ij})$, which is the probability of occurrence at location $i$ ($i = 1, ..., n$) and month $j$ ($j = 1, ..., 12$), assuming that observations are conditionally independent given $\pi_{ij}$. At the first stage of the hierarchical model, the observed data (occurrence of species) was modeled as a GLM (Generalized Linear Model) by using the logit link function for binary data but also incorporating one spatial and one possible temporal effect. That is,

$$Z_{ij} \sim \text{Ber} (\pi_{ij})$$

$$\text{logit} (\pi_{ij}) = X_{ij}\beta + Y_j + Z_k + W_i$$

where $\beta$ is the vector of regression parameters, $X_{ij}$ is the vector of the explanatory covariates at the month $j$ and at the location $i$, $Y_j$ is the component of the temporal random effect at the month $j$, $Z_k$ is the random effect of the fishers, and $W_i$ represents the spatially structured random effect at the location $i$. This model assumes independence between the data; however, the geographical location introduces some correlation since the occurrence of a species at nearby locations is influenced by similar environmental factors. Hence, nearby locations should show similar occurrences of the studied species. The spatial effect, $W_i$, should account for this influence. Note that this modeling process describes the variability in the response variable as a function of the explanatory variables with the addition of a stochastic spatial effect, which models the residual spatial autocorrelation.

For all of the parameters involved in the fixed-effects, a vague Gaussian prior distribution ($\beta \sim \text{N} (0, 0.01)$) was used, and thus the posterior distributions for all parameters were derived from the data. For the spatial effect, a prior Gaussian distribution with a zero mean and covariance matrix was assumed depending on the hyperparameters $k$ and $\tau$, which determined the range of the spatial effect and the total variance, respectively (see Muñoz et al., 2013 for more detailed information about spatial
effects). Moreover, for the temporal component, a LogGamma prior distribution was assumed on the log-precision $\lambda_y$ ($a = 1, b = 5\times10^{-5}$).

As usual in this context, the resulting hierarchical Bayesian model has no closed expression for the posterior distribution of all of the parameters, and numerical approximations are needed. In this study, an Integrated Nested Laplace Approximation (INLA) methodology (Rue et al. 2009) and software (http://www.r-inla.org) were used as alternatives to the Markov chain Monte Carlo methods. The main reason for this choice is the speed of calculation: MCMC simulations require much more time to run, and performing predictions are so far practically unfeasible. In contrast, INLA produces almost immediate accurate approximations to posterior distributions even in complex models. Another advantage of this approach is its generality, which makes it possible to perform Bayesian analysis in a straightforward way and to compute model comparison criteria and various predictive measures so that models can be compared easily (Rue et al. 2009). INLA’s performance has been compared with MCMC and has shown a similar reliability (Held et al. 2010).

Both inference and prediction were performed simultaneously using the Stochastic Partial Differential Equation module (Lindgren et al. 2011), which allows for fitting the particular case of continuously indexed Gaussian fields with INLA, as is the case with this study’s spatial component.

The variable selection was performed beginning with all possible interaction terms based on the Deviance Information Criterion (DIC) (Spiegelhalter et al. 2002) and on the cross validated logarithmic score (LCPO) measure (Roos and Held 2011). Specifically, DIC was used as a measure for goodness-of-fit, while LCPO was used as a measure of the predictive quality of the models. DIC and LCPO are inversely related to the compromise between fit, parsimony, and predictive quality.

In addition, in order to avoid extrapolating the predictions to outside the range of the environmental conditions encountered in the two datasets used for the models, we only predicted probability of presence in areas for which the environmental values were contained in the 90% quantile interval represented by the original datasets.
**Model validation**

The model validation was performed through an internal 10-fold cross validation based on randomly selected training and test datasets created by a random selection of 80% and 20% of each dataset, respectively (Fielding and Bell 1997), using the ‘PresenceAbsence’ package in R (Freeman and Moisen 2008). The model performance was assessed using the area under the receiver-operating characteristic curve (AUC) (Fielding and Bell 1997) and the “True Skill Statistic” (TSS) (Allouche et al. 2006).

AUC has been widely used in the species distribution modeling literature (Elith et al. 2006). It measures the model’s ability to discriminate between sites in which the species is present and those in which the species is absent. The values for AUC range from 0 to 1, where 0.5 indicates a performance no better than random, values between 0.7-0.9 are useful to indicate results of presence/absence different from random, and values > 0.9 are excellent to ensure that the results are different from random. TSS corrects AUC for the dependence of prevalence on specificity (i.e., ability to correctly predict absences) and sensitivity (i.e., ability to correctly predict presence)(Allouche et al. 2006).

In addition, the information available on the presence of the parrotfish species for all the prediction area was extracted from the AQUAMAPS website (Kaschner et al. 2013) in order to verify whether or not the Bayesian models’ predictions matched theirs. In particular, the datasets extracted from AQUAMAPS were used as secondary test datasets to compute the AUC and TSS measures. The sampled datasets were restricted to the coastal Northeastern area of Brazil, while the Bayesian models predicted a broader and more complete view of the distribution of this species on a macro scale (*Fig. 2*). Hence, the dataset from AQUAMAPS worked as a control for the predictive ability of the Bayesian approach.
Figure 2: Sampling locations of our personal dataset (black circle) and AQUAMAPS (red circle) dataset of the the studied species: *Scarus trispinosus* (A); *Sparisoma frondosum* (B); *Sparisoma axillare* (C).

**Results**

Fifty-four parrotfish landings were sampled in the two studied locations, although most of them landed in Rio do Fogo (N =40). Both *Sparisoma frondosum* and *S. axillare* were recorded in 37 landings comprising 1.3 tons caught. Almost one ton of *Scarus trispinosus* was recorded in 26 of these landings. The annual total catch was estimated to be 9.4 tons of *S. trispinosus* and 15.4 tons of *S. frondosum* and *S. axillare*. This estimation was computed as an extrapolation of the recorded landings for the fishing days and the number of fishers in the locations.

At the time of the study, there were 60 parrotfish fishers using gillnets, spear guns, or handlines. Most of them (60%) used gillnets and handlines to catch *Sparisoma axillare* and *S. frondosum*. Spearfishing was used by 40% of the fishers specifically to catch *Scarus trispinosus*. Parrotfish fishing operations were done in sailboats in reef environments ranging from 4 to 12m. The fishing trips lasted from 4 to 8 hours beginning early in the morning, mainly between December and May. The main predictors for the occurrence of parrotfish in the Northeastern Brazilian coast were bathymetry, sea surface temperature (SST), and distance to the coast. The higher net primary
production was only relevant to explain the distribution of *Scarus trispinosus* (Table 1).

**Table 1:** Numerical summary of the posterior distribution of the fixed effects for the best model of the three species studied. This summary contains mean, the standard deviation, the median and a 95% credible interval, which is a central interval containing 95% of the probability under the posterior distribution (SST = Sea Surface Temperature; NPP = Net Primary Production).

<table>
<thead>
<tr>
<th>Species</th>
<th>Predictor</th>
<th>Mean</th>
<th>SD</th>
<th>Q0.025</th>
<th>Q0.5</th>
<th>Q0.975</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>S. trispinosus</em></td>
<td>Intercept</td>
<td>-5.69</td>
<td>1.48</td>
<td>-6.86</td>
<td>-5.85</td>
<td>-3.37</td>
</tr>
<tr>
<td></td>
<td>Bathymetry</td>
<td>4.66</td>
<td>1.06</td>
<td>2.75</td>
<td>4.59</td>
<td>6.99</td>
</tr>
<tr>
<td></td>
<td>Distance to the coast</td>
<td>-1.22</td>
<td>0.54</td>
<td>-1.20</td>
<td>-0.92</td>
<td>-0.05</td>
</tr>
<tr>
<td></td>
<td>SST</td>
<td>2.74</td>
<td>1.12</td>
<td>1.92</td>
<td>2.66</td>
<td>5.13</td>
</tr>
<tr>
<td></td>
<td>NPP</td>
<td>0.53</td>
<td>1.42</td>
<td>0.78</td>
<td>0.51</td>
<td>2.95</td>
</tr>
<tr>
<td><em>S. frondosum</em></td>
<td>Intercept</td>
<td>-7.46</td>
<td>1.92</td>
<td>-8.79</td>
<td>-7.33</td>
<td>-4.03</td>
</tr>
<tr>
<td></td>
<td>Bathymetry</td>
<td>11.34</td>
<td>2.16</td>
<td>9.83</td>
<td>12.77</td>
<td>15.81</td>
</tr>
<tr>
<td></td>
<td>Distance to the coast</td>
<td>-1.64</td>
<td>0.81</td>
<td>-2.20</td>
<td>-1.10</td>
<td>-0.03</td>
</tr>
<tr>
<td></td>
<td>SST</td>
<td>4.65</td>
<td>1.43</td>
<td>3.67</td>
<td>4.63</td>
<td>7.59</td>
</tr>
<tr>
<td><em>S. axillare</em></td>
<td>Intercept</td>
<td>-3.95</td>
<td>0.78</td>
<td>-4.45</td>
<td>-3.92</td>
<td>-2.53</td>
</tr>
<tr>
<td></td>
<td>Bathymetry</td>
<td>6.55</td>
<td>0.98</td>
<td>5.84</td>
<td>6.50</td>
<td>8.56</td>
</tr>
<tr>
<td></td>
<td>Distance to the coast</td>
<td>-1.54</td>
<td>0.45</td>
<td>-1.12</td>
<td>-0.98</td>
<td>-0.02</td>
</tr>
<tr>
<td></td>
<td>SST</td>
<td>3.63</td>
<td>0.92</td>
<td>2.02</td>
<td>3.56</td>
<td>4.97</td>
</tr>
</tbody>
</table>

The random spatial effect and the random effect representing the behavior of fishers were relevant for all models and species, while slope and month did not affect the variability of parrotfish distribution.

The best fitted model of the distribution for *Scarus trispinosus* showed a positive relationship with bathymetry (posterior mean = 4.66; 95% CI = [2.75, 6.99]), sea surface temperature (posterior mean = 2.74; 95% CI = [1.92, 5.13]), and net primary productivity (posterior mean = 2.53; 95% CI = [1.28, 3.95]; Table 1). It was also observed that the median posterior probability of the occurrence of *Scarus trispinosus* on the Brazilian coast was higher in lower latitudes where higher values of sea surface temperature and net primary productivity were found (Fig. 3A). Conversely, the expected presence of this species decreased as the distance to the coast increased (posterior mean = -1.22; 95%
CI = [-1.20, -0.05]).

**Figure 3:** Median of the posterior probability of the presence of the studied species: *Scarus trispinosus* (A); *Sparisoma frondosum* (B); *Sparisoma axillare* (C) and MPA’s locations: Parcel Manuel Luís (1), Atol das Rocas (2), Fernando de Noronha (3), Abrolhos Archipelago (4) and Trindade Island (5).

The spatial effect indicating the intrinsic variability of the distribution of *Scarus trispinosus* after the exclusion of the environmental variables was consistent with the probability maps (**Fig. 4A**). This effect showed (through the posterior mean) a large hot spot for this species on the northern coast of Brazil and at specific locations (namely latitude 3°51'S and longitude 33°49'W, and latitude 20°29-32'S and longitude 29°17-21'W). These locations correspond with current biological reserves: Atol das Rocas and the Trindade islands (**Fig. 4A**). Habitats associated with deeper and warmer waters and at lower latitudes showed a greater probability for the presence of both species of *Sparisoma*. 
Figure 4: Median of the posterior spatial effect of the studied species: Scarus trispinosus (A); Sparisoma frondosum (B); Sparisoma axillare (C) and MPA’s locations: Parcel Manuel Luís (1), Atol das Rocas (2), Fernando de Noronha (3), Abrolhos Archipelago (4) and Trindade Island (5). 

In particular, the presence of Sparisoma frondosum was positively affected by bathymetry (posterior mean = 6.55; 95% CI = [5.84, 8.56]) and sea surface temperature (posterior mean = 4.65; 95% CI = [3.67, 7.59]) but negatively influenced by a decrease in distance, indicating that the further away from the coast, the higher the probability of occurrence of this species (posterior mean = -1.64; 95% CI = [-2.20, -0.03]) (Table 1). For this species, the median posterior showed a higher probability of occurrence in deeper waters and oceanic islands along the Brazilian coast (Fig. 3B). This distribution was confirmed by the spatial effect, which identified hot spots for their occurrence in Parcel Manuel Luís, Fernando de Noronha, Atol das Rocas, Abrolhos Archipelago and Trindade, and all oceanic islands or islets located at lower latitudes (Fig. 4B).

Similarly, the prediction of occurrence of Sparisoma axillare indicated positive effects of bathymetry (posterior mean = 11.34; 95% CI = [9.83, 15.81]) and sea surface temperature (posterior mean = 3.63; 95% CI = [2.02, 4.9]) and a negative effect of distance from the coast (posterior mean = -1.54; 95% CI = [-1.12, -0.02]; Table 1). Figure 3(C) and Figure 4(C) show that habitats associated
with deeper waters that are further away from the coast have a higher probability of occurrence of *Sparisoma axillare*. Lower probabilities for the occurrence of this species were found at higher latitudes.

The analyses of the model prediction performances found AUC values greater than 0.70 for all models, indicating a good degree of discrimination between locations in which the species was present and those in which it was absent (*Table 2*). All TSS values ranged between 0.60 and 0.80, which also represents a good ability of the model to predict true negative and true positive predictions. The values of AUC and TSS found using the AQUAMAPS datasets (macro-scale) achieved lower values than the ones obtained using the Bayesian approach (*Table 2*); however, both AUC and TSS showed values higher than 0.65, indicating predictions of good performance on a macro-scale as well.

*Table 2*: Model prediction performance statistics for three species studied. AUC (Area Under the receiver-operated characteristic Curve) and TSS (True Skill Statistic). AUC\textsubscript{aquamaps} and TSS\textsubscript{aquamaps} indicate the measures obtained using the AQUAMAPS dataset.

<table>
<thead>
<tr>
<th>Species</th>
<th>AUC</th>
<th>TSS</th>
<th>AUC\textsubscript{aquamaps}</th>
<th>TSS\textsubscript{aquamaps}</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Scarus trispinosus</em></td>
<td>0.78</td>
<td>0.68</td>
<td>0.69</td>
<td>0.66</td>
</tr>
<tr>
<td><em>Sparisoma frondosum</em></td>
<td>0.84</td>
<td>0.72</td>
<td>0.72</td>
<td>0.70</td>
</tr>
<tr>
<td><em>Sparisoma axillare</em></td>
<td>0.87</td>
<td>0.79</td>
<td>0.71</td>
<td>0.73</td>
</tr>
</tbody>
</table>

**Discussion**

*Environmental predictors of species distribution*

Fishery-dependent data were used to improve the understanding of the distribution of three different species of parrotfish of conservation concern on the entire Brazilian coast using Bayesian spatial-temporal hierarchical models. It was shown that depth was an important determinant for the
occurrence of the studied parrotfish. *Scarus trispinosus* was likely to be distributed in shallower waters closer to the shore, while the other two species of *Sparisoma* were more likely to be distributed in deeper waters but with increasing probabilities at increasing distances from the coast. The distribution of all three species was negatively related to the latitude, showing that the spatial effect is a relevant factor in their distribution.

Despite the limited information available, *Scarus trispinosus* has been described as a species with a more restricted distribution, establishing populations mostly near the coast. The positive relationship between *Scarus trispinosus* and primary production found in this study may explain the more restricted distribution of this species due to its specialized feeding habits (Bernardi et al. 2000, Streelman et al. 2002), which results in intense grazing that enhances the productivity of benthic algal assemblages by removing large algae with low specific productivity (Hatcher 1988). In addition, the distribution prediction shown in this study supports the patterns of a decreasing occurrence at higher latitudes, which is explained by the fact that the tropics sustain higher primary productivity (Carpenter 1986, Hatcher 1988).

Conversely, *Sparisoma axillare* and *S. frondosum* have been identified as species that occur over a deeper geographical range, mainly in the Brazilian oceanic islands (Moura et al. 2001). These descriptions are confirmed by the results found in this study regarding depth.

Similarly, discussions on the relevance of the spatial factor on herbivore fish species distribution have already shown that at high latitudes, richness and abundance decrease, mainly due to the evolutionary histories of different species and habitat features, such as primary production and temperature (Ferreira et al. 2004, Floeter et al. 2005). The positive relationship between parrotfish species and temperature result from their temperature tolerance limits (Moyle and Cech 2003). This illustrates the dependence of their digestion process on a thermally sensitive, diverse assemblage of intestinal microflora, indicating that the distribution patterns of herbivorous fish are driven by temperature-related feeding and digestive processes (Floeter et al. 2005).
Spatial predictors for species distribution

Identifying the spatial distribution of threatened marine fish populations is essential for developing appropriate marine spatial planning (Douvere 2008) and management measures, such as the establishment of marine protected areas (Jones 2004). The understanding of spatial distribution is also useful in defining essential fish habitats (Rosenberg et al. 2000), mainly for reef fish, which have patchy distributions (Sale 1998). For parrotfish, this is particularly important because despite their growing relevance for fisheries, little is known about their spatial ecology.

The spatial random effects of the three species showed different spatial patterns observed in the maps of the spatial effect. This could be due to the fact that the spatial random component is often used to capture the effect of important missing predictors (Dormann 2007, Dormann et al. 2007) or to account for ecological processes (e.g., dispersal or aggregative behavior) (Merow et al. 2014). In our case, the spatial effect probably reflects the type of seabed because it identified areas in which there are known reef complexes that could be the potential habitats of these species.

The Brazilian northeast and the northern portion of the southeastern coast were shown to be areas with a positive spatial effect for the three species of parrotfish, mainly in regions with multiple reef complexes. Hence, it would be advisable to establish spatial planning that ensures the protection of such sensitive areas and perhaps to increase the protection in surrounding areas, such as the major coral reef hot spot of Archipelago of Abrolhos.

A species habitat analysis should be able to identify the areas within the distribution of a species that contribute most to sustaining the long-term viability of a population. Although it may be complicated to define the boundaries of sensitive habitats, the identification of these areas combined with efficient fishery management recognizing the importance of such areas represents the first step toward the conservation of these species; however, accuracy is not always easy to achieve because there is often a large amount of variability in the measurements of the response and environmental variables (Latimer et al. 2006). This variability leads to uncertain predictions and, consequently, to
uniformed decision making. It is therefore important to develop and apply tools, such as the statistical approach used in this study, that account for measurements with significant variability.

**Fishers’ behavior as a predictor of species distribution**

The results show that the random effect of fishers’ behavior was significant to explain part of the variability in the distribution of the three species that is not explained by the environment. As expected, this shows that some fishers have more success than others when exploiting parrotfish. This could be due to their experience, the fishing gear used, the fishing ground, or some joint effect of all of these factors.

More importantly, it is clear that fishers’ personal experience and choices will have an effect on how fish are harvested. Therefore, in addition to establishing protected areas, fishery management should focus on measures that regulate fishing operations, such as temporary closures to assure fish reproduction and restrictions on non-selective fishing gear in unprotected places (McClanahan and Mangi 2004). This is especially urgent given the already threatened conservation status of the three studied species.

**Dataset limitations, statistical reliance, and ecological findings**

Large-scale predictions, such as the entire Brazilian coast, allow for broader and more complete views of ecosystem status, but their use often leads to some degree of compromise in the analysis. This is because the quality and quantity of data available for large ecosystems and long time-series are often insufficient, while mapping essential habitats requires the highest level of accuracy. The Bayesian interpolation and extrapolation are sufficiently reliable for the purpose of effective decision making and are supported by a range of evaluation criteria that demonstrate a good predictive performance of this approach as well as its advantages in terms of ecologically interpretability. The data extracted from AQUAMAPS confirmed our large-scale extrapolations for the entire Brazilian coast because the observed presences in the AQUAMAPS dataset matched the predicted presences of the Bayesian models with a high level of accuracy, as demonstrated by the AUC and TSS indexes.
The analyses performed in this study also confirmed the suitability of the existing marine protected areas, such as Parcel Manuel Luís, Atol das Rocas, Fernando de Noronha, Abrolhos Archipelago and Trindade, reinforcing the ecological accuracy of the method. The Bayesian spatial-temporal approach identified essential habitats along with a full specification of associated uncertainty, therefore improving knowledge about the habitat of the parrotfish species along the Brazilian coast and providing practical tools for reef conservation management. However, because both species and environmental data were sampled over a limited period of time and space, the models fitted here can only reflect a snapshot of the expected relationship. Future studies should compare the spatial distribution of these species with more detailed data from fishery-independent surveys (i.e., visual census abundance data), which is often considered to be a more reliable abundance index because of its scientifically rigorous design.

Despite these issues, this first approximation for an area in which in-depth information is not available at the time could direct preliminary choices of areas to be managed in addition to helping direct efforts in data collection and future research.

**Threatened species and management suggestions**

The restricted coastal distribution of *Scarus trispinosus* is worrisome due to the fact that small-scale fisheries operate mostly in shallow reef areas where this species is present, making it highly susceptible to fisheries. In fact, the decline of *Scarus trispinosus* is currently observed along the Brazilian coast, mainly in areas with heavy fishing pressure (Floeter et al. 2006, Francini-Filho and Moura 2008). In some parts of the southeastern Brazilian coast, this species is already considered ecologically extinct (Floeter et al. 2007), and the same fate has the potential to occur in the northeastern coast as well. Similarly, *Sparisoma axillare* and *S. frondosum* have also declined in abundance in some places on the Brazilian southeast coast (Bender et al. 2014) and have been intensively caught on the northeast coast by trap fishery, including trap fishery for exportation (Ribeiro 2003).
For such a large coastline, protection measures must be fishery-specific and use a spatial approach. In the northeastern region, for example, parrotfish fisheries have some sort of natural closures from June to November due to the low underwater visibility (it affects spearfishing, but not trap fishing) and the open season for the more profitable lobster, which attracts most fishers. On the other hand, when lobster fishing is officially closed, parrotfish can suffer a much higher fishing pressure. This exemplifies how the protection of one species (lobster) may increase the pressure upon another. Moreover, it illustrates that local regulations on gears could be more suitable and likely to promote compliance than a fishing ban period since fishers already experience four months of natural interruption in parrotfish exploitation.

The recent inclusion of *S. trispinosus* as an endangered species and of *Sparisoma axillare* and *S. frondosum* as vulnerable species in the Brazilian Red List of Threatened Species implies an automatic banning of the fishery for the first species and the requirement of management measures for the latter two over the entire coast. However, Brazil lacks the financial and human resources to implement a *de facto* moratorium and/or management. The Brazilian coast is simply too large an area with too many scattered fishing communities that would probably not even be properly informed of such measures. Also, some of these communities may partially rely on the exploitation of these species. Therefore, an effective permanent or temporary moratorium and management actions on parrotfish harvesting would have a better potential of being effective if coupled with programs that investigate and address the livelihood needs of the affected communities. Otherwise, parrotfish harvesting could become another unreported, unregulated, and illegal fishery. Different places around the world have faced similar dilemmas and have developed solutions, such as the diversification of economic alternatives that support biodiversity conservation (e.g., parrotfish ecotourism) (Tallis et al. 2010).

Based on the results presented, we recommend the establishment of additional protected areas in which the larger populations of the three studied parrotfish species are mostly expected to occur. For some areas, it appears to be reasonable to allow tourism activities, such as parrotfish viewing.
This may be a feasible and liable opportunity primarily for *S. trispinosus*, which is predicted to occur in shallow waters around the coral reef area. However, we also emphasize the need to address the impacts such measures may have on local communities’ livelihoods and the need to mitigate possible negative consequences. The identification of the occurrence areas of target species in general could be an essential tool to direct the spatial management of the fleet as well as to direct additional studies to detect nurseries and high-abundance areas.

**References**


Capítulo 2

**Effects of fishing gear selectivity on vulnerable parrotfish (Labridae: Scarini) species**
Effects of fishing gear selectivity on vulnerable parrotfish (Labridae: Scarini) species

Abstract

There is evidence that small-scale fisheries are exploiting large numbers of parrotfishes from Brazilian reefs, leading to significant changes in the community structure. Specifically, three now vulnerable species, *Scarus trispinosus* (Valenciennes, 1840), *Sparisoma frondosum* (Agassiz, 1831) and *Sparisoma axillare* (Steindachner, 1878), have been intensively targeted on the Brazilian northeast, although little is known about such fisheries. The vulnerable status of these species has brought about the need to officially regulate their fisheries. Here, the effects of different gear types on the fishery of these three species are analyzed regarding catch composition, size and species selectivity. Landings of gillnet, speargun, and handline fishing were sampled during one year, when information of each fishery operation and size frequencies of fishes caught were recorded. Gillnets are the most non-selective gear, catching a greater proportion of immature individuals of *S. trispinosus*. Handlines showed the lowest values of capture per unit effort (CPUE) and only caught *S. axillare* and *S. frondosum* above the size at first maturity; it did not catch *S. trispinosus*. Speargun is the only gear that caught a higher proportion of mature individuals of *S. trispinosus*, which by no means should exempt it from further regulations, as it is important to assure that neither immature nor exceptionally large individuals are caught. Gear regulation is urgently needed if parrotfish harvesting is to be allowed, with comprehensive measures, such as size slot delimitation, in order to achieve parrotfish fisheries sustainability and avoid overfishing and changes in life history traits of targeted species.

**Keywords:** Reef fishes, fisheries management, spearguns, gillnets, size slot.
Introduction

Reef fisheries are an important source of income and protein to many poor coastal populations around the world (Moberg and Folke, 1999). Although reef fisheries are mostly performed by small scale and artisanal fishermen, improved gear technology and growing coastal populations and market demands have significantly increased the pressure on reef fish stocks (Cinner and McClanahan, 2009). Such pressures have led to many significant effects on reef communities, such as reduction in species diversity and biomass, loss of resilience and phase shifts (Hughes et al., 2007; Mumby et al., 2007). Avoiding these effects requires the maintenance of some key ecosystem processes, including predation, herbivory and fish and coral recruitment (Dulvy, 2004; Bellwood, 2004). Many of these processes are performed by fishes, markedly those representing functional groups like top predators and large herbivorous, such as parrotfish (Labridae: Scarini).

Parrotfish are large-body and long-living herbivorous fishes that are associated with tropical and subtropical reef habitats around the world (Choat and Randall, 1986). As benthic algae consumers, parrotfish are classified into three functional groups (excavators, scrapers and grazers) and exert top-down control of macroalgae (Streelman et al., 2002; Mumby et al., 2006; Francini-Filho et al., 2008). The intensity of the ecological function performed by parrotfish is determined by both the local fish abundance and individual body-size, with higher abundances and larger individuals contributing disproportionally more to the grazing function (Bonaldo and Bellwood, 2008; Lokrantz et al., 2008).

Hence, overfishing of parrotfishes and removal of large individuals can simultaneously affect multiple ecosystem functions (Bellwood et al., 2012). Unfortunately, fishing pressure on parrotfishes has grown in last decades around the world (Edwards et al., 2013), including the southwestern Atlantic (Francini-Filho and Moura, 2008; Previero, 2014; Bender et al., 2014). In Brazil, for example, parrotfishes are targeted along the coast with the use of different gears, including gillnets, handlines and spearguns (Fracini-Filho and Moura, 2008; Previero, 2014; Bender et al., 2014). Some of these target species have shown alarming signs of decline, as observed with species of the genus
Sparisoma, including *S. axillare* and *S. frondosum* (Bender et al., 2014). Even more seriously, the largest Brazilian parrotfish, *Scarus trispinosus* (Valenciennes, 1840), which is an endemic long-living species, is now listed as Endangered by the Union for Conservation of Nature (IUCN; Ferreira et al., 2012). Unfortunately, large-bodied species, such as *S. trispinosus*, tend to be more vulnerable due for several factors, including late maturity and low intrinsic rates of population increase (Reynolds et al., 2001).

As an attempt to halt declining populations of fishing species, in December 2014 the Brazilian Ministry of the Environment listed five species of parrotfish, among many other groups, in the Brazilian Red List of Endangered Species (Decree nº 445; Brazil’s Red List, 2014). Four of the five listed species were classified as *vulnerable*, including *S. axillare* and *S. frondosum*, while *S. trispinosus* was listed as *endangered*.

Notwithstanding the justifiable biological concern, studies approaching the fisheries of parrotfish are still rare (Previeiro, 2014; Bender et al., 2014) and to the extent of our knowledge, none has examined the effects of different gears on their harvesting. The effects that gears have in a given fishing are important to be understood because they may change catch composition, catch per unit effort (CPUE) and fish size frequencies (McClanahan and Mangi, 2004; Mangi and Roberts, 2006; Campell and Pardede, 2006).

Besides, evolutionary responses in fish history can be induced by size-selective gears (Kuparinen and Merilä, 2009; Liang et al., 2014), such as earlier maturation, reduced fecundity and the gradual replacement of large-bodied individuals for small-bodied ones, a process known as *fishing-down* (Welcomme, 1999). The fishing-down process predicts that the body length and weight of exploited fishes at the same age decrease consistently over time due to the removal of the large and usually pricier large-bodied individuals (Welcomme, 1999).

Therefore understanding gear effects allows the identification of better management strategies that could result in the maintenance of fish populations and long-term fisheries yield. In this study, we assessed gear size selectivity and fishing pressure on the three most caught species of parrotfishes
in the Brazilian northeast, a region where parrotfish are abundant and increasingly targeted by fishermen: greenback parrotfish (*Scarus trispinosus*, Valenciennes, 1840), agassiz's parrotfish (*Sparisoma frondosum*, Agassiz, 1831) and gray parrotfish (*Sparisoma axillare*, Steindachner, 1878). Specifically, we identified the influences of each fishing gear used on the proportion of juvenile caught and on size frequencies, expecting to provide such essential information for management, which could help ensure the health of reef habitats and fish stocks.

**Material and Methods**

*Study area*

This study concerns analyses done on data gathered during landings from fishing that took place in waters within 3 miles off the coast, in the north part of the oriental coast of “Rio Grande do Norte” state, Brazil (5º00’–35º30’S – 35º10’–35º30W). The entire area is included within an Environmental Protected Reef Area, the APARC (from the Portuguese acronym, “Área de Proteção Ambiental dos Recifes de Corais”) established in 2001. The area has 180,000 ha and is mostly fished by people from nearby towns and villages (approximately 700 fishermen) (Figure 1). A complex of coral reef, formed by various types of benthic environments (rhodolith, prairies of phanerogams, corals, algae and sandy fund), characterizes this area (Amaral et al., 2005).
**Figure 1:** Map of the study area, sampling locations and fishing gears used by location (GN40 – Gillnet 40mm; GN50 – Gillnet 50mm; GN60 – Gillnet 60mm; SG – Speargun; HL – Handline).

Fisheries in the area are solely small-scale, done mostly using small sail vessels, between 4-6m long, with small engines. These vessels may employ various types of fishing gears, although not simultaneously, with the predominance of bottom-set panel gillnets with stretched mesh size from 30 to 60mm (knot-to-knot), handlines and spearguns.

About 60 fishermen, mostly from two villages (Maracajaú and Rio do Fogo) were estimated to be specialized at targeting parrotfishes. This specific fishery is also performed with the main three fishing gears: gillnets, handlines and spearguns. Fishermen from Rio do Fogo are the only ones who use gillnet (25%; N = 15) to catch parrotfishes. They use 40 to 50mm (knot-to-knot) mesh size gillnets to catch mainly *S. axillare*, *S. frondosum*, and 50mm to 60mm mesh size gillnets to catch *S. trispinosus* (**Figure 1**).

The remaining parrotfish fishermen use either handline or spearguns. Specifically, handline fishery is performed by 41% (N=25) of the fishermen to catch *S. axillare* and *S. frondosum* in only one village (Maracajaú). This fishery uses a little crab (*Uca* genus) as bait. Lastly, 34% (N = 20) of parrotfish fishermen use spearguns to catch *S. trispinosus* (in Rio do Fogo and Maracajaú; **Figure 1**). Since gillnet landings were in general highly specific, other species that could be landed together were not registered.

The parrotfish fishery using the gears described is done by sailboats in waters that range from 4 to 12m deep, on reefs environments. Usually the fishermen make short trips of about 4-8 hours, which always start early morning, mainly between December and May. This period of the year is more suitable for these fisheries for two main reasons. First, because lobster fishing, the most profitable local activity, is forbidden during this period, so the fishermen catch parrotfishes as an alternative resource; second, because the weather conditions are more favorable to diving (less wind/rain and more warm/clear water).
Data sampling

We sampled parrotfish landing monthly in Maracajaú and Rio do Fogo harbors, from September 2013 to August 2014. One of us was at the harbors during four consecutively days (from 10:00am to 4:00pm, approximately) each month, spending two days in each locality per field trip. During sampling, we recorded information about species caught, gears used, crew size, date and time duration of the fishing. We then estimated the annual total catch based on days of fishing in a year, using the catch registered and number of fishers in the locations.

We randomly chose five individuals of each species of parrotfish from each fish landing to be measured and weighted. We also identified the sex of the individual when it was either a *S. axillare* or *S. frondosum*, because these species present sexual dimorphism.

We measured and weighted 355 parrotfishes from 37 landings: five from Maracajaú and 32 from Rio do Fogo (*Table 1*). We could not extend our sampling for two main reasons. First, not all the fishermen were collaborative and sometimes they did not allow the record of the fish biological parameters. Second, the selling of the fish is always a dynamic and fast process that takes place right upon the fishermen’s arrival; thus, several times the catch was sold before we could measure and weight it.

**Table 1**: Number of parrotfish measured and weighted, per species, during landings in each sample site.

<table>
<thead>
<tr>
<th>Species/N° of landings sampled per locality</th>
<th>Number of individuals measured and weighted per locality</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maracajaú (5 landings)</td>
<td>Rio do Fogo (32 landings)</td>
</tr>
<tr>
<td><em>S. axillare</em></td>
<td>30</td>
<td>85</td>
</tr>
<tr>
<td><em>S. frondosum</em></td>
<td>30</td>
<td>85</td>
</tr>
<tr>
<td><em>S. trispinosus</em></td>
<td>-</td>
<td>125</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>60</strong></td>
<td><strong>295</strong></td>
</tr>
</tbody>
</table>

For these reasons, we could not obtain further biological parameters for these species in the study area. Hence, information about size at first maturity (*L*₅₀) of *S. axillare* and *S. frondosum* was obtained from Véras (2008), who established the *L*₅₀ of these species using specimens collected also
from small-scale fisheries performed in an area about 400 km away from the current study area. This author estimated the size at first maturity for *S. frondosum* at 17 cm of total length (TL) for females and 17.7 cm of TL for males, and for *S. axillare*, 20.2 cm of TL for females (Veras, 2008). Veras (2008) did not estimate the size at first maturity for *S. axillare* males due to the low number of individuals sampled.

Information about size at first maturity of *S. trispinosus* was obtained from Freitas (2015), who also established the L₅₀ (38.5 cm of TL) of this species using specimens collected through artisanal fishery in the Abrolhos Bank (1500 km away from the study area).

These parameters estimated from the literature were obtained in two areas that show similar ecological features in relation to our study area (Veras, 2008; Freitas, 2015): reef environments with hot spots of parrotfish occurrence.

**Data analysis**

Since the catch statistics varied markedly between boats and between fishermen, we computed the catch per unit effort (CPUE) as the total catch in a fishing operation (in kg.), standardized per haul duration (in h) and crew size (in n⁻¹; CPUE in kg.h⁻¹n⁻¹; Hallwass et al., 2010).

Kruskal-Wallis tests were used to test for differences among CPUE values, as the data did not show a normal distribution, even after the logarithmic transformation. In order to obtain a balanced number of samples among gears, samples were randomly chosen using the “samples” function in R (R development Team, 2014). Pair-wise comparisons were computed using the Dunn test to determine which CPUE values were significantly different. In addition, a non-metric multidimensional scaling (MDS) was applied to identify similarity between fishing gears. The Bray-Curtis index was used as a similarity measure and the package “vegan” of the R software was used to perform the analysis.

We used one-way ANOVA comparisons to test for differences among the gear types regarding the fish total length (TL). After obtained a balanced CPUE dataset, we log transformed the values to
down weight extreme values and to ensure a normal distribution and homoscedasticity. When we found some overall significance, we computed pair-wise comparisons using Tukey–Kramer honest significant differences (HSD) test to determine which gears were significantly different. In addition, we performed a Multidimensional Scaling (MDS) to identify similarity among fishing gears on the TL. Data were scaled and Euclidean distance matrixes were used as similarity measure.

Finally, we used a Pearson's Chi-squared test to compare the proportion of mature and immature individuals of *S. trispinosus* caught by different gears using the “chisq.test” function in R. This test was used only for *S. trispinosus* because all individuals of *S. axillare* and *S. frondosum* were caught above the size of first maturity.

**Results**

A total 54 of fish landings were sampled between September 2013 and August 2014 in the area of study. *S. trispinosus* was present in 26 of these landings, while *S. frondosum* and *S. axillare* were registered in 37 landings each. Some landings had more the one species present.

The total catch of parrotfish registered was 2.3t, being 1.2t of *S. trispinosus* and 1.1t of both *S. axillare* and *S. frondosum* together. The latter two were summed because these species were usually caught together either with handlines or gillnets, and many times it was not possible to weigh them separately. The annual total catch of *S. trispinosus* was estimated in 9.4 tons, while *S. frondosum* and *S. axillare* were estimated at 15.4 tons, totaling 24.8 tons of parrotfish fished per year in the study area.

For *S. trispinosus*, 54% of the landings were from spearguns and 46% were from gillnets (which 27% were 50mm mesh size gillnets and 19% were 60mm). For *S. axillare* and *S. frondosum*, 40% of the landings were from handlines, whereas 60% were from gillnets (which 20% were from 40mm mesh size gillnets and 40% were 50mm).

The CPUE values varied between gears (Kruskal-Wallis chi-squared; p-value < 0.001; Table 2). Handline is the gear type that had the lowest CPUE values (mean 0.92; 2 +/- 0.37). On the contrary,
gillnet 50mm knot-to-knot showed the highest CPUE values (mean 4.2; 6 +/- 0.41), followed by gillnet 60mm (mean 2.8; 4.66 +/- 1), gillnet 40mm (mean 2.31; 4.58 +/- 0.5) and speargun (mean 2; 8.1 +/- 0.83; Figure 2), respectively.

Table 2: Comparison among CPUE values of five gears used on parrotfish fisheries (*Dunn test at 5% probability).

<table>
<thead>
<tr>
<th>Gears</th>
<th>Gillnet_40</th>
<th>Gillnet_50</th>
<th>Gillnet_60</th>
<th>Spear</th>
<th>Handline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gillnet_50</td>
<td>0.058</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gillnet_60</td>
<td>0.224</td>
<td>0.209</td>
<td>0.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spear</td>
<td>0.301</td>
<td>0.148</td>
<td>0.407</td>
<td></td>
<td>0.014¹</td>
</tr>
<tr>
<td>Handline</td>
<td>0.014¹</td>
<td>0.000¹</td>
<td>0.001¹</td>
<td>0.003¹</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2: Mean CPUE of parrotfish per fishing gear to into the complex of coral reef [CPUE = catch (Kg) × fishing duration (hours)^-1 × crew size^-1].

Except for handline, the data indicated that all the other gears are similar among them, particularly gillnets of 50mm and 60mm knot-to-knot (Figure 3).
Figure 3: Two-dimensional MDS plot of the CPUE (catch (Kg) × fishing duration (hours)\(^\text{1}\) × crew size\(^\text{1}\)) per fishing gear, using the Bray-Curtis similarity index.

Fishing gear selectivity

Only females of *S. axillare* were sampled in the landings. On the other hand, the samples of *S. frondosum* provided a more equivalent gender division: 56.7% of sampled were female. For *S. trispinosus*, it was not possible to distinguish males and females because this species does not present sexual dimorphism.

There was no significant difference among mean lengths of *S. axillare* and *S. frondosum* caught with different gears (*Table 3*). Individuals of *S. trispinosus* caught with gillnets (50mm and 60mm knot-to-knot) did not differ in average length either. However, individuals of *S. trispinosus* caught with spearguns showed significantly higher average length than the ones caught with other gears (*Table 3*).

*Table 3*: Comparison among average lengths of three species of parrotfish caught by different fishing gears (N = 30 per treatment; \(^\text{1}\)Tukey test at 5% probability; NA – does not apply).
Mean lengths (cm) of parrotfish caught by different fishing gears

<table>
<thead>
<tr>
<th>Species</th>
<th>Gillnet 40mm</th>
<th>Gillnet 50mm</th>
<th>Gillnet 60mm</th>
<th>Handline</th>
<th>Speargun</th>
<th>F value</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>S. axillare</em></td>
<td>27.2</td>
<td>27.6</td>
<td>NA</td>
<td>27.4</td>
<td>NA</td>
<td>0.562</td>
<td>0.572</td>
</tr>
<tr>
<td><em>S. frondosum</em></td>
<td>25.7</td>
<td>25.9</td>
<td>NA</td>
<td>26</td>
<td>NA</td>
<td>0.111</td>
<td>0.953</td>
</tr>
<tr>
<td><em>S. trispinosus</em></td>
<td>NA</td>
<td>27.2</td>
<td>30</td>
<td>NA</td>
<td>39.3¹</td>
<td>47.053</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Frequency distributions of *S. axillare* and of *S. frondosum* indicate that these species are being caught above the size at first maturity (L50 - average size at which 50% of the individuals are mature), regardless of the fishing gear used (*Figure 4 and 5*).

**Figure 4**: Length frequency distribution of grey parrotfish (*S. axillare*) caught by gillnet with 40mm of mesh size (A; N = 35), gillnet with 50mm of mesh size (B; N = 50), and handline (C; N = 30). (L50 – estimated size at first maturity of this species = 20.2cm).

**Figure 5**: Length frequency distribution of agassiz’s parrotfish (*S. frondosum*) caught by gillnet with 40mm of mesh size (A; N = 35), gillnet with 50mm of mesh size (B; N = 50), and handline (C; N = 30). (L50 – estimated size at first maturity of this species = 17cm for females and 17.7cm for males).

On the other hand, length frequency distribution of *S. trispinosus* indicates that this species is
being caught mostly before it reaches maturity, mainly by gillnets. The higher proportion of mature individuals was found in catches from spearfishing (Figure 6). Differences on proportion of mature and immature individuals of *S. trispinosus* caught by all gears were significantly different (Pearson's Chi-squared test; p-value < 0.001).

**Figure 6:** Length frequency distribution of greenback parrotfish (*S. trispinosus*) caught by gillnet with 50mm of mesh size (A; N = 30), gillnet with 60mm of mesh size (B; N = 35) and speargun (C; N = 60). (L₅₀ – estimated size at first maturity = 38.5cm).

**Discussion**

*Current trends of parrotfish harvesting and its effects*

The purpose of this work was to assess gear-selectivity and fishing pressure on the three species of parrotfishes most commonly caught in the Northeastern Brazilian coast and to develop tools to support the guidelines for the management of parrotfish fishery.

Our results highlight a pattern similar to the trends of coral reef herbivorous fishes described by Edwards et al. (2013) – a relatively high number of fish with a small body size in areas where fishing is allowed. Indeed, the maximum length sampled in landings was relatively lower than the maximum length attained for *S. axillare* and *S. frondosum*, according to the literature. Here, the maximum length measured for *S. axillare* was 31cm (two individuals), whereas the maximum length registered for this species is 37cm of total length (TL; Moura et al., 2001). For *S. frondosum*, the maximum length measured was also 31cm (two individuals) whereas the maximum length registered is 35cm of TL (Moura et al., 2001).
This is not necessarily bad news for *S. axillare* and *S. frondosum* because these two species are being caught above the size of first maturity, therefore fishermen are neither removing the pre-reproductive small ones nor the most fecund larger ones. However, this could also indicate that the larger individuals were already fished and now are rare in the population.

For *S. trispinosus* the scenario is worse. While the maximum length attained for this species is 80 cm of TL (Moura et al., 2001), the largest individual in this study measured was 60 cm and the remaining ones were all below 50 cm of TL, most of them below the size at first maturity. This could be an indication that larger individuals are already very rare in the area.

Even though this latter hypothesis requires validation due to the low number of individuals sampled here, the loss of older, and therefore larger fish, threatens the maintenance of fish stocks, because harvesting the larger individuals has biological and ecological damaging effects on fish population (Birkeland and Dayton, 2005). Specifically, older fishes have an exponentially greater fecundity, higher larvae production and longer spawning season, therefore the selective removal of the big ones affect all of these features and the population as a whole (Berkeley et al., 2004; Bobko and Berkeley, 2004). Also, the removal of larger individuals selects for slower growth and for reproduction at a smaller size (Conover and Munch, 2002), causing early maturation, reduced fecundity and the fishing-down process (Welcomme, 1999). In particular, the fishing-down process (Welcomme, 1999) or miniaturization (Liang, et al., 2014) predicts that the body length and weight of exploited fishes at the same age decrease consistently over time through the gradual replacement of large-bodied individuals for small-bodied ones (Stergiou, 2002; Castello, 2013a). As a large-bodied species, *S. trispinosus* tend to be more vulnerable to the fishing-down process.

From an ecological perspective, the entire food web and the structure of the fish community may change due to the selective exploitation of larger fishes, even if these are lower trophic level species (Friedlander and DeMartini, 2002). In the case of parrotfishes, smaller individuals (< 20 cm) do not have the same potential to excavate the substratum as the larger ones (> 20 cm), which extract up to 7 kg m\(^{-2}\) y\(^{-1}\) of benthos from shallow reef areas (Bruggemann et al., 1996).
The spearguns, used to catch *S. trispinosus*, showed the second highest value of CPUE and caught a higher proportion of mature individuals. As speargun fishermen actively hunt, and visually select the fish by size, those mature individuals are also most likely the biggest ones available. While this could protect immature individuals, it could also threaten the largest ones, if such fishing does not follow fishing restrictions.

Following the results shown here, some specific management measures will be needed for the conservation of the three parrotfish species.

**Gear management measures**

The measures to achieve parrotfish harvesting sustainability should include the permission of only those gears that have the least impact on local stocks. For parrotfishes, gillnets are the most non-selective gear, catching a high proportion of immature individuals of *S. trispinosus* and having the highest CPUE values, besides catching the largest amounts of the three species. On the contrary, the handline showed the lowest average CPUE, with all the individuals caught above the size at first maturity. Spearguns caught a higher proportion of mature individuals of *S. trispinosus*, but still requires management control because this gear still caught a large quantity of immature individuals, and also because the largest individuals must be maintained in the population.

Sustainability is more likely to be achieved by banning the use of gillnets, which would especially benefit *S. trispinosus*. On the other hand, it would represent a reduction on the fishing of *S. axillare* and *S. frondosum*, which are caught at reasonable sizes by gillnets.

Furthermore, to ensure the conservation of parrotfish, it is also essential to determine a slot size limit (Brousseau and Armstrong, 2011) to prevent the high mortality of larger and more fecund individuals (terminal males). Such measures would be useful to protect *S. trispinosus*, where we could not observe large individuals, despite the fact that part of the fisheries is based on visual selection by the fishermen, and also to protect *S. axillare*, where males were not sampled. Such disequilibrium between males and females could be an indicative of unsustainable fishing (Hawkins and Roberts,
meaning that individuals are being caught before they reach the size for sex change.

We specifically recommend the size slot measure to be established at $L_{50}$ for the minimum size of all species. The maximum size should be established in a way to ensure the maintenance of large individuals in the population to preserve the genetic variability and also to guarantee higher levels of reproduction (Birkeland and Dayton, 2005). In order to established the maximum size limit, a specific study for each species is required.

A slot size for the catch is most appropriate to be implemented for handline and speargun fishing, because with these gears fishermen can actively choose the fish to be caught, either returning the others to the water, in the case of handline, or not shooting very small and larger individuals of $S.\ trispinosus$ in the case of speargun.

While the implementation of gear control and slot size limit may oppose the latest Brazilian Red List, which recommended the total banning of $S.\ trispinosus$ fishery, as this was classified as Endangered, it could support the request for management for $S.\ axillare$ and $S.\ frondosum$. These two species, classified as Vulnerable, can still be fished, as long as fishing is done under restrictions. Such restrictions are still to be defined based on scientific evidence and advice.

The Brazilian Red List caused uproars by different groups of fishermen, who questioned the criteria for inclusion of the different species and persuaded the minister of fisheries and aquaculture to review the list. A repeal of the list would be a serious hindrance for the conservation and management of multiple species (Lees, 2015). On the other hand, if this list is implemented, all the vulnerable species will require specific management measures, and this study is a timely contribution for, at least, parrotfish. However, the legal acceptance of the list on itself will not assure parrotfish management. This is because fishery management in Brazil, except for a few areas, tends to be rather lax. Hence, our recommendations per se or the total banning of any fisheries will only be meaningful under enforcement.

An additional important issue is the international demand for Brazilian parrotfish. Every month, tons of $S.\ frondosum$ and $S.\ axillare$ from large-scale trap fishery together with others species of reef
fish are exported to places such as the United States and the European Union (Cunha, 2012). Thus, another key action to reduce the pressure on Brazilian parrotfishes would be to ban their exportation, mainly because the consumers in such countries are unaware of the impacts they cause when they eat Brazilian parrotfishes. Hence, addressing the market as a potential solution to decrease the pressure on important reef species could be an important step, although a hard one to take due to economic pressure.

Conclusions

This study is the first that aims to address the issue of gear selectivity used in the parrotfish fisheries. It is shown here that some species can undertake the pressure of gillnets, while others cannot. As a precautionary approach, it is recommended that gillnets be banned, even if temporarily until further studies are performed. However, ideally, this decision should be discussed with fishermen to achieve compliance and success in the protection of parrotfish species, otherwise it would only stimulate poaching. Fishermen’ involvement could strength the legitimacy of management, avoiding upheavals and drawbacks to conservation, as recently observed with the new Brazilian Red List.

Additionally, it is recommended the adoption of a slot size for, at least, two of the parrotfish studied, *S. trispinosus* and *S. axillare*. The first one would be due to the complete absence of large individuals from the sampling, including from fishing done with spearguns, when fishermen get to visually choose what they want and tend to target the largest ones available. That situation on itself suggests that there has been some significant pressure on larger individuals. For the latter species, the recommendation is due to the absence of males in the sampling, which suggests that fishing is removing individuals before they have a chance to change sex.

Because protection is urgently needed for the conservation of marine species, research on the fishing effects caused by gear selectivity is important for fisheries management. Further information about biological parameters of parrotfish species could support this study and refine future
management measures, but in the absence of those and given the first alarming signals, a precautionary approach with the prohibition of gillnets to catch parrotfish and the definition of a slot size for the other gears is an urgent first step.

References


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