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Effects of time-area closure on tropical tuna purse-seine fleet dynamics through some fishery indicators

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Abstract – Time-area closures have become a frequently used tool to control fishing effort and protect feeding and spawning areas. However, because time-area closure strata are mainly based on biological and ecological considerations, and do not accounts for fishermen's behavior-at-sea, this type of regulation tool may not entirely achieve its objectives. With the aim of comparing the impact of two different time-area regulations: (1) a moratorium on Fish Aggregating Devices (FAD) sets (1997–2005) and (2) a no-take area for surface fleets (2005–2010) on the dynamics of the European (EU) tuna purse seine fleet operating in the eastern tropical Atlantic, several fishery indicators were evaluated through a Before-After, Control-Impact (BACI) approach. The results showed that prior to any regulation, the fleet used to be concentrated within the Gulf of Guinea area. During the first years of the moratorium on FAD (from November to January within a large region in the eastern Atlantic) there was a movement towards outside the protected area, increasing the total sets on FAD (restricted fishing activity). In general, this moratorium fulfilled its objectives; however, it was not respected during the last years of this regulation. The no-take time-area closure restricted all tuna catches for the surface fisheries but only in November and within a small area (i.e., the Picolo zone). As a result, there was an increase in activities on free schools outside the no-take area. Our findings suggest the use of some simple fishery indicators to understand fleet dynamics as a complement of ecological information before implementing new time area closures. Furthermore, since tunas are highly mobile species, anticipating the possible re-allocation of effort of purse seiners to adjacent areas in response to the spatial regulation is required to design different candidate time-area closures and to evaluate their effectiveness to protect juvenile tunas.

Key words: Time-area closure / Fleet dynamics / Tropical tuna / Fishery indicators

1 Introduction

Seasonal area closure has been used by managers to protect harvested species in mature fisheries (Branch et al. 2006; Agardy et al. 2011). However, this management tool is more likely to be useful when species are of low mobility or sessile, while for highly mobile species such tool may have little effectiveness in protecting them (Hilborn et al. 2004; Harley and Suter 2007; Jensen et al. 2010). For highly mobile species, it was suggested from simulation studies that to obtain some benefits, a very large closure area (as large as 85% of the total area of the stock) may be required (Le Quesne and Codling 2008).

This case study concerns the tropical tuna surface fishery (purse seiners and baitboats) which is a multispecies fishery on yellowfin (*Thunnus albacores*), skipjack (*Katsuwonus pelamis*) and bigeye tuna (*T. obesus*). Tuna schools are detected visually at the surface of the sea and the main fishing modes depicting purse seine operations are non-associated school sets (mainly dominated by large yellowfin) and natural, or artificial, drifting floating object sets (in this case the catch is composed by juvenile yellowfin and bigeye and by juvenile and adult skipjack).

1.1 Spatial regulations in the eastern tropical Atlantic Ocean

In 1996, by means of recommendation [96-01], the International Commission for the Conservation of Atlantic Tunas (ICCAT) was aware of the large increase in the catches of bigeye tuna and juveniles observed since the beginning of the

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Table 1. Main characteristics of the two management measures adopted by ICCAT for tropical tunas.

	Moratorium on FAD	Time-area closure
Years	1997–2005	2005–2010
Months	November-January	November
Area	4° S-5° N and 20° W and the African coast	5° N and Equator 0° and 10° W to 20° W (Picolo Zone)
Restrictions	Fishing on FAD	All surface fishing gears

1990s in the Atlantic Ocean. Hence, within the framework of the Bigeye Tuna Year Program (BETYP), ICCAT requested that further analysis must be carried out on these issues to determine protected fishing areas and seasons through observer programs for all type of fleets. In the case of the EU purse seine fleets (mainly Spain and France), different assumptions were considered to explain the increase in juvenile catches. Among others, it was a change in catchability due to the extension of the use of artificial floating objects (or Fish Aggregating Devices, hereafter named FAD), in new areas in the eastern Atlantic Ocean (Ariz and Gaertner 1999).

In such a context, the purse seine fishery has been the subject of several regulatory measures. In 1997, the French and Spanish tuna boat owner companies implemented a voluntary protection plan for juvenile tunas, which consisted of a ban on FAD fishing operations during a three-month period over a large portion of the Gulf of Guinea. This moratorium was adopted and extended to all surface fleets by ICCAT in 1999. As there were few changes since the voluntary moratorium, the entire period of 1997–2005 is named hereafter as moratorium on FAD.

In 2004, ICCAT adopted recommendation [04-01] "Multi-year conservation and management program for bigeye tuna", with the goal of conserving and managing bigeye tuna stocks and because of the concern about the increase in illegal, unreported and unregulated (IUU) fishing activities. This recommendation entered into force in June 2005, and consisted in resizing the area limits of the former recommendations and reducing the months' period (Table 1). Unlike recommendations [98-01] and [99-01], which banned the use of FAD, recommendation [04-01] prohibited tuna catches in the restricted stratum for all surface fishing gears, which is named hereafter as closure or no-take area.

Different studies have evaluated the effects of these spatial regulations, mainly on the catches (Diouf et al. 1999; Goujon and Labaisse-Bodilis 2000; Ariz et al. 2001; Goujon 2004a; Goujon 2004b; Ariz et al. 2005; Cass-Calay et al. 2006; Brooks and Mosqueira 2006; Ariz et al. 2009; De Bruyn and Murua 2010). However, there is no document that has evaluated the consequences of the establishment of a spatial regulation on purse seine fleet behavior at sea. Even if the idea of implementing a spatial regulation is to protect the harvest species, it will affect the users in some way, and thus it is necessary take into account the fleet response to improve the fishery management (Johannes et al. 2000; Wilen et al. 2002; Salas and Gaertner 2004; Kaiser 2005; Branch et al. 2006; Poos and Rijnsdorp 2007). For this reason, the aim of this paper was to evaluate the effects of two types of spatial regulations on the purse seine fleet behavior using different fishery indicators.

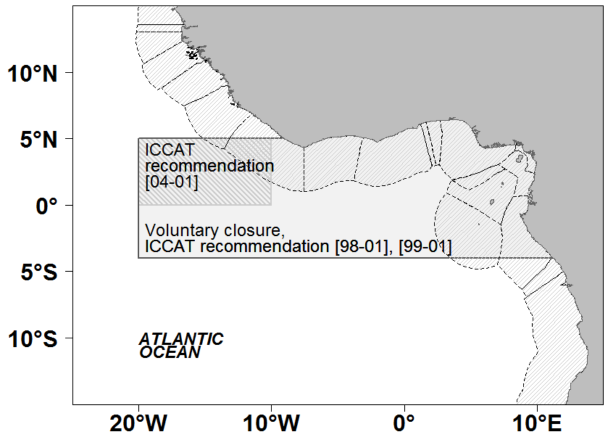

Fig. 1. Zones of the different spatial regulations: (1) the voluntary moratorium and ICCAT recommendations [98-01] and [99-01] on Fishing Aggregating Devices (FAD) were instituted during the period 1997–2005 from November to January of the following year (gray rectangle); (2) the no-take regulation in November that replaced the moratorium on FAD was in the Picolo zone from 2006 up to the present (small shaded rectangle). The shaded contour represents the economic zones (200 nautical miles).

2 Materials and methods

2.1 Data

The analysis was based on logbook data reported by EU purse seiners (France, Spain, and associated flags) before the multispecies correction procedure made on a routine-basis with samples taken on landing sites. Consequently, some misidentification between species may occur. It was decided, however, to work with these declarative data because they are more representative in terms of size category of the fish in a specific set than corrected data on the fishing modes (i.e., in contrast to the corrected data which reflect the sampling species composition over a large strata, the declarative data better reflect the size categories of tunas caught during a specific set, associated with a specific fishing mode and specific spatial coordinates).

For the moratorium on FAD period an increment is expected in the activities on free schools both inside and outside the moratorium on FAD area (Fig. 1), whereas for FAD activities there should be an increment outside moratorium area. On the other hand, the fishing activities (except those on free school) are expected to decrease inside the area (e.g., days with catch) once the moratorium enters into force. Regarding the no-take recommendation [04-01], a total reallocation of surface fishing effort is expected and, as a consequence, a rise in fishing activities outside the area during the month of November on both free schools and FAD as well as the corresponding catches. A summary of the characteristics of each regulation is presented in Table 1.

2.2 Fishery indicators

To analyze the activity of the purse seine fleet and to estimate whether the fleet dynamics changed as a consequence of the two management measures, different indicators were used on a monthly basis (Table 2). These indicators were averaged for the vessels operating in a given month. Such indicators were: the total number of fishing days (Dy^+); the number of $1°\times1°$ squares explored successfully (Sq^+) which represent the success of the fleet in terms of catch independently of the fishing method used; the fishing time (FT) which represents the time spent by the fleet in the zone; the number of sets on free schools ($FrSc$), used to detect whether there was an increase in the effort associated with this method due to the interdiction on FAD; the number of sets on FAD (FAD), assumed to represent directly the effects of the regulation measures (as mentioned previously the aim of the regulation on FAD was to reduce the catch of juveniles). In addition, these last two indicators were considering positive sets and unsuccessful sets (i.e., without catch). Catch with FAD ($FadC^+$), catch of juveniles with FAD ($JuvC^+$) and catch of large yellowfin tuna on free schools (YFT^+) are representative of the fishing modes selected by fishermen.

Fishery indicators were performed for the two periods considered (1995–2005 and 2000–2008). With the aim of pointing out a contrast between before and after the corresponding spatial regulation, the first period was divided from 1995 to 1997 (before) and from 1997 to 2005 (after) and the second period was from 2000 to 2004 (before) and from 2005 to 2008 (after). Not all the vessels operated in both periods of time. Consequently, to ensure that the results represent the effects of each regulation, only vessels with at least 50% of presence in each period were considered. This supposes that these vessels would have more knowledge about spatial and temporal strata. Furthermore, some vessels operated only before or after each regulation, and in this case the information supplied by them did not take into account the effects of the regulations. Thus, the indicators were calculated on the basis on information provided by 33 and 25 vessels for the first and the second period, respectively.

2.3 Statistical analysis

Impact assessment aims to evaluate (i) whether or not a stress has changed the environment; (ii) to determine which components are adversely affected; and (iii) to estimate the magnitude of the effects. Theoretically, when information is available prior to the potential impact, the design is often referred to as a Before-After Control-Impact (BACI) design (Smith 2002). In addition, when historical data are available it is possible to estimate the effects of an impact, and if it is possible to have a control zone it will improve the estimation of such an impact (Eberhardt and Thomas 1991; Wiens and Keith 1995).

Since the moratorium region might suffer changes outside as well as inside for many reasons (e.g., changes in fishing effort over the years, large-scale environmental conditions, etc.) it was difficult to define a control zone. Consequently, the assessment of the effects on purse seine fleet dynamics was conducted by a Before-After design (see Appendix 1 for an overview of BACI analysis). This is the simplest approach, which involves data prior to the activity and compares them with data after the activity. The typical approach to analysis is to treat the data as independent samples (Eberhardt and Thomas 1991; Wiens and Keith 1995; Smith 2002).

The analysis[1] was carried out using ANOVA when the indicator data satisfy the assumptions of normality and homoscedasticity, or a Kruskal-Wallis test when assumptions were violated.

The data were divided inside and outside depending on the regulation measure and coded to differentiate the before and after period, permitting taking replicated samples at repeated times, because each year the impacted area was sampled by the vessels. The inside-outside interaction was difficult to interpret and to evaluate; thus, to determine if there was an effect outside of the area the same analysis with the corresponding data was carried out.

Notice that before the entry into force of the no-take regulation there was already an effect from the moratorium on FAD. To attempt to mitigate this effect, the period before closure was considered from 2000, because from this year all fleets had to comply with the moratorium on FAD and thus it was assumed that normal conditions were the moratorium.

In addition to the BACI approach, descriptive analyses were done to show the spatial distribution of the number of sets in both fishing methods (free schools and FAD) and before-after of the spatial regulations. To do this, an estimate was made of the average of the number of sets of each fishing method by each time a cell ($1° \times 1°$) was visited. The maps were carried out by using R package PBSmapping[2].

3 Results

3.1 Moratorium on fish aggregating devices

3.1.1 Before EU voluntary protection plan

Before the implementation of the moratorium on FAD (1995–1997) for the three-month period (November–January), each EU vessel carried out, on average, more fishing activities within the area than outside the moratorium area (Fig. 2). Only activities related with free schools had similar values throughout the time series. It must be stressed that within the protected area in November and December there were more sets on

[1] The analysis was conducted by using R version 2.11.1 URL http://www.R-project.org/

[2] PBSmapping: Mapping Fisheries Data and Spatial Analysis Tools. R package version 2.61.9, http://CRAN.R-project.org/package=PBSmapping

Table 2. Fishery indicators average Before-After each spatial regulation (moratorium on FAD and Picolo no-take area) and inside and outside each zone. Main statistics from Before-After analysis inside and outside of each spatial regulation (notice that fishing activities inside Picolo no-take area were banned). When the indicators were normal and homoskedastic (the variance of the errors over the sample are similar), an ANOVA was applied; the otherwise Kruskall-Wallis rank sum test was applied.

Moratorium on FAD					
		Inside		**Outside**	
Indicator	Description	Before	After	Before	After
Dy^+	Days with catch	10.2	5.8	4.7	5.1
Sq^+	Square visited with catches	7.3	4.4	3.5	4.1
FT	Fishing time (h)	282.3	251.8	145.9	160.7
FrSc	Number of free school sets	7.7	7.9	3.5	1.9
FAD	Number of FAD sets	8.6	2.1	3.6	6.1
$FadC^+$	FAD catch (t)	227.0	93.5	85.5	134.0
$JuvC^+$	Juveniles < 1.8 kg catch (t)	57.8	6.7	26.8	9.8
YFT^+	YFT catch on Free school (t)	99.9	91.0	114.2	30.6

Inside Moratorium on FAD								
ANOVA					Kruskall-Wallis			
Indicator	Sum Sq	*df*	*F*	Pr(>*F*)	Indicator	λ^2	*df*	*p*-valu
Dy^+	104.4	1	29.071	$8.54 \times 10{-}6$	*FT*	4.127	1	0.042
Sq^+	48.2	1	30.434	$6.04 \times 10{-}6$	*FrSc*	0.056	1	0.813
$JuvC^+$		1	24.345	$3.05 \times 10{-}5$	*FAD*	13.580	1	0.0002
					$FadC^+$	9.431	1	0.002
					YFT^+	0.056	1	0.813
Outside Moratorium on FAD								
Dy^+	0.60	1	0.132	0.720	*FrSc*	2.645	1	0.104
Sq^+	1.49	1	0.542	0.470	$JuvC^+$	1.182	1	0.277
FT	725.3	1	0.691	0.415	YFT^+	4.880	1	0.027
FAD	19.8	1	4.418	0.048				
$FadC^+$	7793	1	0.776	0.389				

No-take area			
	Inside	**Outside**	
Indicator	Before	Before	After
Dy^+	3.5	4.5	8.2
Sq^+	2.6	3.2	3.9
FT	124.8	174.8	226.5
FrSc	3.5	3.5	7.2
FAD	2.1	3.8	3.4
$JuvC^+$	3.6	6.6	14.0
YFT^+	60.0	24.5	102.0
$FadC^+$	142.8	118.1	137.7

Outside No-take area				
ANOVA				
Indicator	Sum Sq	*df*	*F*	Pr(>*F*)
Dy^+	30.01	1	6.663	0.036
Sq^+	1.14	1	1.060	0.337
FT		1	12.141	0.010
FrSc	29.34	1	6.712	0.036
FAD	0.45	1	0.769	0.410
$JuvC^+$	122.24	1	1.255	0.300
YFT^+	13344.1	1	22.551	0.0021
$FadC^+$	850.9	1	0.343	0.576

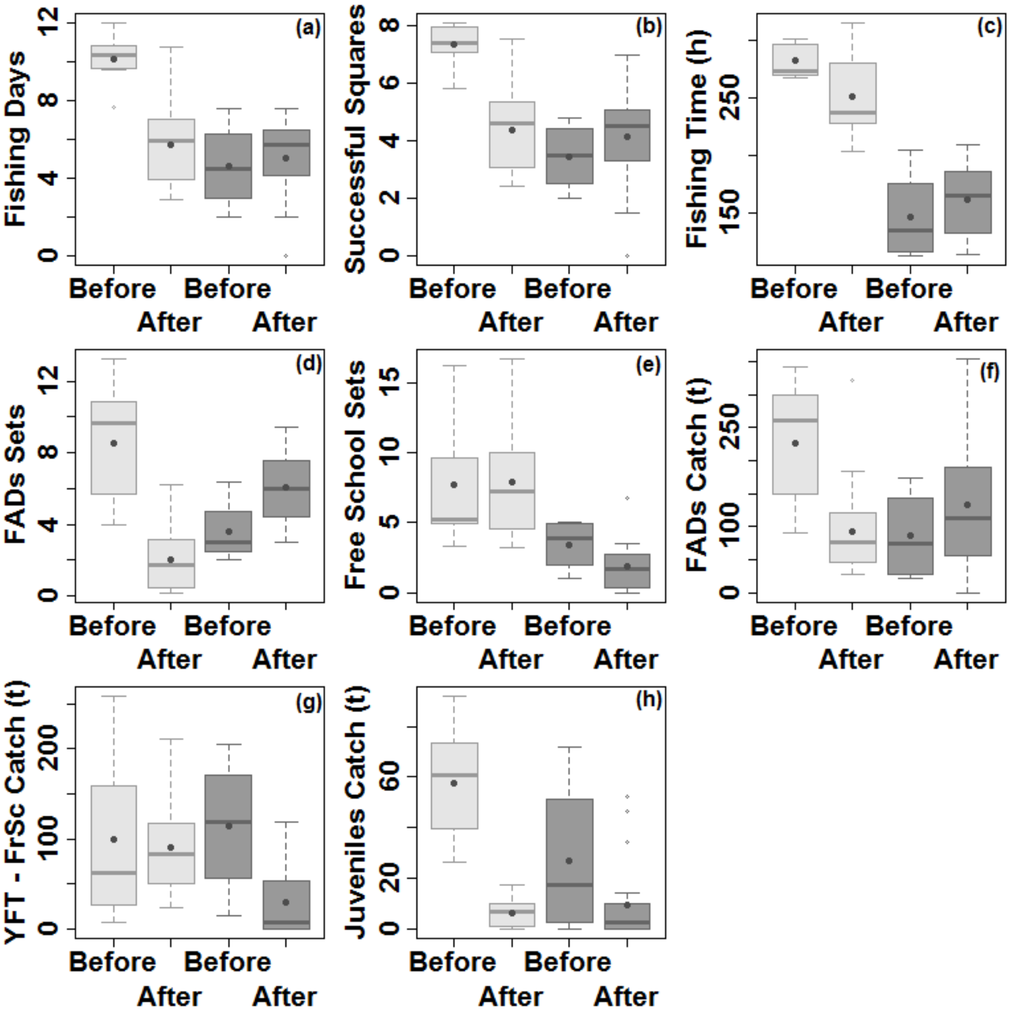

Fig. 2. Fishery indicators box-plot inside (light gray) and outside (dark gray) the moratorium on FAD for the three-month period before (1995–1997) and after (1997–2005). The average and the median are represented by points and stripes, respectively.

FAD than on free schools (Fig. 2d more detail in Fig. S1e, Appendix 2). Nevertheless, there was an increase in the number of sets on free schools in January (Fig. S1f, Appendix 2), while sets on FAD decreased, mainly inside the FAD moratorium area in the same months period (Fig. S1e, Appendix 2). Therefore, catches associated with each fishing method followed the same trend (Fig. 2f, g and Fig. S1g, h, Appendix 2). This pattern was similar for the catches of juveniles (<1.8 kg), during November–December 1995 and 1996 where the catches were the highest (Fig. 2h and Fig. S1d, Appendix 2). On the other hand, inside the moratorium on FAD zone the number of fishing days (Dy^+), the number of $1° \times 1°$ squares visited with catch (Sq^+), and the fishing time (FT) remained similar before the voluntary ban on FAD fishing entered into force (Fig. 2a, b, c, respectively, more detail in Fig. S1, Appendix 2).

3.1.2 After ICCAT recommendation

Once the voluntary moratorium on FAD followed by the ICCAT regulation was implemented, there were some changes in the patterns of the indicators analyzed (Fig. 2). During November to January, the fishing days (Dy^+) and the number of successful squares (Sq^+) depicted a similar trend, both within and outside the moratorium on FAD area (Fig. 2a, b) while, in contrast, fishing time (FT) reminded higher inside the area (Fig. 2c).

With respect to sets on FAD (FAD), there was a decrease inside the area, as expected. Nevertheless, this indicator increased outside and, specifically around the moratorium zone (Fig. 3e). Since recommendation [99-01], there were no further modifications and the measures established in this recommendation remained constant in the following years. It must be pointed out that when the voluntary moratorium on FAD was in force (until January 2000) the FAD sets were made principally outside (Fig. 3e). However, when ICCAT recommendation [99-01] entered into force, the EU fleet carried out this fishing method both inside and outside the zone (Fig. 3f).

The juveniles catch (<1.8 kg) inside the moratorium on FAD area was similar to that outside (Fig. 2h). On the contrary, the number of sets on free schools ($FrSc$) remained

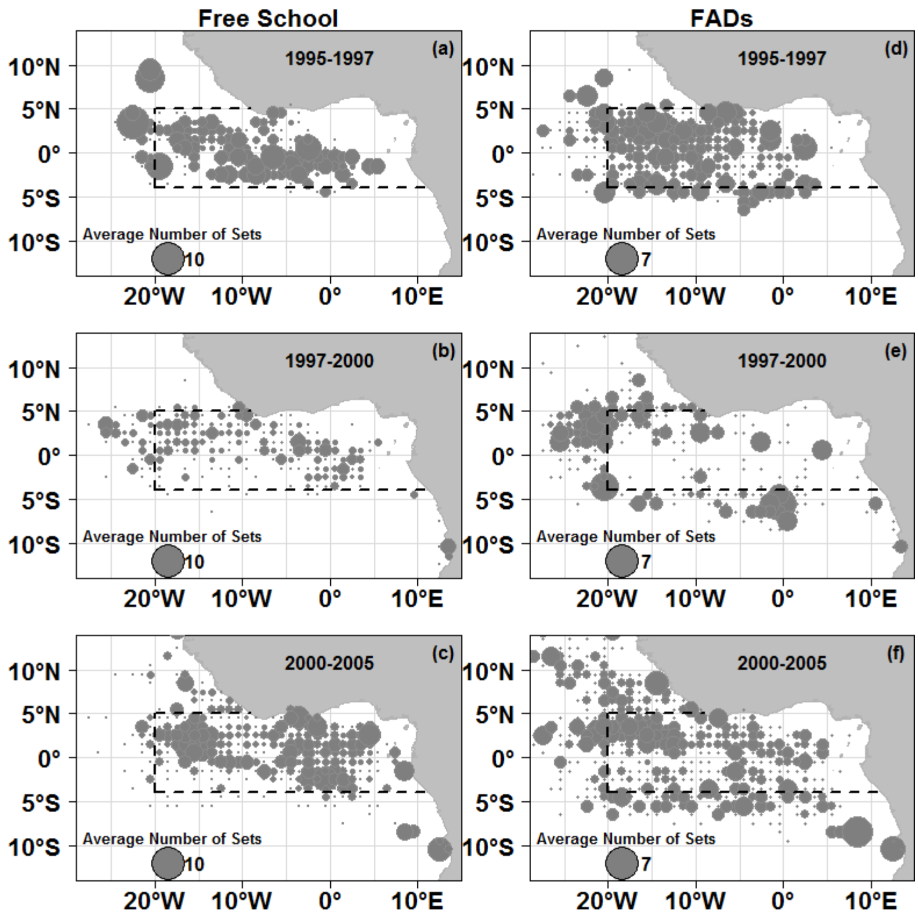

Fig. 3. Spatial distribution (only for the three-month moratorium on FAD) of the average number of sets on free schools and FAD (by 1° × 1° square); corresponding to (a, d) before moratorium for the period 1995–1997, (b, e) the EU purse seiners voluntary moratorium on FAD 1997–2000, and (c, f) after the moratorium on FAD adopted by ICCAT (recommendation [99-01]), 2000–2005. Dashed black lines correspond to moratorium area.

concentrated inside (Fig. 3b, c), reaching their peak in January; the same trend was logically observed for the catch of large yellowfin tuna on free schools (YFT^+) (Fig. S1f, h, Appendix 2).

3.1.3 Before-after approach

Because it was difficult to interpret interactions in a BA design, the analysis was conducted separately inside and outside the moratorium area.

Inside moratorium on FAD area

From the BA analysis applied to inside the moratorium area, significant differences were evident in almost all the indicators, except the number of sets on free schools (*FrSc*) and the catches of large yellowfin tuna associated with this method (YFT^+) (Table 2). The fishing days (Dy^+), the number of successful squares (Sq^+) and the fishing time (*FT*) decreased once the moratorium on FAD entered into force (Fig. 2a, b, c). Regarding the objective of the moratorium, there were significant differences in the number of sets on FAD (*FAD*) made inside the area and therefore FAD catches (Table 2) as well as juveniles catch ($JuvC^+$) (Fig. 2d, f, h).

Outside moratorium area

With regard to the outside region, only the number of sets on FAD (*FAD*) and the large yellowfin catch (YFT^+) differed significantly before and after the moratorium (Table 2). For the first indicator there was an increase, while the second decreased (Fig. 2d, g, respectively). Despite fishing days (Dy^+), successful squares visited (Sq^+) and fishing time (*FT*) decreased inside the moratorium area, no significant differences on these indicators were observed outside (Table 2). On average, the FAD catch ($FadC^+$) was higher after the moratorium, although this increase was not significant (at the 5% level) (Table 2).

3.2 Time-area closure

3.2.1 Before ICCAT recommendation

As mentioned in the Materials and Methods section, ICCAT prohibited all surface fishing activities inside the Picolo

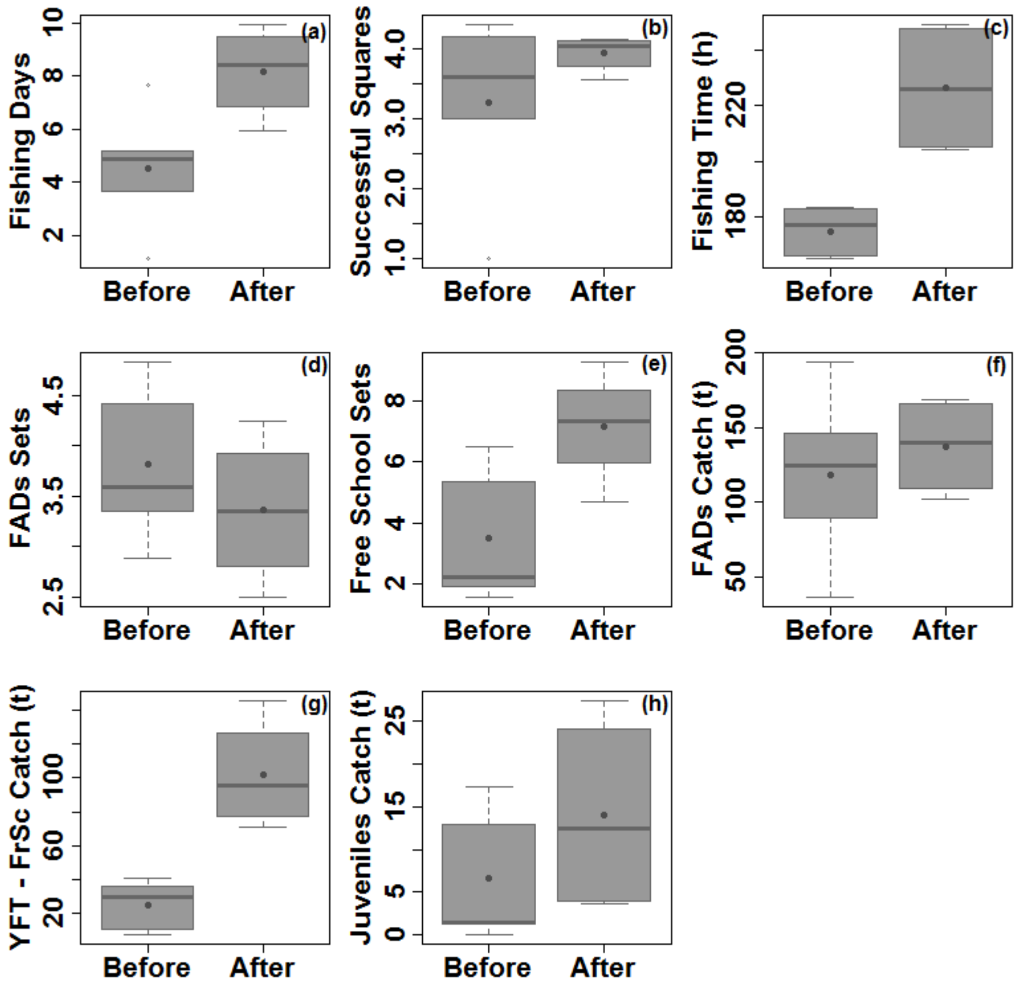

Fig. 4. Fishery indicators box-plot outside the Picolo zone for the regulation month (November) before (2000–2004) and after (2005–2008) the ICCAT recommendation [04–01]. The average and the median are represented by points and stripes, respectively.

area during the month of November after 2004; thus, fishery indicators were available and analyzed only outside no-take area. It should be noted that it was difficult to perceive the impact of such a small time-area closure (one month and a small area), while, on the contrary, the outside stratum was very large (Fig. 1). Despite this size difference, before the no-take area was established some indicators behaved in average similarly both inside and outside (Table 2). The large yellowfin catch on free schools (YFT^+) (Table 2, more detail in Fig. S2h, Appendix 2) and the FAD catch ($FadC^+$) (Table 2, more detail in Fig. S2g, Appendix 2) were both higher inside than outside the area, and this despite that the fleet spent more time outside than inside (Table 2). It should be noted that except the month of regulation the EU purse seine fleet had more activities outside the no-take area, but conversely, during the month of regulation (November), there was an increase in the fishery indicators (Fig. S2, Appendix 2). Only the catch of large yellowfin tuna and the corresponding number of sets on free schools (YFT^+ and *FrSc* respectively) did not present this general pattern (Fig. S2f, h, Appendix 2).

3.2.2 Before-after approach

Outside the closure area

The fleet increased its efficiency (i.e., days with catch) and fishing time significantly, but there was no difference in the number of successful squares visited (Table 2). The number of fishing days (Dy^+) increased significantly after the implementation of the spatial no-take regulation (Fig. 4a), while the effective area explored (Sq^+) remained unchanged (Fig. 4b). Unlike the situation observed during the moratorium on FAD, the number of sets on FAD (*FAD*) and the associated catch ($FadC^+$) did not increase (Fig. 4d, f, and Table 2).

In contrast to the slow increase in juveniles catch, there was a significant increase in the number of sets on free schools (*FrSc*) and their associated catches (YFT^+) (Fig. 4h, e, g, and Table 2). After the implementation of the closure area, the number of sets on free schools (*FrSc*) was located all around the Picolo area (Fig. 5b), while the sets on FAD (*FAD*) remained widespread throughout the area outside (Fig. 5d).

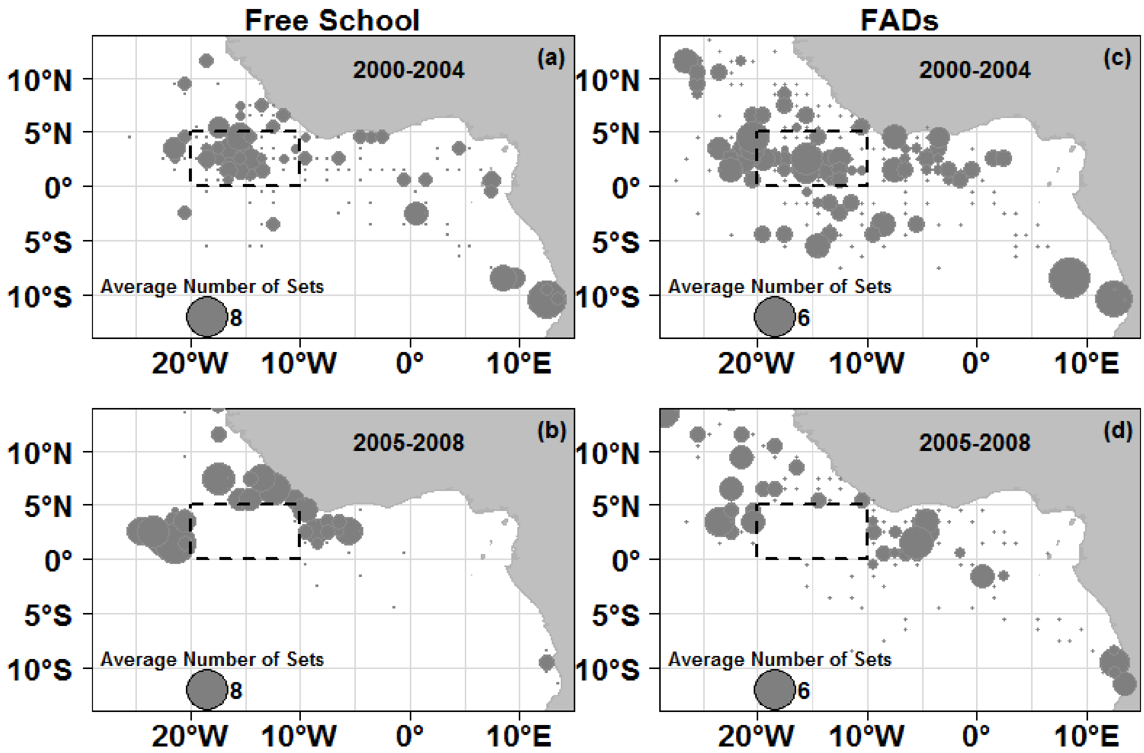

Fig. 5. Spatial distribution during the no-take regulation month (November) of the average number of sets on free schools and FAD (by 1° × 1° square); corresponding to (a, c) before the implementation of the no-take area in 2000–2004, and (b, d) after the ICCAT recommendation [04-01] for the period from 2005 to 2008. Dashed black rectangle corresponds to the Picolo no-take area.

4 Discussion

Marine protected areas (MPA) could be considered as a powerful tool to face ever-increasing over-exploitation of marine resources and deterioration of ocean habitats (Agardy et al. 2011). According with Hastings and Botsford (2003), MPA could have two fundamental objectives: preserve biodiversity and maximize fishery yields. The use of MPA, however, could have shortcomings, Agardy et al. (2011) mention five main types of such shortcomings: (1) MPA that as a result of their small size or poor design are ecologically insufficient; (2) inappropriate MPA plan or management; (3) MPA that fail due to the degradation of the unprotected adjacent areas; (4) MPA that do more harm than good due to unexpected consequences of management; and (5) MPA that seem to protect when in fact offer no such protection.

Furthermore, MPA should be selected on the basis of biological, oceanographic, physiographic, socio-cultural, political and economic criteria (Zacharias et al. 2006). Defining a time-area closure, in terms of no-take or prohibiting a specific fishing practice (e.g., FAD fishing), is not trivial, since the effectiveness of a spatial regulation for migratory fish depends on different factors such as: (1) the state of the stock; (2) some biological parameters (e.g., natural mortality of juveniles and exchange rates among fishing grounds); and (3) fishery characteristics (e.g., the fishery strategies developed due to the multi-species nature of the tropical purse seine fishery). In addition, it has been shown that in presence of catch quotas, as recently adopted for bigeye, seasonal or permanent closure area may have the unwanted effect of increasing effort in adjacent areas open to fishing (Dinmore et al. 2003; Hilborn et al. 2004) and consequently such regulation should be implemented in conjunction with other control measures (Horwood et al. 1998; Murawsky et al. 2000; Stefansson and Rosenberg 2005; Kaiser 2005; Jaworsky et al. 2006; Little et al. 2010).

The location and size of MPA are crucial issues which will determine the possible negative or positive effects from MPA enforcement, such as: (1) the reallocation of fishing effort outside the protected area; (2) MPA effectiveness facing oceanographic variability across space; (3) the time required for see the effects on stocks; and (4) the impact of overall higher total bycatch derived from the displacement of fishing effort to less productive areas (Zacharias et al. 2006).

In the mid 1990s, ICCAT was concerned about the large increase in the catch of bigeye tuna and juveniles due to the massive use of FAD since the early 1990s, as well as some indirect effects such as potential changes in migration patterns and in health indicators (i.e., concept of ecological trap; Hallier and Gaertner 2008) or the unexpected consequences on non-target associated pelagic species. Hence, ICCAT requested that further analysis be conducted on these issues to determine fishing areas and seasons with the objective of reducing the fishing mortality exerted on juveniles and specifically to mitigate the effect of the FAD fishing operations.

In response to this issue the EU purse seine fleet established, on a voluntary basis, a moratorium on the use of FAD that included a large area in the Gulf of Guinea in which high activities on FAD and juvenile catches were historically observed from November to January. However, the possibility of also targeting non-associated large yellowfin allowed the fleet to remain inside the moratorium area, which is evidenced by viewing the lack of changes in some fishery indicators such as fishing time, number of sets and yellowfin catch made on free schools before and after the moratorium. One may expect a shift in fishing mode due to the compliance of the moratorium and consequently an increase in the number of sets on free schools, but such a situation did not occur (i.e., inside the area the indicator remained at the same level while outside there was a no significant decrease). The lack of increase in the related activities could be due to the fact that it was not worth fishing on free schools until January, when the season for large yellowfin starts (Goujon 2004a). The increase in FAD sets was a way to compensate for the losses in catch inside the area due to the ban on FAD fishing. However, the gain in FAD catches outside the area was not significant from a statistical point of view, and this might be the reason why the fleet increased its activities with this fishing method inside the area during the last four years of the moratorium. It must be kept in mind that the EU purse seine fleet continued to fish on FAD but the catches on juveniles remained low in comparison to the catches before the moratorium. A possible explanation could be the skippers' ability to distinguish tuna schools that have only juveniles (Goujon 2004b).

The apparent stability in fishing time suggests that the fleet simply reallocated its effort to search and set on free schools. Nevertheless, our findings showed that the fishery indicators related to successful activities (fishing days, successful squares explored, catch of juveniles) decreased inside the area during the period of the moratorium on FAD. Since it is known that the moratorium stratum has been specifically designed to reduce FAD fishing, and bearing in mind the decrease in activities observed inside the area, one can conclude that the major part of the EU purse seine fleet respected the moratorium on FAD. However, few activities on FAD were observed, especially in November, which means an infringement of that regulation (Goujon 2004a; Goujon 2004b; Ariz et al. 2005; Ariz et al. 2009).

The absence of significant changes in the different indicators outside the moratorium area could be due to the fact that the EU fleet could continue to fish inside the area. However, although a comparison was not conducted between inside and outside the area for reasons explained in the Methods section, the results showed a barely significant increase in the number of sets with FAD outside the protected area (Table 2). This phenomenon has been described in other regulated fisheries with a spatial moratorium (Poos and Rijnsdorp 2007; Powers and Abeare 2009), but the related catches did not increase significantly, which suggests that it was not possible to compensate for the losses inside the area.

In general, the moratorium on FAD was more respected during the time that it was implemented on a voluntary basis (Fig. 3e, more detail in Fig. S1, Appendix) than it was formally established by ICCAT for all fleets. It must be stressed that the non-compliance of the FAD moratorium by some purse seiners operating under the flag of Ghana hindered the evaluation of this type of spatial regulation and limited the conclusions of management studies conducted by ICCAT (ICCAT 2009). Ariz et al. (2009) reported that landings of skipjack and bigeye tuna increased during the period of 2000–2003 inside the moratorium area with respect to before the regulation entered into force. These species are caught mainly on FAD and concern small sized tunas (Fonteneau et al. 2000).

Because of the IUU fishing activities, ICCAT modified the moratorium and a new time-area closure (termed Picolo area) entered into force in 2005. The Picolo area is known to support large concentrations of juvenile tunas likely due to oceanographic-specific conditions (Evans et al. 1981; Prince et al. 2010) and to the abundance of mesopelagic fishes, such as *Vinciguerria nimbaria*, which is one of the favorite preys of juvenile tunas in this region (Menard et al. 2000).

Compared to the moratorium on FAD strata, however, there was a large reduction in terms of space (by almost 25% of the surface of the previous regulation) and time (only November, i.e., 33% of the period of the moratorium). Another major change was the fact that the new spatial regulation referred to the restriction of all types of surface fishing activities.

Cass-Calay et al. (2006) and Brooks and Mosqueira (2006) indicated that the new closed area would result in an increase in catches of all species landed in the total Atlantic. The results here confirm these predictions. Effectively, the inside no-take area was respected, but there were some increases in the indicators outside the area. This may be due to the fact that it was possible to fish in a stratum that was known to have a high density of tropical tunas and fishing activities on FAD. Hence, there were no restrictions to fish with this method in the rest of the Gulf of Guinea and, as a result, the catches associated with this method were not expected to undergo any change. Nevertheless, the catch of juveniles increased in comparison to before the ban (Ariz et al. 2009). In general, it was difficult to account for the effects of this stratum since it was too small in surface and too short in time. Furthermore, within the framework of a BACI analysis, the results of the no-take area must be used with caution because the period that was considered as "before regulation measure" had already supported some restrictions in fishing activities (the Picolo area was included in the moratorium region on FAD).

According to the results, there is some evidence that this closed area resulted in an increase of the fishing activities of the EU purse seine fleet outside the area, and likely for other vessels operating in the eastern tropical Atlantic. This issue led ICCAT to reconsider the effectiveness of such a time-area closure to protect juvenile tunas, and some changes in surface area, in the time closure and in the restriction on FAD activities were considered (recommendation [08-01]). These changes would be a return to the moratorium that was established in 1997. This issue highlights the importance of defining the boundaries of a spatial regulation, especially in highly mobile species because most migratory species have some periods and/or zones in which they congregate and become vulnerable to fishing activities (Zacharias et al. 2006).

The use and effectiveness of area closures as a management tool have been estimated with respect to changes in community structure (Fisher and Frank 2002; Dinmore et al. 2003; Hiddink et al. 2006; Jaworsky et al. 2006), abundance species (Greenstreet et al. 2006; Lincoln-Smith et al. 2006; Smith et al. 2008; Jensen et al. 2010), yield resource (Holland and Brazee 1996; Holland 2003; Hart 2006), economic profits (Smith and Wilen 2003; Sanchirico et al. 2006; Armsworth et al. 2010). However, there are few studies that consider the fishermen component (Wilen et al. 2002; Murawsky et al. 2005; Kellner et al. 2007; Powers and Abeare 2009). Some authors (Johannes et al. 2000; Wilen et al. 2002; Salas and Gaertner 2004; Kaiser 2005; Branch et al. 2006; Poos and Rinsdorp 2007) noted the importance of taking into account fishermen's responses to management measures, basically because fishermen adapt their fishing practices to continue to catch the fish. Together with this, the effects on fishing effort (in terms of target species) and its spatial re-allocation as a response of fleet are logically evaluated. While in this study the nominal fishing effort showed almost no changes as a result of regulatory measures, when the analysis was conducted by fishing mode (in number of specific sets), it was possible to better understand the fishermen's responses to spatial regulations.

This study is an example of how different time-space management regulations (the moratorium on FAD and the no-take area) could have positive and negative effects on the fleet behavior and therefore on the target species. Johannes et al. (2000) mentioned the importance of considering the fishermen's ecological knowledge in making management decisions. Even if our objective was not to evaluate the effects of the voluntary basis moratorium (1997–2000), it seemed to have had better results in protecting the resource. On the other hand, we did not estimate both effects of the moratorium on FAD and the no-take area to the months of the year free of regulation measures. However, Ariz et al. (2009) reported a decrease in the annual total landings of the three principal species caught by the Spanish purse seine fleet since the moratorium on FAD, which may have led to some changes in fishing strategies. The important issue of how to manage the multispecies feature of the tropical purse seine fishery was also partially analyzed by Harley and Suter (2007). These authors estimated the potential to reduce purse seine bigeye catch considering no reduction in skipjack catch of a time-area closures on FADs in the eastern Pacific Ocean, finding that even with a decrease in bigeye catches it would be insufficient for sustainability.

One conclusion of this study is that as a complement to ecological information and population dynamic models, modeling the fleet dynamics is required to anticipate the fishermen's responses to different scenarios in regard to different spatial regulation measures, as well as to evaluate the effects of combining other management regulations with time-area closure.

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Appendix 1: Before-After, Control-Impact (BACI) design

Data prior to an impact are normally difficult to obtain for evaluating its effect on most biological resources (Wiens and Keith 1995; Smith 2002). When historical data are available for the impact area, it is possible to compare means for samples from these data and periods after the event. If there is no such effect, it is expected that these means are equal, and if there is such an effect, a statistical difference is taken as evidence of effect (Underwood 1992; Wiens and Keith 1995; Smith 2002). This approach is called Before-After design (BA) which is without control locations to compare, and the observed changes could be due to causes other than the impact (Smith 2002). When conducting this design, it is assumed that the other factors besides the impact affecting a resource are homogenous during the whole period.

The statistical model for the analysis of data, X_{ik} is

$$X_{ik} = \mu + \alpha_i + \tau_{k(i)} \tag{1}$$

where μ is the overall mean, α_i is the effect of period (i = before or after), and $\tau_{k(i)}$ represents times within period. The statistical model for this analysis was the same as in Equation (1).

A variation of the above design is to sample more than one location in the impacted area, and it is suggested that some control locations be added to compare with the impacted area (Underwood 1992; Smith 1993; Wiens and Keith 1995; Smith 2002). This design is the BACI approach and consists in taking samples in all locations at replicated times before and after the event. Therefore, the BACI design consists of two treatments, (1) before-after, which is the main treatment, and (2) the control-impact (Smith 1993).

The implied model is

$$X_{ik} = \mu + \alpha_i + \tau_{k(i)} + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk} \tag{2}$$

where μ, α_i and $\tau_{k(i)}$ are the same as in the BA design and $(\alpha\beta)_{ij}$ is the interaction between period and location, and ε_{ijk} represents the remaining error.

However, normally there is only one location impacted. For this reason it is suggested to have more than one control location to permit evaluating with more certitude if the change was due to the impact and requires taking replicated measurements before and after the event in all the locations (Underwood 1992; Smith et al. 1993). Nevertheless, the response variable could be different from one location to another. For this reason, it is important to establish more than one control location to reach replication (Underwood 1992; Smith et al. 1993; Smith 2002). A further important fact is the temporal variation because the populations will not remain homogeneous all the time, and this could lead to some changes in the response variable (Underwood 1992; Smith et al. 1993).

In this study, the assessment of the effects on the purse seine fleet dynamics was conducted by a Before-After design, since it was not possible to define a control site because the outside area might also have been affected by the spatial regulation in different ways (e.g., changes in fishing effort over the years, large-scale environmental conditions, etc.) or even by the regulation per se.

Appendix 2

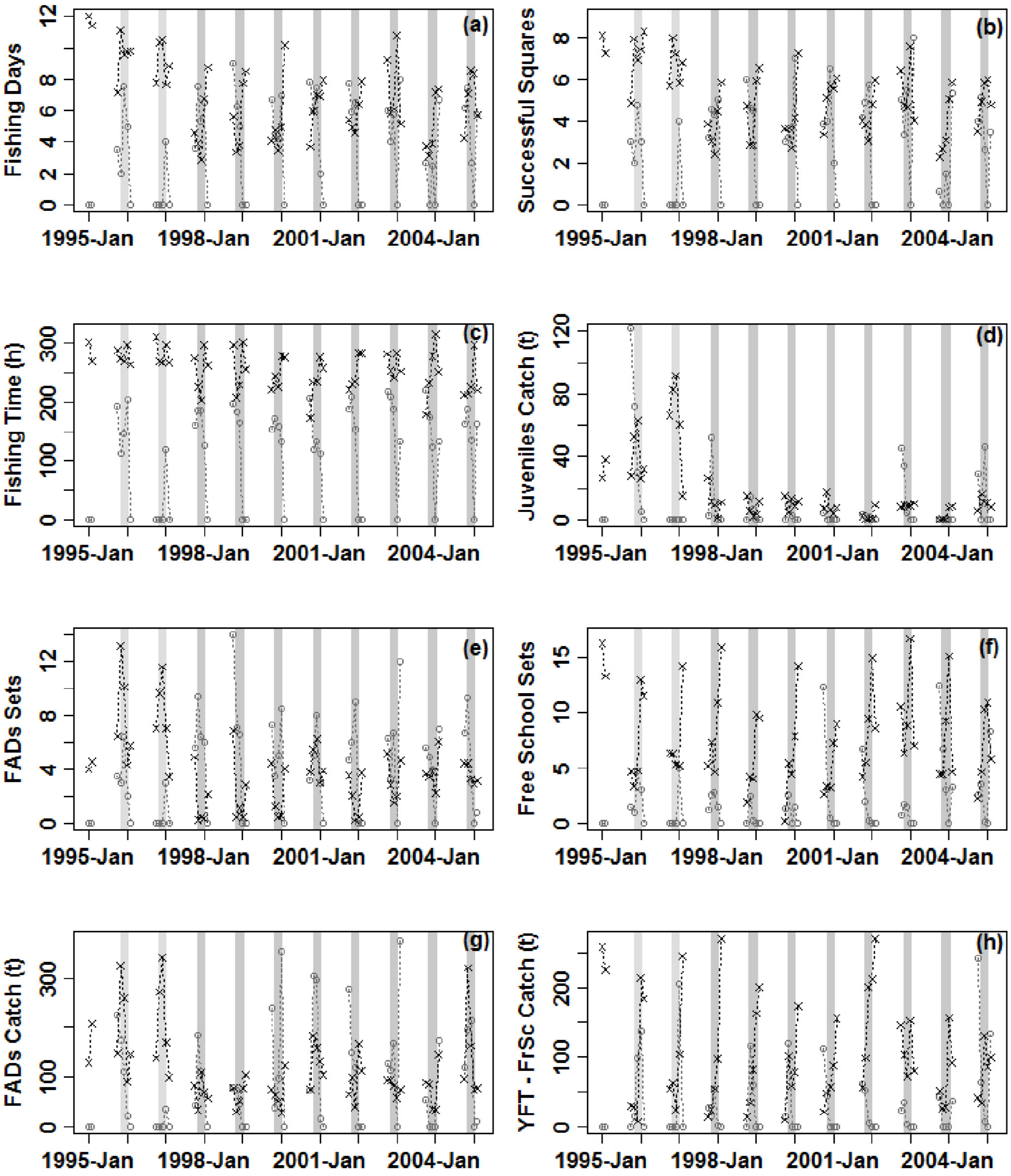

Fig. S1. Fishery indicators inside (-x-) and outside (-o-) during the three-month moratorium on Fish Aggregating Devices, FAD (± one month). Bars in light gray and bars in dark gray represent the restricted months before and when the moratorium on FAD was implemented, respectively.

Appendix 2: continued.

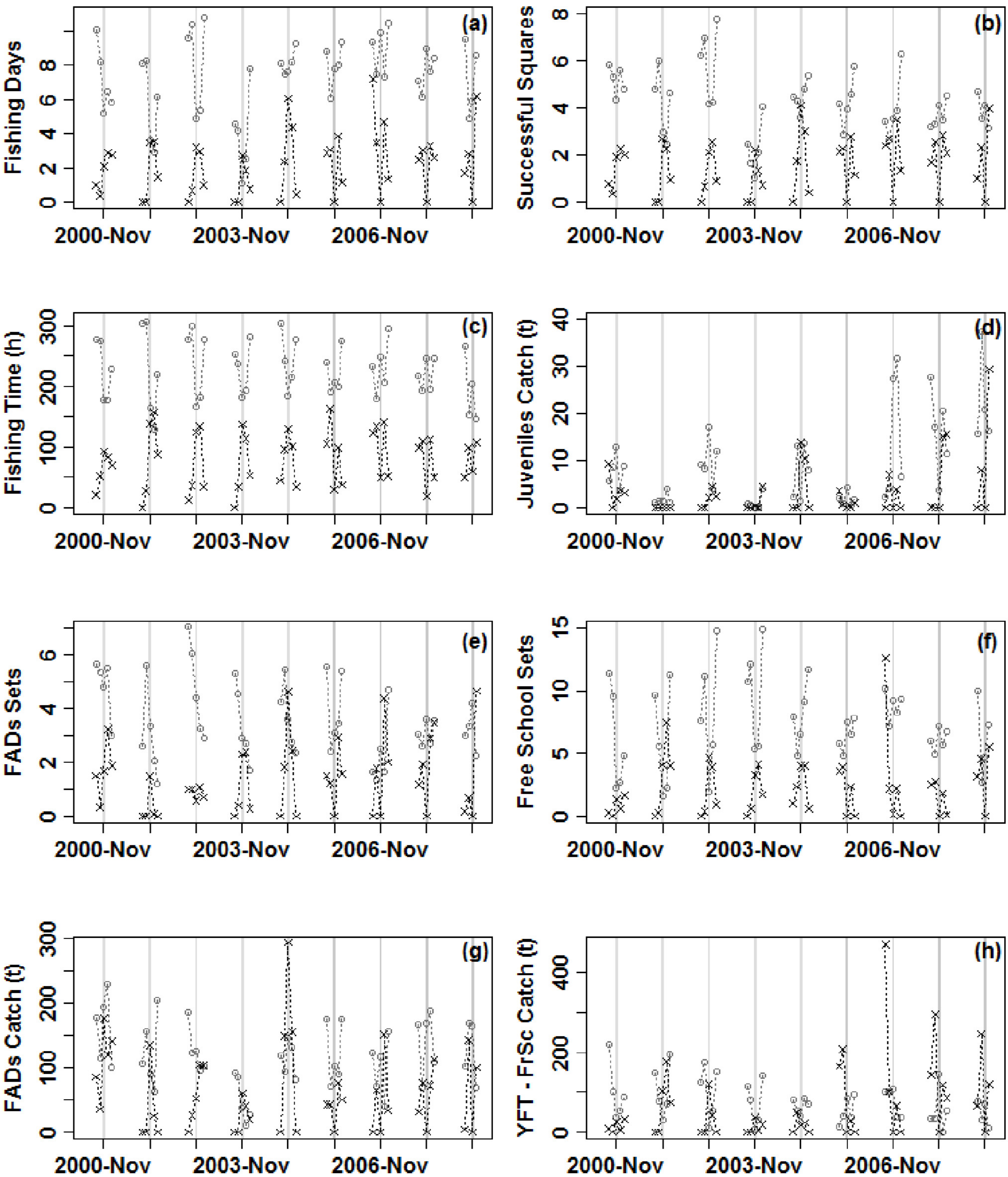

Fig. S2. Fishery indicators inside (-x-) and outside (-o-) during the regulation month of November (± two months) when the closure in the Picolo zone was established. Bars in light gray represent November before closure and bars in dark gray indicate when the regulation was implemented.

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