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RESEARCH ARTICLE

Studying the contribution of different fishing gears to the *Sardinella* small-scale fishery in Senegalese waters

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Abstract – This study investigated variations of landings of two key species, *Sardinella aurita* and *Sardinella maderensis*, in Senegalese waters over a ten-year period (2004–2013). Using generalized additive models, it was found that fishing gear played a major role in explaining differences in monthly landings for both species (51–71% deviance explained). Its effect was more significant in the southern part of Senegal. Fishing effort (number of trips) accounted only for 4–18% of variability in landings. Purse seine (PS) fishing was the most important contributor to the landings of both species. In addition, in the southern area, surrounding gillnet fishing was also important for *S. maderensis*. Modeling results showed that the relationship between monthly effort and landings was generally positive and leveling off, while it was dome shaped for PSs and surrounding gillnets. Thus, when estimating fishing effort indices for management in Senegal, it is necessary to account for differences in fishing gears and the non-linear relationship between fishing effort and landings.

Keywords: Effects of fishing / Generalized additive model / *Sardinella aurita* / *Sardinella maderensis* / Purse seine / Surrounding gillnet / Senegal

1 Introduction

In Senegal, a lack of employment opportunities, increasing demand for fish, and an absence of effective management policies have led to an increase in the artisanal fishing sector over the last few decades. The canoe fleet has increased from 4968 in 1982 to about 20 000 canoes in 2013 (Fig. 1). The general move to motorized boats of the Senegalese artisanal fleet began in 1952, and was encouraged by incentive policies (Chauveau and Samba, 1990). Today most artisanal canoes are propelled by outboard motors of 15–60 hp. This situation has facilitated the local adaptation of larger fishing gears, such as purse seine (PS) which were introduced in Senegal in 1973 (Chauveau and Samba, 1990) and gillnets. The use of these types of fishing gears requires a sizeable crew and a large hold capacity per canoe. In recent years, several fishmeal factories have been established in the fishing villages Cayar and Joal-Fadiouth.

Motorization has considerably expanded the area for artisanal fishing by giving access to more remote fishing areas. It simultaneously reduced travel time and extended fishing time, leading to an unprecedented increase in fish landings. The artisanal fleet intensely targets small pelagic fish which represent more than 85% of its total landings (Diei-Ouadi, 2005). The two most targeted species are *Sardinella aurita* (72%) and *Sardinella maderensis* (28%), accounting for 86% of total landings of small pelagic species from Senegalese waters (FAO, 2012). Total landings of both species increased

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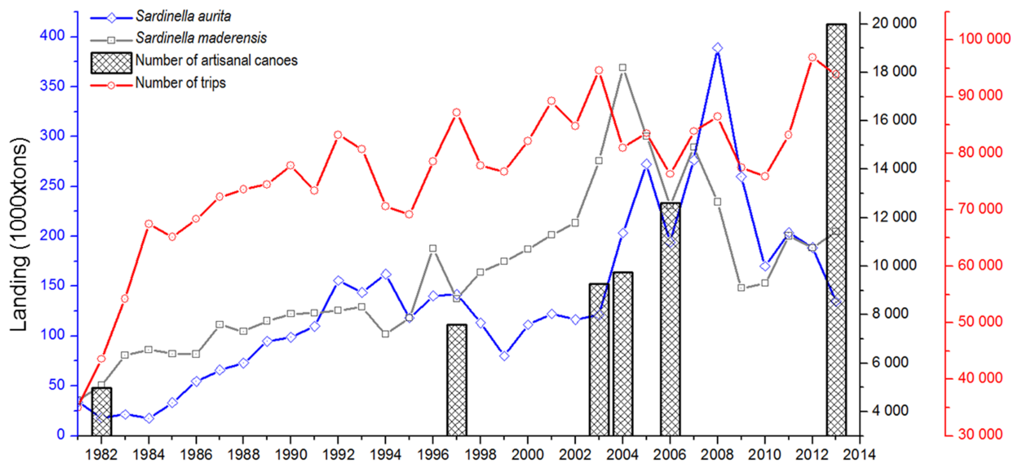

Fig. 1. Annual landing (tons) of *Sardinella* and fishing effort for the small-scale fishery in Senegal from 1981 to 2013. Landing of *Sardinella aurita* (blue line with lozenges) and *S. maderensis* (gray line with squares) and fishing effort (red line with circles) were extracted from the CRODT database. The number of canoes for 1982, 1997, 2003, 2004 and 2006 were obtained from the FAO (2008) and for 2013 from Belhabib et al. (2014).

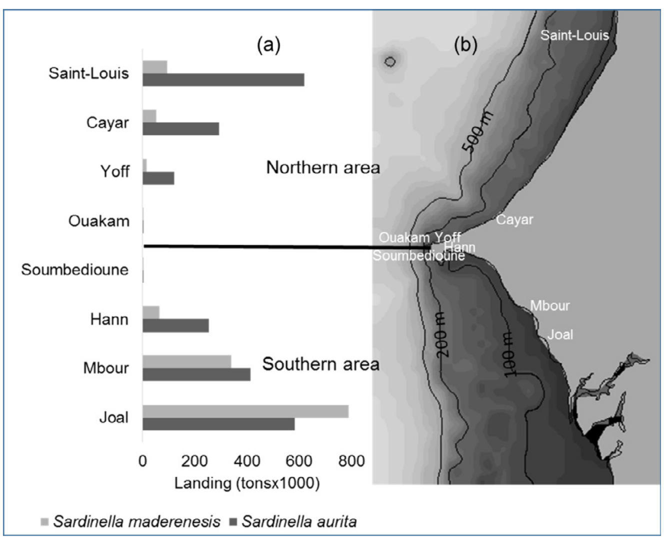

Fig. 2. (a) Total landing of *Sardinella aurita* (black bars) and *S. maderensis* (gray bars) by landing port summed over the period 2004–2013. (b) Map of landing ports along the Senegalese coast. The artisanal fleet operates generally within the area limited by the 500 m isobaths.

from about 55 000 tons in 1981 to around 527 000 tons in 2008, before decreasing to 255 000 tons in 2013 (Fig. 1). The corresponding number of trips increased from around 35 000 trips to 94 000 trips between 1981 and 2013 (Fig. 1). This increase led to both *Sardinella* stocks being considered overexploited since 2006, mainly by the artisanal fishing sector (FAO, 2006).

Understanding how artisanal landings are related to fishing activity and to the type of fishing gears used in Senegal is important for managers and decision makers. Therefore, the aim of this study was to investigate the influence of small-scale fishery types on the variability of *S. aurita* and *S. maderensis* landings along the Senegalese coast using statistical modeling. Generalized additive models (GAMs) have been used to investigate the effect of environmental variability on marine species distributions, including Atlantic mackerel (*Scomber scombrus*), sprat (*Sprattus sprattus*), whiting (*Merlangius merlangus*), anchovy (*Engraulis encrasicolus*), horse mackerel (*Trachurus mediterraneus*), and narrownose smooth-hound shark (Borchers et al., 1997; Augustin et al., 1998; Daskalov, 1999; Jaureguizar et al., 2016). GAMs have been applied to analyze the effects of zooplankton and oceanography on the pre-spawning herring distribution around the Shetland Islands (Maravelias and Reid, 1997), while Bellido et al. (2001) investigated the interannual fluctuations of squid abundance in Scottish waters. Murase et al. (2009) examined the effect of environmental variables on the distributions of Japanese anchovy, sand lance, and krill applying GAMs. More recently, GAMs were used to define possible temperature ranges associated with high abundance of round *Sardinella* and anchovy off Senegalese waters (Diankha et al., 2015). GAMs have also been applied to standardize commercial landings (see review in Maunder and Punt, 2004).

2 Materials and methods

2.1 Small-scale fishery landings data

The landings data were extracted from the database held by the Centre for Oceanographic Research, Dakar-Thiaroye (CRODT). The data collecting methodology has been described by several authors (Pechart, 1982a, b; Laloë, 1985; Laloë and Samba, 1990; Thiao, 2009). The data were recorded in eight main Senegalese ports: Saint-Louis, Cayar, Yoff, Ouakam, Soumbedioune, Hann, Mbour, and Joal (Fig. 2b). The number of trips per fishing gear was recorded on a daily basis, while landings data were randomly collected for about five days a week. After aggregating the data by port, gear and period (fortnightly), total landings per port were estimated by multiplying mean landings of sampled trips by the total number of fishing trips. The landing estimates for the eight ports were raised to the national level using the regional extrapolation factors provided by the seasonal artisanal fisheries census (Thiao, 2009; Chaboud et al., 2015). For this study, data from five landing ports grouped into two areas were used for the period 2004–2013: Saint-Louis and Cayar, in the northern area and Hann, Mbour and Joal in the southern area. These ports were selected because the data for fishing effort and gear were considered more reliable. Moreover, 94% of *S. aurita* and 99% of *S. maderensis* were landed in these ports (Fig. 2a).

We analyzed monthly landings (in tons) of *S. aurita* and *S. maderensis.* Fishing effort was expressed as the number of trips by fishing gear. The fishing gears considered were PSs and gillnets. There were six types of gillnets: bottom set gillnets (BSGs), surface-set gillnets (SSGs), bottom-drift gillnets (BDGs), surface-drift gillnets (SDGs), surrounding gillnets (SGs) and trammel (T) nets. The SGs were not used in the northern area.

The fishing gears and their deployment are described in detail in Bousso (1994). Here, we only provide a short summary. The Senegalese PS is a large wall of netting used to catch fish schools. It has floats along the top line with a lead line threaded through rings along the bottom. Once a school of fish is located, the pirogue encircles the school with the net. The lead line is then pulled in, "pursing" the net closed on the bottom, preventing fish from escaping by swimming downward. A BSG consists of a single netting wall kept more or less vertical by a float line and a weighted ground line. The net is set on the bottom, or at a certain distance above it and kept stationary by anchors or weights on both ends. A SSG is set at the surface. A drifting gillnet is a wall of netting that hangs in the water column (near the bottom, BDG or near the surface, SDG). It is kept afloat at the intended depth using a system of weights and buoys attached to the head rope, footrope, or float line. Surrounding gillnets (SG) are set vertically, in shallow waters, encircling fish. After the fish have been encircled by the net, noise or other means are used to force them to gill or entangle themselves in the netting. A trammel net consists of three layers of net. A slack, small-mesh, inner panel of netting is sandwiched between two outer layers of netting, which have a larger mesh size. It is held vertically in the water by weights on the bottom (lead line), and floats on the top (float line).

2.2 Modeling approach

To study the relationship between monthly landings and fishing effort, as a first step, the Pearson correlation coefficient (r) between landings and effort was calculated for each gear. Only fishing gears with significant correlation were considered further. In the second step, generalized additive models (GAMs) (Hastie and Tibshirani, 1986) were used to explain variations in monthly landings of *S. aurita* and *S. maderensis* by month, year, fishing gear and fishing effort by fishing gear. Month and year (without interaction) were included in the model to account for seasonal migrations and interannual variability. The "mgcv" packages in R software (Wood, 2013) were used. Several distribution functions (Gaussian, Poisson and Gamma) were tested. The Gaussian distribution (log-link function) and tensor product smoothers ("ti" in mgcv) were finally applied because they provided the best fit and the lowest Akaike information criterion (AIC). The maximum degree of freedom (k) for each spline smoother was fixed to four (4) to avoid overfitting (Escalle et al., 2016). The contribution of each variable to the total explained deviance was obtained by using the "relaimpo" R package, which provides the relative importance of each explanatory variable (Grömping, 2006). The same model was also applied to landings per unit effort (LPUE); however, no notable differences were found. Therefore, we only present the results for landings.

3 Results

3.1 Landings and fishing effort

Overall, most landings of *S. aurita* and *S. maderensis* were caught by PSs (Table 1). PSs had the highest overall fishing effort (number of trips). For *S. aurita*, PS were responsible for 61% and 42% of total fishing effort, in the northern and southern areas, respectively, and 99% and 98% of total landings of both species. For *S. maderensis*, the corresponding figures were 52% of fishing effort and 93% of landings in the northern area, while in the southern area, they were only 22% of fishing effort and 57% of landings for this species.

For *S. aurita*, SDGs were second in importance for fishing effort (26%) in the northern area, but not important for landings (1%), while in the southern area SSG effort was second (28%), but again with few landings (<1%).

For *S. maderensis* in the northern area, effort by SDG was second in importance (24% effort, 7% landings), while in the Southern area, the second most important gear for landings (37%) was SGs, with only 10% of effort.

In summary, across the two species and the different fishing gears, the ranks in fishing effort and corresponding landings did not always agree.

3.2 Variations in landings of *S. aurita*

The relationship between monthly landings of *S. aurita* and corresponding fishing effort was positive for all gears, but seemed to level off, or even decrease, at different effort values for the different gears (Fig. 3a and b). In both areas, Pearson's correlations coefficients between landings and effort were strongest for PS ($r = 0.71$, $p < 0.001$ and $r = 0.55$, $p < 0.001$, for the northern and southern areas, respectively). Weaker but significant correlations were also found for SDG ($r = 0.38$, $p < 0.01$) in the northern area and in the southern area for SSG and SDG ($r = 0.20$, $p < 0.01$ and $r = 0.60$, $p < 0.01$, respectively).

The GAM results confirmed the non-linear relationship between fishing effort and landings for *S. aurita* (Fig. 4). In the northern area, positive relationships were found for SSG, SDG and PS and monthly fishing efforts, with landings starting to level off above around 500 trips for SSG and PS (Fig. 4a–c). In the southern area, no such leveling off was observed. On the contrary, landings strongly increased for higher monthly efforts for SSG and SDG (Fig. 5d and e), while for PS, the relationship was dome-shaped, positive up to 1000 trips and decreasing thereafter (Fig. 5g).

The full model for monthly landings of *S. aurita* explained 71% of total deviance in the northern area, and 77% in the southern area (Table 2). Fishing gear was the most important explanatory variable with 51% deviance explained in the northern area, and 71% in the southern area (Table 2). The fishing effort (main effect) was second, explaining 18% of deviance in the northern area and 4% in the southern area. The

Table 1. Total landings (tons), corresponding fishing effort (number of trips) and LPUE (landings per unit effort) per fishing gear for *Sardinella aurita* and *Sardinella maderensis* in the northern and southern area off Senegal for the period 2004–2013. Bottom set gillnet (BSG), surface-set gillnet (SSG), bottom-drift gillnet (BDG), surface-drift gillnet (SDG), surrounding gillnet (SG), purse seine (PS) and trammel (T).

Fishing gear	Northern area					Southern area				
	Fishing effort	%	Landings (tons)	%	LPUE (tons/trip)	Fishing effort	%	Landings (tons)	%	LPUE (tons/trip)
Sardinella aurita										
BSG	39 426	12	286.08	<1	0.007	174 284	16	6417.07	<1	0.037
SSG	433	<1	0.88	<1	0.002	303 547	28	4899.50	<1	0.016
BDG	902	<1	8.93	<1	0.010	0	0	0	0	0.000
SDG	81 637	26	10 642.66	1	0.130	112 495	10	10 398.64	<1	0.092
SG	0		0	0	0.000	34 260	3	854.65	<1	0.025
PS	192 716	61	901 851.12	99	4.680	465 956	42	1 224 819.81	98	2.629
T	523	<1	0.41	<1	0.001	7096	<1	1617.28	<1	0.228
Sardinella maderensis										
BSG	81 488	23	397.50	<1	0.005	684 780	34	31 133.12	3	0.045
SSG	828	<1	9.15	<1	0.011	528 143	26	25 008.06	2	0.047
BDG	1406	<1	26.22	<1	0.019	0	0	0		0.000
SDG	86 440	24	10 448.98	7	0.121	116 387	6	10 416.85	<1	0.090
SG	0	0	0	0	0.000	208 291	10	442 060.77	37	2.122
PS	189 684	52	136 571.69	93	0.720	447 380	22	685 847.34	57	1.533
T	2048	<1	2.76	<1	0.001	47 300	2	744.38	<1	0.016

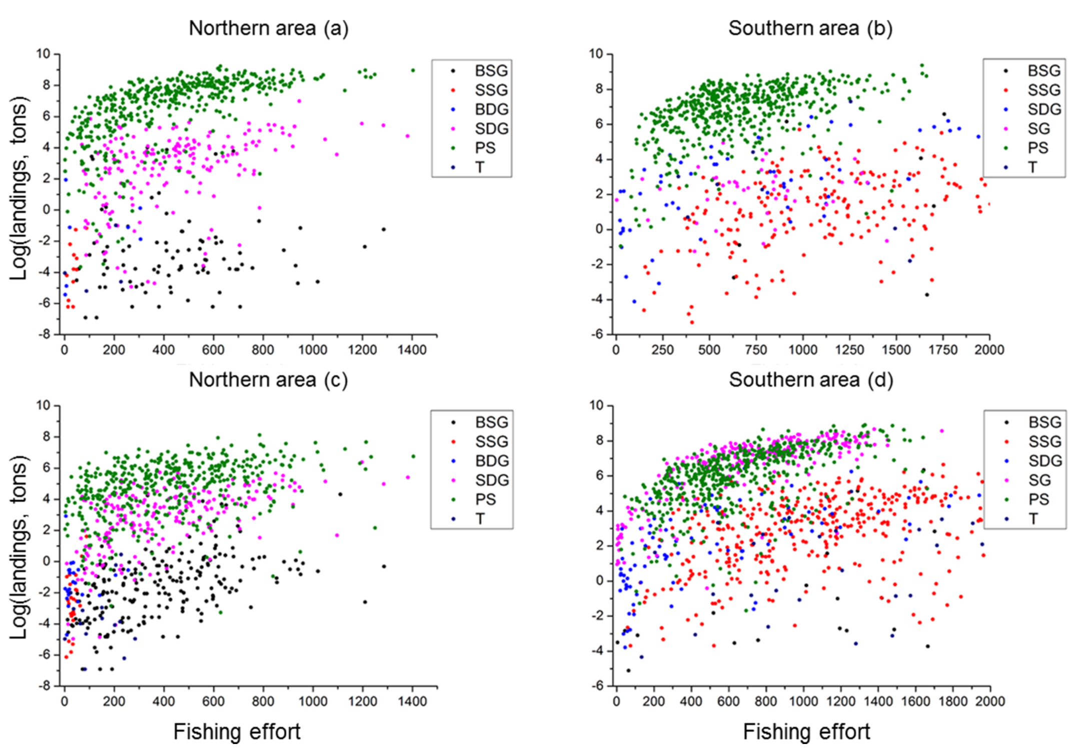

Fig. 3. Relationship between monthly landings of *Sardinella aurita* (a, b) and *Sardinella maderensis* (c, d) and fishing effort (number of trips) by fishing gear in the northern and southern area in Senegalese waters (2004–2013).

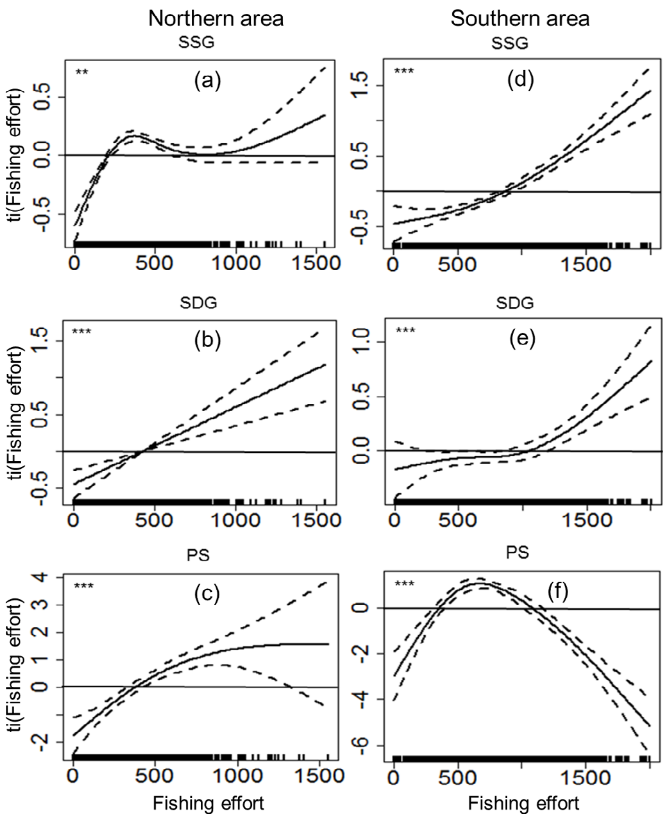

Fig. 4. Estimated smooth curves obtained by the GAM applied to landings of *Sardinella aurita* in the northern area (first row) and the southern area (second row): surface-set gillnet (SSG, a and d); surface-drift gillnet (SDG, b and e) and purse seine (PS, c and f). Dashed lines represent two standard error boundaries around the covariate main effects. Significance codes: ***0.001; **0.01; *0.05. The *x*-axis shows the density of points for each covariate and the *y*-axis reflects the relative importance of each covariate.

explanatory power of temporal variables (month and year) was negligible, accounting only for 2% or less.

As fishing effort was expressed in number of trips for all fishing gears, the values of the model coefficients provide information on the "catchability", i.e. catch per unit of effort of the different gears. SSG and SDG had a similar range of coefficient values, while the range was much larger for PS, indicating that landings varied much more as fishing effort increased for PS compared to the other two gears (Fig. 4).

3.3 Variations in landings of *S. maderensis*

The relationships between *S. maderensis* landings and fishing effort in the northern and southern areas were positive for all gears (Fig. 3c and d), similar to those found for *S. aurita*. In the northern area, the Pearson correlation between *S. maderensis* landings and the corresponding PS fishing effort was significant ($r = 0.40$, $p < 0.001$) (Fig. 3c), while in the southern area, the correlation for SG was somewhat stronger compared to PS (SG: $r = 0.77$, $p < 0.001$; PS: $r = 0.66$, $p < 0.001$) (Fig. 3d).

The GAM results confirmed that the relationship between monthly landings of *S. maderensis* and the corresponding

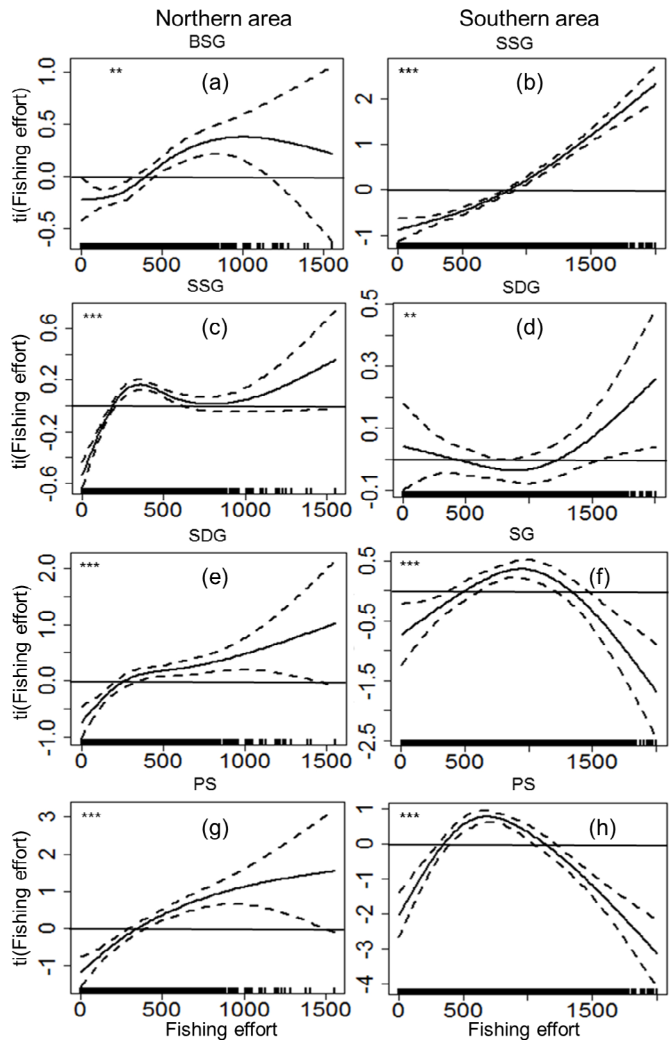

Fig. 5. Estimated smooth curves obtained by the GAM applied to landings of *Sardinella maderensis* in the northern area (first column) and the southern area (second column): bottom set gillnet (BSG, a); surface-set gillnet (SSG, b and c); surface-drift gillnet (SDG, d and e); surrounding gillnet (SG, f) and purse seine (PS, g and h). Dashed lines represent two standard error boundaries around the covariate main effects. Significance codes: ***0.001; **0.01; *0.05. The *x*-axis shows the density of points for each covariate and the *y*-axis reflects the relative importance of each covariate.

fishing effort was non-linear (Fig. 5). The relationships for each gear resembled those found for *S. aurita* (Fig. 4). In the northern area, the relationships were positive for fishing efforts up to around 900, 300, 500 and 700 trips for BSG, SSG, SDG and PS, respectively (Fig. 5, left column). In contrast, in the southern area, three types of relationships were observed, positive rather linear for SSB, slightly bowl-shaped for SDG, and dome-shaped for SG and PS (Fig. 5, right). For SG and PS, landings increased up to around 1000 trips for SG and 600 trips for PS, and decreased thereafter (Fig. 5f and h).

Overall, the explanatory variables accounted for 75% of the variability in monthly *S. maderensis* landings variability in the northern area, and 67% in the southern area. Fishing gear was the most important explanatory variable explaining 65%

Table 2. Percent of explained deviance by each covariate tested for explaining variations in the monthly landing of *Sardinella aurita* and *Sardinella maderensis* in two areas in Senegalese waters. The *p*-values for all variables are <0.01.

Variable	*Sardinella aurita*		*Sardinella maderensis*	
	Northern area	Southern area	Northern area	Southern area
Year	1	2	<1	4
Month	1	<1	2	<1
Fishing effort (by fishing gear)	18	4	8	9
Gear	51	71	65	54
All	71	77	75	67

of total deviance in the northern area and 54% in the southern area. The explanatory power of fishing effort was relatively moderate, 8% deviance in the northern area and 4% in the southern area. The contributions of month and year were low in both areas.

In contrast to *S. aurita*, the GAM coefficients for fishing effort for *S. maderensis* for SSG and SDG had a similar narrow range of values, while the range was much larger for PS, indicating that landings varied much more as fishing effort increased for PS compared to the other two gears (Fig. 4).

4 Discussion

In a context of sustainable management of marine resources, this study highlighted notable differences in the efficiency and contribution of different fishing gears to the landings of national small-scale fisheries on small pelagic fishes, *S. aurita* and *S. maderensis*, in the two main Senegalese fishing areas. These two species are the most targeted by small-scale fisheries (more than 75% of landings). The study applied non-linear statistical models (GAMs) to explain the variability of monthly landings of the two *Sardinella* species. The results showed that the deployed fishing gears were the most important explanatory variable. Nonetheless, fishing effort (number of trips) also had a significant effect for both species in both areas. The relative explanatory power of fishing gear and fishing effort differed somewhat according to area and species. The main effect of fishing effort for *S. aurita* landings was larger in the northern area compared to the southern area. As for *S. maderensis* landings, the explanatory power of fishing effort and fishing gears (main effects) was comparable in both areas. These contrasting results between species might be due to their physiological differences (Ba et al., 2016), their mode of exploitation, and their spatial distribution, which differ in many ways (Cury and Fontana, 1988). Despite certain differences, the species have similar diets and occupy almost the same geographical areas over the Senegalese continental shelf (Cury and Fontana, 1988).

This study revealed that variation in efficiency of PS fishing (non-linear relationship between landings and effort) combined with the wide use of this gear controlled the variability of *S. aurita* landings in both areas. PS also had the highest LPUE of all gears, hence the highest fishing efficiency per trip (Table 1). This gear is especially suitable to target *S. aurita* (Samba and Samb, 1996) and is very efficient in fishery where the species occur in schools (Brehmer et al., 2007). Regarding the variations of *S. maderensis* landings, the most efficient fishing gear differed between areas. In the northern area, PS fishing activity had the largest LPUE (Table 1), while in the southern area, the SG had the highest LPUE, with dome-shaped efficiency as a function of fishing effort, similar to PS. The fact that PS had the most considerable effect on *S. maderensis* in the northern area could be explained by the ban of gillnets in Cayar (President of Cayar CLPA, *pers. comm.*), while BSG, SSG and SDG were actively used in Saint-Louis. In other words, this work confirmed that fishing effects are closely related to the efficiency of the gear used. These findings are consistent with those of Jennings and Kaiser (1998) who pointed out that fishing effects depend on the type of fishing gear used and the characteristics of the habitat where they are deployed.

In addition to fishing gear, fishing effort was an important variable. Overall, relationships between fishing effort and landings were non-linear. The relationships from the major contributors, PSs and surrounding gillnets, were dome-shaped. Similar results have been found by several authors (Laurec and Le Guen, 1981; Lorenzen et al., 2016). The measurement of fishing effort has always been a fundamental part of fisheries science, and it becomes even more important when fisheries are managed using effort-limiting controls (Rothschild, 1972; Taylor and Prochaska, 1985). However, its estimation, particularly in Senegalese artisanal fisheries, remains problematic because the number of trips does not measure fishing effort accurately. Fishing effort is the amount of fishing gear of a specific type used on the fishing grounds over a given unit of time spend to fish (e.g. hours trawled per day, number of hooks set per day, or number of hauls per day) (FAO, 1997). Therefore, attempts should be made to better estimate artisanal fishing effort in Senegal, even though fishing effort is still a difficult parameter to quantify (Mangel and Bede, 1985), mostly in the artisanal sector and particularly in African countries like Senegal. However, caution is needed when considering fishing effort because there are two types of estimates of fishing effort, nominal fishing effort and effective fishing effort (Beverton and Holt, 1957; Gulland, 1969). The nominal fishing effort, as stated by Robins et al. (1998), refers to any measure of resources devoted to exploiting a stock during a unit of time, while effective fishing effort refers to real pressure exerted by fishers on a stock for a unit of time (Cunningham et al., 1985).

The variations in landings unexplained by the tested variables could be attributable to varying environmental conditions along the Senegalese coast, which are influenced by seasonal coastal upwelling, mostly from October to May

(Teisson, 1982). In the northern area, the continental shelf is narrow, so the upwelling occurs near the coast, while in the southern area the upwelling is a trapped cold water tongue in the middle of the continental shelf, surrounded by warmed waters (Ndoye et al., 2014; Diankha et al., 2015). This heterogeneous structure could explain the difference observed in the effect of the tested variables in both areas. Moreover, it is widely recognized that variations in environmental conditions, particularly in upwelling areas, influence recruitment (Cury and Roy, 1991; Demarcq and Samb, 1991; Tiedemann and Brehmer, 2017), distribution, abundance and availability of fish (Zeeberg et al., 2008; Klemas, 2012; Diankha et al., 2015; Thiaw et al., 2017). Beyond the effect of fishing gear, it has been pointed out that the variations of upwelling intensity are the cause of seasonal and interannual fluctuations observed in the abundance of *S. aurita* along the north-west African coast (Braham et al., 2014; Diankha et al., 2015; Mbaye et al., 2015).

5 Conclusion

This study demonstrated that the variations in landings from the artisanal fisheries of *S. aurita* and *S. maderensis* were mainly explained by fishing gear, while fishing effort also played a role. PS activity was responsible for most landings and its variability for *S. aurita* in both areas, because of its proven high efficiency on schooling small pelagic species. In the southern area, the importance of fishing gear for *S. maderensis* landings was almost equally shared by SG and PS, while in the northern area, PS played again the major role. Obviously, environmental variability plays an important role in controlling the variability of *Sardinella* densities, which resulted in differences in mean LPUE between areas. The study further demonstrated the importance of appropriate definitions of fishing effort for fishery management. As highlighted in this study, the ongoing stratified catch sampling design used by CRODT appears to be efficient. A simplistic definition of fishing effort, as proposed by Belhabib et al. (2014) who only consider the number of canoes, is problematic.

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