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Fishing characteristics and catch composition of the sardinella fishery in Ghana indicate urgent management is needed

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ABSTRACT

The sardinella (Clupidae) fishery in Ghana is vital to food and economic security for millions of people along the coast. Sardinella catches, however, have recently been declining and little is known about the current fishery characteristics. To address this gap, we sampled 8 sites along the coast of Ghana from 2017–2018 and collected data on over 14,000 fishes from 332 fishing trips of fishers targeting the two species of sardinella locally exploited, i.e. the round sardinella (*Sardinella aurita*) and the flat sardinella (*Sardinella maderensis*). The primary fishing gears were beach seines, purse seines, and gill nets. We distinguished three distinct types of purse seines based on mesh size: "poli" had mesh sizes of 3 cm or below (despite regulations deeming these illegal); "watsa" had mesh sizes of greater than 3 cm; and "poli-watsa" had a combination of mesh sizes across this range. Differentiation of gill nets was based on either monofilament (called "set net") or cotton (called "ali"). These fishing nets ranged in length from 54 m to almost 1000 m, and poli-watsa was the most dominant gear as it was responsible for 37% of the total catch. Fishing vessels ranged from 5 – 23 m and crew sizes were from 2 – 30 individuals per vessel. Fish dissections and landings data indicated that *S. aurita* had a length at maturity of 14.7 cm and 62% of landed individuals were immature. The length at maturity for *S. maderensis* was 15.2 cm and 75% of landings were immature. Poli-watsa was the dominant gear for *S. aurita*, which was captured in significantly deeper areas (mean = 31.8 m) than *S. maderensis*, which was mostly caught with gill nets at a mean depth of 22.8 m. Considering the dominance of juveniles in the landings, coupled with recent declines in catch per unit effort, management is urgently needed to prevent collapse of this economically, socially, and ecologically important fishery.

1. Introduction

Fisheries contribute significantly to global food security and wellbeing (Kaiser et al., 2005). Across the world, fisheries have been evolving and responding to an increasing demand for fish protein along with a globalized seafood marketplace (Kent, 1997). Much of this has been facilitated by technological advancements and fisher behavior (Jennings et al., 2001). Some of these include the advent of woven materials leading to the manufacture of finer and stronger fishing nets with relatively high catch efficiencies, the introduction of large trawl nets, freezer trawlers to store and preserve large catches, and sonar devices to more precisely locate fish. Understanding how fish stocks interact with fishing characteristics and gears is critical for setting management policies to ensure sustainable exploitation or rebuilding of overfished stocks (Hilborn et al., 2020). In many developing countries, however, such data on fisheries are lacking.

Ghana is one of the most densely populated fishing countries in West Africa with a coastline of approximately 550 km (Nunoo et al., 2016), a continental shelf area of 23,700 km^2, and an annual fish landing of 329,000 tonnes (Asiedu et al., 2018). Nearly half of the country's population lives in villages and cities within 100 km of the coast (CIESIN, 2002) and fish is an extremely important source of animal protein, with per capita consumption exceeding 20 kg yr^{-1} (FAO, 2018). Ghana's fisheries range in size and are characterized as artisanal, semi-industrial, and industrial depending on the technology employed, distribution of catch, and volume landed (Amador et al., 2006; MOFAD, 2015). The marine fisheries of Ghana provide approximately 80% of the fish that is locally consumed and the highest production is delivered by the sardinella (Clupidae) fishery (FAO, 2016a,b). Thus, the livelihoods and subsistence of many fishers and accompanying households in Ghana depend on sardinella (Bailey et al., 2010). These sardinella

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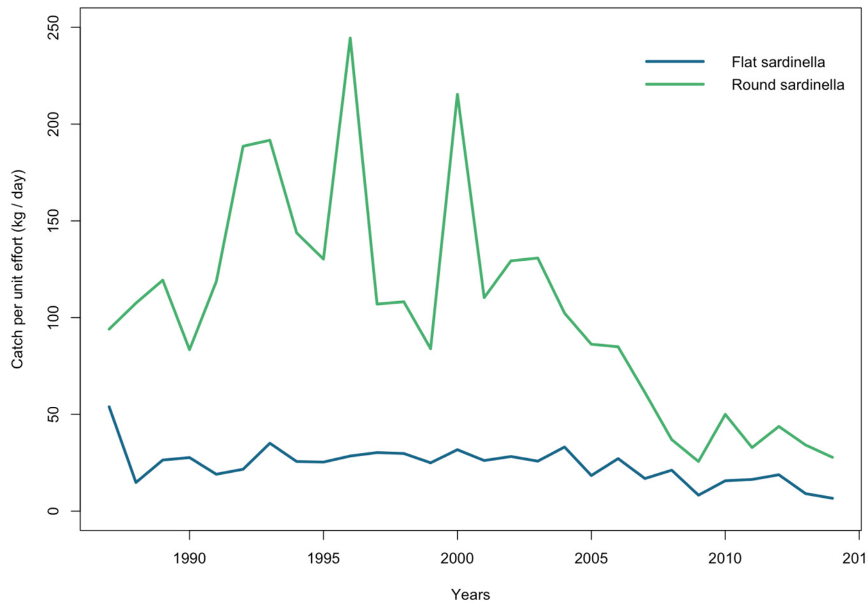

Fig. 1. Catch per unit effort in the sardinella fishery of Ghana since 1987 (FAO, 1989, 2016a,b).

stocks are composed of the round sardinella (*Sardinella aurita* and the flat sardinella (*Sardinella maderensis*; Koranteng, 1994; Kwei and Ofori-Adu, 2005).

Sardinella stocks formed the mainstay of the marine fisheries in the entire Gulf of Guinea up until the early 1970s (Hammond, 1962; Ansa-Emmim, 1973) and also constituted the base of socioeconomic activities for many fishers along the coast of Ghana (Kwei, 1988). Although the sardinella fishery in Ghana has a long history that spans multiple centuries, evidence suggests that it was fully developed in the 1940s to provide fish protein for local consumption and to supply fisheries resources for a cannery and a fishmeal plant (Koranteng, 1991). The annual catch per unit effort (CPUE) in the sardinella fishery of Ghana was relatively high between 1990 and 2000, with peaks in 1996 and 2000, especially with respect to *S. aurita*, but has been declining since the mid-2000s (Fig. 1). The decline in the CPUE is believed to be a result of overfishing coupled with environmental variability (FRU/ORSTOM, 1976; Koranteng, 1991; Perry and Sumaila, 2007). Many studies have acknowledged various changes in the fishery that might be contributing to recent declines in populations, such as introduction of outboard engines to facilitate long fishing trips, adoption of synthetic netting such as monofilament, the introduction of purse seines, and the illegal, unreported and unregulated fishing done by foreign fleets (e.g., Kwei, 1961; Lawson and Kwei, 1974; FAO, 1980; Koranteng, 1994; Afoakwah et al., 2018). The current dwindling state of the sardinella fishery is affecting the livelihoods of local fishers and approximately 23% have moved on to another occupation (Dovlo et al., 2016).

Outside of total sardinella landings, however, little is known about the current fishery dynamics and catch composition. Policy-makers and managers need basic reliable data on the extent to which juveniles are being captured and removed from the population leading to recruitment overfishing, as well as how catches relate to fisher and vessel dynamics. Results of previous studies on the sardinella fishery have been small in scale or of inadequate resolution to inform fisheries management, and virtually no detailed research has been done in the last 20 years. Hence, this study sought to provide data on the dynamics and catch composition of the sardinella fishery in Ghana to offer a current snapshot of attributes, thus serving as a starting point for conversations about viable management options. These data are meant to serve as a descriptive guide for fisheries scientists and managers to use in producing models and assessment tools for sustainable management of the sardinella fishery in Ghana, which is critical for national food security, livelihood, and wellbeing.

2. Materials and methods

2.1. Study site and data collection

This study was conducted across eight fishing communities in Ghana. These included Half-Assini and Axim in the Western Region, Elmina and Winneba in the Central Region, Bortianor and Tema in the Greater Accra Region, and Keta and Denu in the Volta Region (Fig. 2). Communities were chosen to provide national coverage of the entire Ghanaian sardinella fishery. Each place represents a major sardinella landing site within all four coastal regions of Ghana. The sardinella fisheries are managed by the Ministry of Fisheries and Aquaculture Development which focuses on "the implementation of development interventions that are intended to drive the fisheries sector and industry to contribute more effectively to the overall development of Ghana" (MOFAD, 2015).

Fisheries landings data were collected bi-monthly for 12 months from August 2017 to June 2018. Trained enumerators were stationed at each of the eight landing sites in order to collect data simultaneously for the duration of the study. Fishers were selected opportunistically as they arrived at the shore to sell or trade their catch. Data were collected from fishers that gave verbal consent to measure a subset of their catch. Only fishers targeting sardinella were chosen for data collection. Collecting data on the abundance, size composition, and maturity status (juvenile versus mature) of all sardinella in a single fishing trip was often unfeasible because of the volume being landed or the time it would take to process the fish relative to spoilage and the desire to sell or trade the catch. Therefore, a representative subsample of approximately 20% of the total catch was recorded. Fishes were first identified to species, then the total length (cm) along with reproductive stage (juvenile or mature) and sex was recorded by dissecting each specimen and examining its gonad macroscopically (Tsikliras et al., 2013). Data on key attributes of the fishing trip were also recorded such as crew size (number of individuals), type of fishing gear used, duration of fishing trip (hours), net length (m), vessel length (m), and approximate depth

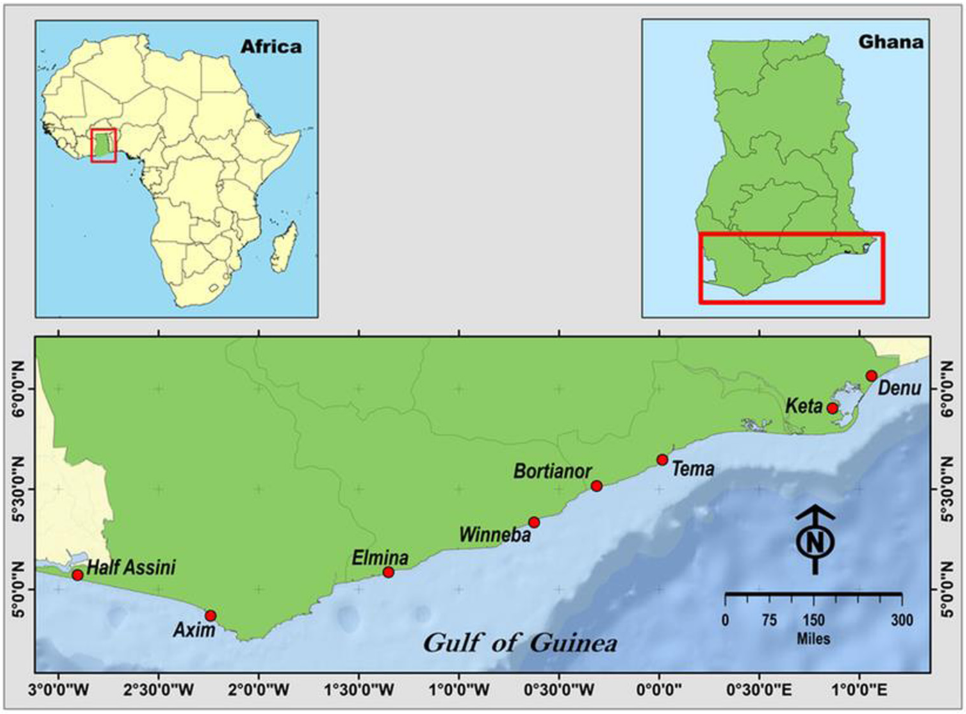

Fig. 2. Sampling sites along the coast of Ghana.

of fishing locations (m). The mesh size of each fishing net was also measured to the nearest centimeter. The sampling days were selected bi-monthly according to moon phase so as to represent both new and full moon phases for each sampling period. For each sampling month, an average of 5 days was dedicated to collect the data.

2.2. Analyses

All model diagnostics were performed visually using frequency histograms, funnel plots, and quantile–quantile plots (Zuur et al., 2007). To determine whether there were differences in fishing characteristics across the different gear types, separate one-way analysis of variance (ANOVA) was performed for crew size, vessel length, net length, fishing trip duration, depth of fishing location, and mesh size. Statistical significance was determined using an alpha value of 0.05 and post-hoc comparison tests using Tukey's Honest Significant Difference (HSD) were conducted to determine specific differences across the gears. We used the exact multinomial test (goodness-of-fit) to determine if the frequencies of the fishing trips recorded for the fishing gears were uniformly distributed. Subsequently, post-hoc pairwise comparisons using Chi-squared tests were conducted to determine the specific differences between the occurrences of fishing trips for a pair of the fishing gears.

To ascertain the depth–frequency distribution of each sardinella species in the coastal waters of Ghana, a density plot using data on the occurrence of each species at depths was created. We performed Kolmogorov–Smirnov test to determine if species differed according to depth (m) of where they were captured. To examine the length–frequency distributions of the sardinella in catches, histograms were created with all data aggregated as well as by month and fishing gear. A Kolmogorov–Smirnov test was used to determine whether the length–frequency distributions differed between the fish species in the landings. A red vertical line representing the length at sexual maturity was superimposed on the length–frequency distributions created from the aggregated data to indicate the proportions of mature and immature fish that were exploited.

The number of individuals per species in each subsample was recorded to determine the relative abundance of both sardinella species for each catch and according to gear type. To determine the length at sexual maturity (L_{mat}) of both sardinella species, ogives were created using logistic regression as described by Jennings et al. (2001) and King (1995). For these analyses, all fish samples for each species were grouped into 1-cm length classes and the proportion mature was determined. The point at which 50% of samples were mature was used to determine L_{mat} for each species. To determine whether it was important to estimate the total length at first sexual maturity (L_{mat}) separately for the males and females of each sardinella species, logistic regressions for the separate sexes, and the combined sexes, were compared using a Chi-squared test.

3. Results

3.1. Fishing characteristics (Figs. 3–5, Table 1 & Supplemental Tables 1–2)

Three broad categories of fishing gears were identified from 332 unique fishing trips: purse seine, gill net, and beach seine. A further breakdown of gear types was necessary due to differences in material or mesh sizes. Specifically, from the analysis of fishing trips three distinct types of purse seines based on mesh size were distinguished: "poli", with mesh sizes of 3 cm or below (despite regulations deeming these illegal); "watsa", having mesh sizes of greater than 3 cm; and "poli-watsa", where nets are a combination of mesh sizes below and above 3 cm. Differentiation of gill nets was based on either monofilament (called "set net") or cotton (called "ali"). Beach seines had no finer scale distinction. Overall, the fishing trips of these gears comprised 12% poli, 9% watsa, 37% poli-watsa, 8% ali, 11% set net and 23% beach seine; fishermen are using poli-watsa nets the most (Fig. 3). The

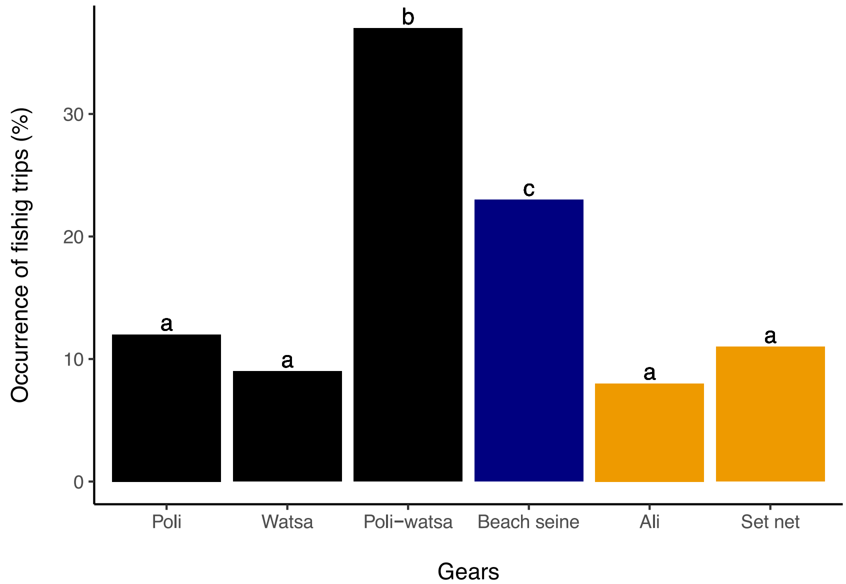

Fig. 3. Frequency of fishing trips expressed as percentages for the gears in the sardinella fishery of Ghana. Letters represent significant ($p < 0.05$) differences between the fishing gears using the exact multinomial test (goodness-of-fit) and Chi-squared tests.

Table 1
Results from separate one-way ANOVAs to test if fishing characteristics differed among the six gear types.

Fishing characteristic	Sum of squares	df	Mean square	F	p-value
Length of vessel (m)	3258	5	651.6	63.41	<0.001
Crew size (no. individuals)	8736	5	1747.1	99.06	<0.001
Fishing trip duration (h)	5945	5	1188.9	191.4	<0.001
Length of fishing net (m)	506 430	5	101 286	3.243	<0.01
Depth of fishing location (m)	20 133	5	4027	27.13	<0.001
Net mesh size (cm)	344.4	5	68.88	44.02	<0.001

frequency of the fishing trips differed significantly among the fishing gears ($p < 0.05$). Post-hoc pairwise comparisons using chi-squared test showed that the occurrence of fishing trip for beach seine differed significantly from poli-watsa ($p < 0.05$) and the frequency of the fishing trips for these two gears differed significantly from ali, poli, set net and watsa. However, the occurrences of fishing trips for the following pairs of gears were uniform: ali and watsa ($p = 0.740$); ali and set net ($p = 0.288$); ali and poli ($p = 0.209$); poli and set net ($p = 0.819$); poli and watsa ($p = 0.348$).

The length of fishing vessels in the sardinella fishery varied among the gears, ranging from 5 m to 23.8 m (Fig. 4a; Table 1; Supplemental Table 1). Approximately 60% of the fishing vessels in the purse seine fishery had lengths greater than 15 m, whereas 74% of vessels in the gill net fishery were less than 10 m. Approximately 89% of the vessels in the beach seine fishery, however, had lengths between 10–15 m. The differences in the vessel length among the gears were significant ($p < 0.05$; Table 1); a post-hoc comparison test also indicated that the vessels in the purse seine fishery were significantly longer than those in the beach seine, ali and set net fisheries (Supplemental Table 2).

The crew size for the gears ranged from 2 to 30 individuals per fishing vessel (Fig. 4b; Table 1; Supplemental Table 1). Two to four individuals per vessel were observed in both ali and set net fisheries. On the contrary, 5–30 fishers per vessel were observed in both purse seine and beach seine fisheries. We found significant differences in the crew sizes among the gears ($p < 0.05$). However, a post-hoc comparison test showed that crew size did not differ significantly among poli, watsa and poli-watsa in the purse seine fishery (Supplemental Table 2). Similarly, crew size did not differ significantly between ali and set net in the gill net fishery. However, the crew size in the gill net fishery was significantly less than the crew size in both purse seine and beach seine fisheries.

Fishing duration per trip varied among the gears, ranging from 4–23 h (Fig. 4c; Table 1; Supplemental Table 1). Long fishing hours were generally observed in the purse seine fishery with an average of 16.4 h. Fishing hours in the set net fishery were relatively short, with an average of 6 h. The fishing duration also differed significantly among the gears ($p < 0.05$). A post-hoc comparison test revealed significant differences in the fishing duration between ali, poli, set net and watsa (Supplemental Table 2).

The range of net lengths in the fishery was 54–959 m (Fig. 4d; Table 1; Supplemental Table 1), with the longest deployed in the set net fishery. Net lengths also differed significantly among the gears ($p < 0.05$). Post-hoc comparisons indicated that the net lengths of poli-watsa and set net were significantly longer than poli (Supplemental Table 2). The depth at which sardinella were fished ranged from 4–100 m with an average of 27 m (Fig. 4e; Table 1; Supplemental Table 1). Users of purse seines fished across a wide range of depths, from 8–100 m, with an average of 34 m. Both gill netters and beach seiners exploited sardinella at depths of 4–54 m with an average of 18 m. The depth of fishing location also differed significantly among the gears ($p < 0.05$). A post-hoc comparison showed that the depth at which set netters operated were significantly shallower than where the purse seines were deployed (Supplemental Table 2).

The range of mesh sizes of each fishing gear were: poli 0.7–3.0 cm, watsa 3.2–7.0 cm and poli-watsa 0.7–6.4 cm, ali 2.0–5.2 cm, set net 1.0–4.6 cm, and beach seine 0.8–7.5 cm (Fig. 4f; Table 1; Supplemental Table 1). The mesh sizes of the nets also differed significantly ($p < 0.05$). A post-hoc comparison test showed

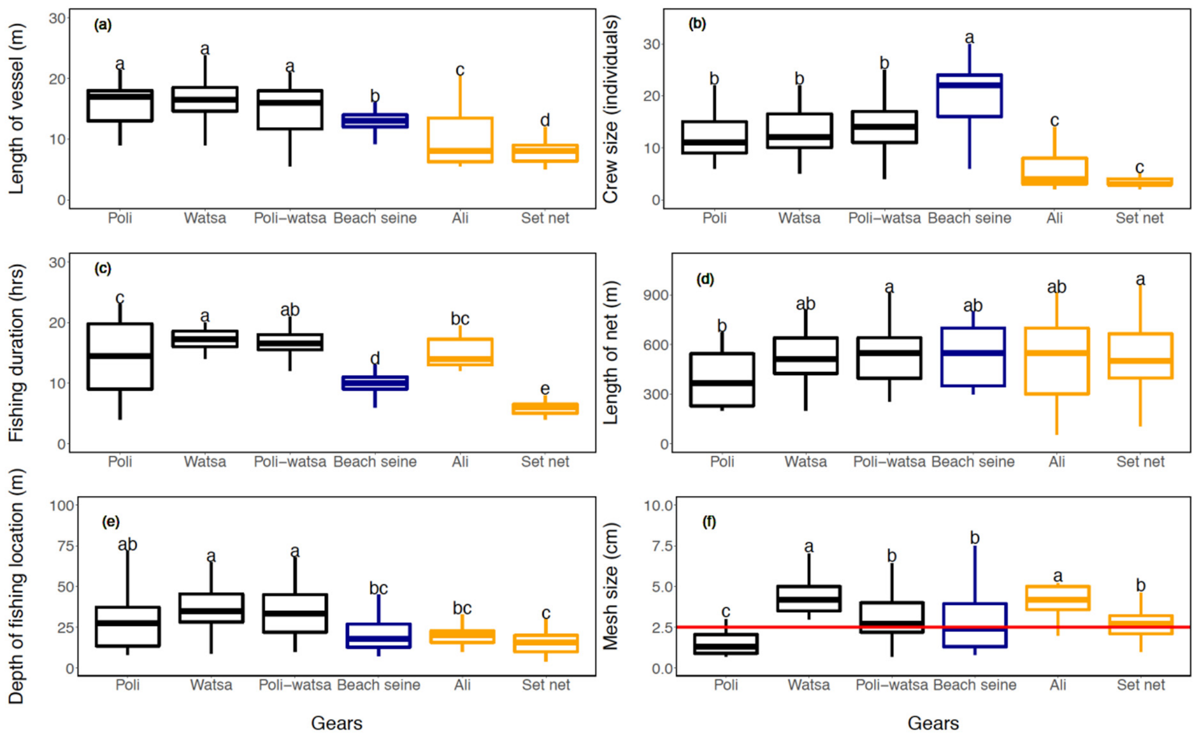

Fig. 4. Box and whisker plots by gear type for: (a) length of fishing vessels (m), (b) crew size (individuals), (c) fishing duration (hrs), (d) length of fishing nets (m), (e) depth of fishing location (m), and (f) mesh size (cm) in the sardinella fishery of Ghana. Colors represent major gear types where black are types of purse seines, blue is beach seine, and orange are gill nets. Lines extending vertically from boxes represent upper and lower extremes, while the boxes represent quartiles and the line is the median value. Letters represent significant ($p < 0.05$) differences between the fishing gears using Tukey's Honest Significant Difference tests. The horizontal red line in the mesh size plot indicates the legal mesh size of 2.5 cm identified in the Fisheries Act of Ghana (Act No. 625 of 2002). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

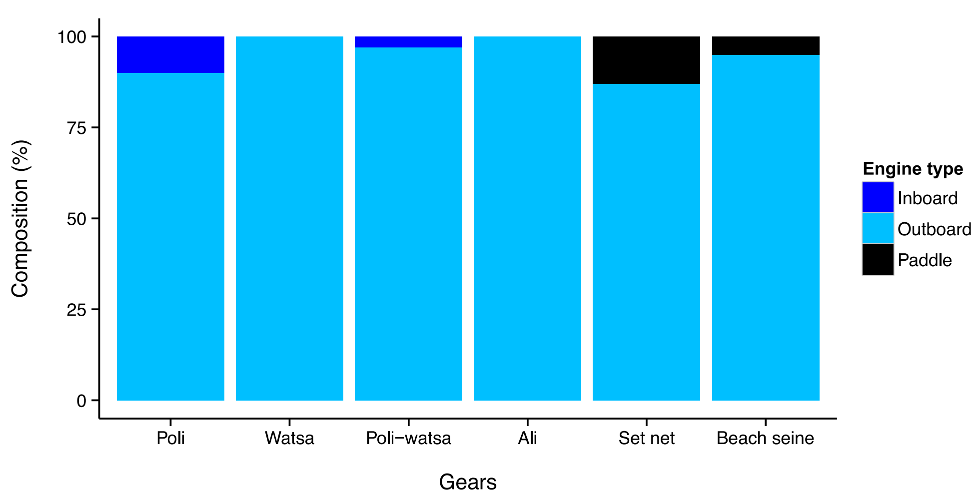

Fig. 5. Percentage composition of inboard motors, outboard motors and paddles for the various gears in the sardinella fishery of Ghana.

that the mesh sizes of poli were significantly smaller than the rest of the gears in the sardinella fishery (Supplemental Table 2).

Results indicate that 96% of the fishing vessels in the sardinella fishery of Ghana were motorized; the remaining 4% however, utilized paddles for their fishing activities (Fig. 5) All the vessels using a purse seine were motorized. Similarly, all the fishing vessels in the ali fishery had outboard-powered motors. Most of these motors were 40-hp outboard motors. In the beach seine fishery, 95% of the vessels relied on outboard motors to set their nets in the coastal waters of Ghana prior to hauling, whereas the remaining 5% used paddles. Approximately 87% of vessels in the set net fishery used outboard motors and 13% used paddles.

3.2. Catch composition and sexual maturity (Figs. 6–8, Table 2 & Supplemental Figs. 1–5)

Size composition of the fish in the landings was determined from length–frequency distributions using 14,088 individuals, comprising 7240 *S. maderensis* and 6848 *S. aurita*. The length distribution of *S. maderensis* in landings was unimodal with a mode of 11 cm (Fig. 6a) whereas that of *S. aurita* had a bimodal distribution with modes of 10 cm and 16 cm (Fig. 6b). The

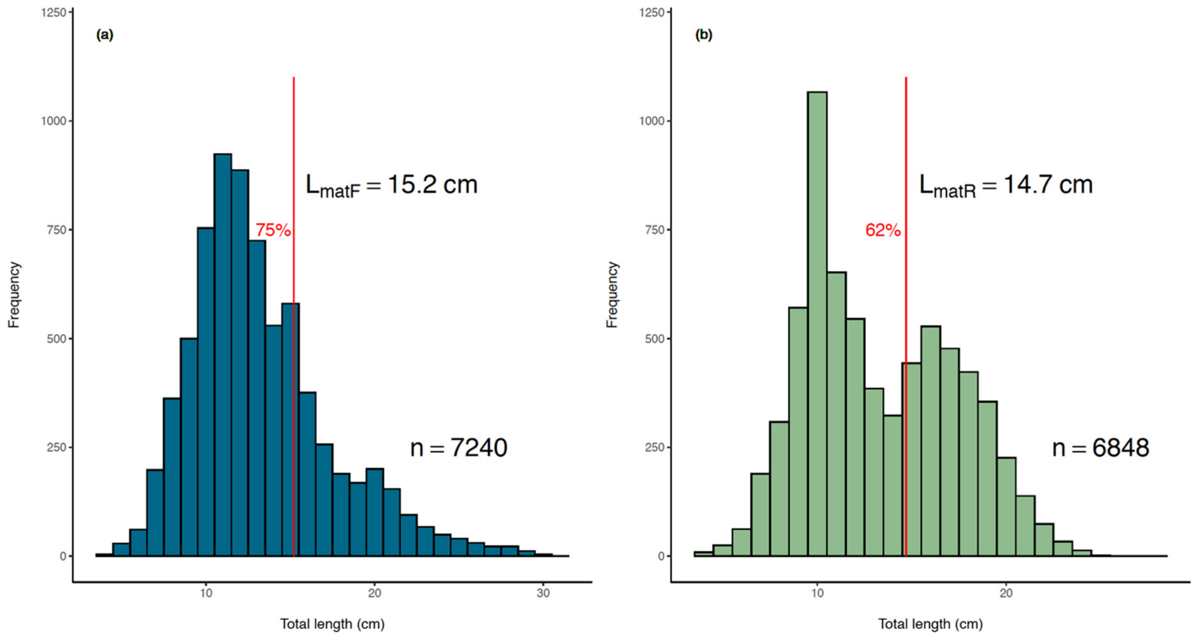

Fig. 6. Length–frequency distributions of (a) flat sardinella (*S. maderensis*) and (b) round sardinella (*S. aurita*) from catches in Ghana. Red lines indicate the length at 50% sexual maturity for flat sardinella (L_{matF}), and for round sardinella (L_{matR}).

Table 2
Estimates of the parameters of sexual maturity curves (male, female, all) for the flat sardinella (*S. maderensis*) in Ghana.

Logistic regression results for flat sardinella				
Flat sardinella (Male)	Estimate	Std. error	z value	*p*
Intercept (α)	−26.21	1.44	−18.25	<0.001
Slope (β)	1.72	0.10	18.06	<0.001
Length at maturity (L_{mat})	15.24	0.03		
Flat sardinella (Female)	Estimate	Std. error	z value	*p*
Intercept (α)	−24.15	1.40	−17.28	<0.001
Slope (β)	1.59	0.09	17.19	<0.001
Length at maturity (L_{mat})	15.19	0.02		
Flat sardinella (Male and Female)	Estimate	Std. error	z value	*p*
Intercept (α)	−25.24	1.00	−25.19	<0.001
Slope (β)	1.66	0.07	24.99	<0.001
Length at maturity (L_{mat})	15.22	0.02		
Comparing logistic regressions between males and females of flat sardinella				
	Df	Chi-square value	*p*	
Length (Combined sexes)	1	4296.8	<0.001	
Sex (Separate sexes)	1	0.50	0.304	
Length:Sex	1	1.00	0.327	

length–frequency distributions of the two fish species in the landings were significantly different ($D = 0.115$; $p < 0.05$). The total length at first sexual maturity (L_{mat}) for both sexes of *S. maderensis* was 15.2 cm ± 0.02 (Fig. 7a; Table 2) and that of *S. aurita* was 14.7 cm ± 0.02 (Fig. 7b; Table 3) suggesting that 50% of flat sardinella individuals measuring about 15.2 cm and above are sexually mature whereas 50% of round sardinella individuals with a total length of about 14.7 cm and above are mature. Superimposing L_{mat} represented by a vertical line on the length–frequency distributions indicates that approximately 75% of *S. maderensis* and 62% of *S. aurita* in the landings were below their respective lengths at sexual maturity (L_{mat}) suggesting that majority of the sardinellas landed in the marine fishery of Ghana are juveniles.

Sardinella individuals with a mean total length below L_{mat} were generally landed in the beach seine, poli, poli-watsa and set net fisheries during the study period (Supplemental Fig. 1). This pattern was more pronounced in the beach seine fishery. On the contrary, sardinella individuals with a mean total length above or around L_{mat} were observed in both ali and watsa fisheries. Furthermore, individual landings of *S. maderensis* and of *S. aurita* in the poli, poli-watsa, set net and beach seine fisheries consisted more than 50% immature fish (Supplemental Figs. 2 & 3) reinforcing that more immature sardinella fish are exploited by poli, poli-watsa, set net and beach seine in Ghana whereas more mature sardinella fish are mainly harvested by ali and watsa in Ghana as more than 50% of individual sardinella landings in the ali and watsa fisheries were adult.

Juveniles were landed in the sardinella fishery of Ghana throughout the year (Supplemental Fig. 4) indicating that recruitment of young ones into the fishery occurs all year-round. Approximately, 86% of *S. aurita* landed in February and 72% in October were juveniles, implying that *S. aurita* juveniles are relatively abundant in the coastal waters of Ghana in these periods. About 60% of adult *S. aurita* were however landed in June and in December, an indication of high abundance of *S. aurita* adults in the coastal waters of Ghana in June and December. The results also showed an increasing order of mature fish occurrence in the *S. aurita* landings in February (14%), April (47%) and June

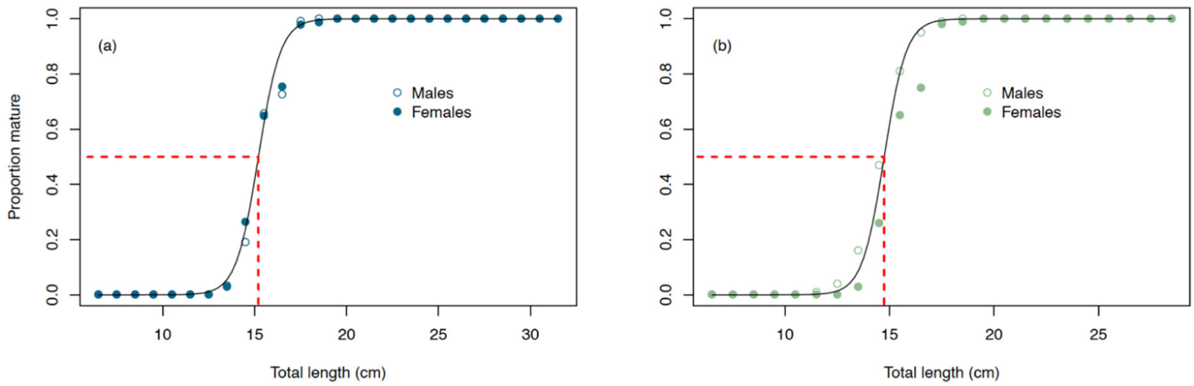

Fig. 7. Proportions of fish for each length that were mature for (a) flat sardinella (*S. maderensis*) and (b) round sardinella (*S. aurita*) in Ghana. Fitted logistic regression is also shown (black lines) as well as length where 50% of population is mature (red dotted lines).

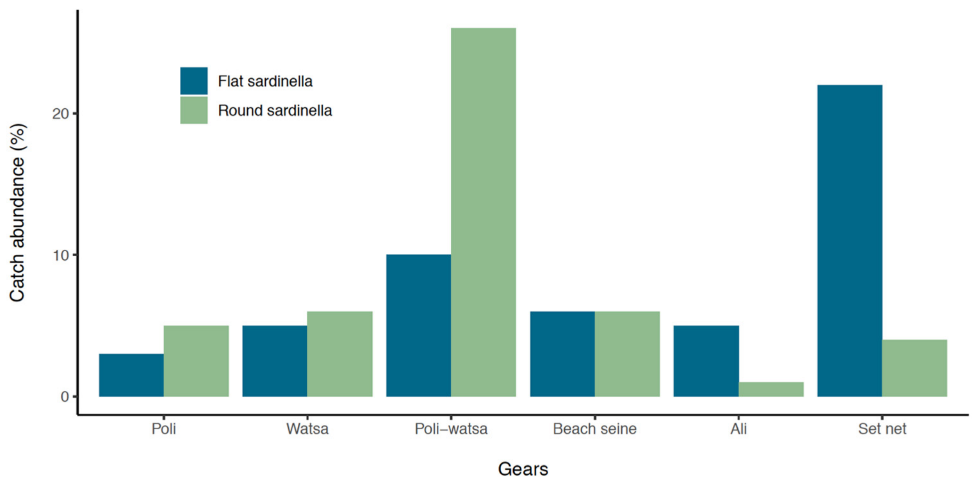

Fig. 8. Catch abundance (%) of flat sardinella (*S. maderensis*) and round sardinella (*S. aurita*) for each fishing gear in the marine fisheries of Ghana.

Table 3
Estimates of the parameters of sexual maturity curves (male, female, all) for the round sardinella (*S. aurita*) in Ghana.

Logistic regression results for round sardinella				
Round sardinella (Male)	Estimate	Std. error	z value	*p*
Intercept (α)	−24.45	1.28	−19.11	<0.001
Slope (β)	1.68	0.09	19.47	<0.001
Length at maturity (L_{mat})	14.55	0.02		
Round sardinella (Female)	Estimate	Std. error	z value	*p*
Intercept (α)	−27.99	1.51	−18.52	<0.001
Slope (β)	1.90	0.10	18.71	<0.001
Length at maturity (L_{mat})	14.73	0.03		
Round sardinella (Male and Female)	Estimate	Std. error	z value	*p*
Intercept (α)	−26.12	0.98	−26.72	<0.001
Slope (β)	1.78	0.07	27.1	<0.001
Length at maturity (L_{mat})	14.67	0.02		
Comparing logistic regressions between males and females of round sardinella				
	Df	Chi-square value	*p*	
Length (Combined sexes)	1	5360.4	<0.001	
Sex (Separate sexes)	1	3.8	0.074	
Length:Sex	1	2.8	0.097	

(59%) corresponding to a decreasing order of 86%, 53% and 41% immature fish in the landings suggesting a possible growth of the juveniles into the adult stage during these periods (Supplemental Fig. 5). We also observed a general decrease in the occurrence of mature individuals after August until December as against an increase in the frequency of juveniles in the same period.

Similarly, 85% of flat sardinella landed in February and 91% in October were juveniles but about 60% of adult flat sardinella were landed in August. The results also showed an increasing order of mature fish occurrence in the flat sardinella landings in February (14%), April (16%) and June (28%) matching up with a decreasing order of 86%, 84% and 72% occurrence of juveniles in the landings indicating a possible growth of the juveniles into the adult phase. The increasing order in the abundance of mature *S. aurita* until June with a decline in August as against a similar pattern that occurred in *S. maderensis* but with a peak in August followed by

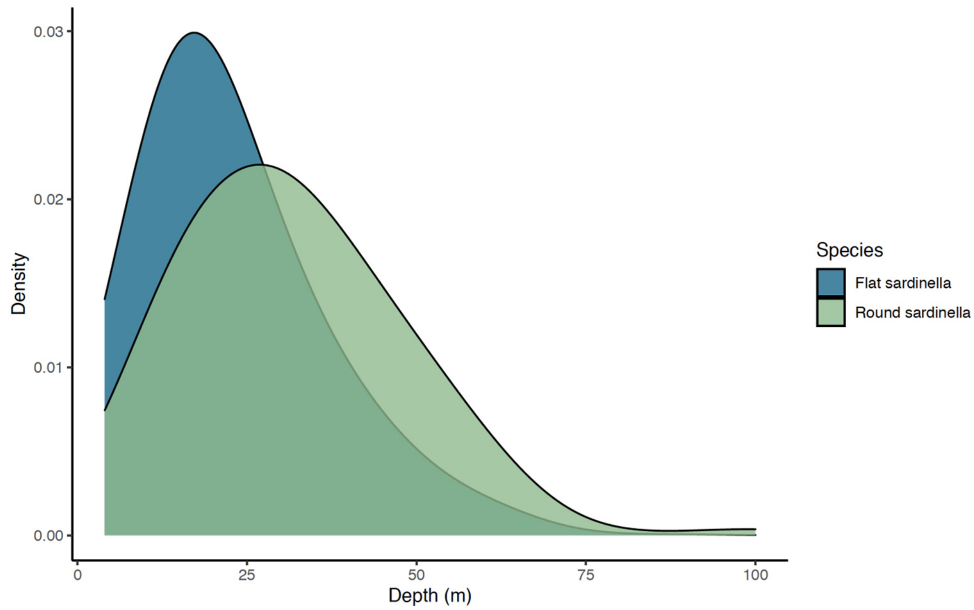

Fig. 9. Abundance (number of individuals expressed as density) of flat sardinella (*S. maderensis*) and round sardinella (*S. aurita*) captured across different depths (m) of the marine waters of Ghana.

a decline in October suggests that *S. aurita* commences its major spawning activity before *S. maderensis* does so.

Among the 332 trips that were recorded in this study, the set net fishery contributed 22% of the *S. maderensis* to the landings, which represented the greatest proportion (Fig. 8). The poli-watsa fishery contributed the highest landing of *S. aurita* (26%). Equal proportions of the two species were landed in the beach seine fishery.

3.3. Occurrence in coastal waters

Generally, the occurrence of sardinella species in the coastal waters of Ghana decreased with increasing depth. Whereas flat sardinella was caught in waters of depths up to 65 m, round sardinella was caught in waters of depths up to about 100 m (Fig. 9) The *S. maderensis* was mostly encountered in waters of 5–24 m in depth but the *S. aurita* was predominantly exploited within waters of depths 20–34 m. The depth–frequency distributions of the two fish species were significantly different ($D = 0.2807$; $p < 0.05$).

4. Discussion

4.1. Fishing characteristics

Our findings indicate that fishers in the artisanal and semi-industrial fisheries of Ghana are utilizing 3 broad categories of fishing gears, namely purse seine, gill net and beach seine to catch sardinella. These categories have also been consistently captured in the recent canoe frame surveys of Ghana (Akyeampong et al., 2013; Dovlo et al., 2016). The consistency in the use of these gears in the sardinella fishery since 1980 suggests that gear innovation has been negligible over the past 40 years. Results of this study further revealed that poli, watsa, poli-watsa, ali, set net and beach seine were the 6 specific fishing gears in the sardinella fishery of Ghana; poli, watsa, poli-watsa are versions of purse seines, and ali and set nets are versions of gill nets. The differences in purse seines were based on mesh sizes whereas differences in gill nets were premised on type of material. Purse seines in the sardinella fishery were differentiated based on mesh size: poli $\leq$3.0 cm; watsa >3.0 cm; and poli-watsa had a combination of mesh sizes peculiar to both poli and watsa. Given that poli-watsa has mesh sizes which are characteristic of both poli and watsa, it is crucial to rely on the range of mesh sizes other than the mean to identify the specific kinds of purse seine in the fishery.

We also found poli-watsa as the preponderant fishing gear in the sardinella fishery of Ghana. The dominance of poli-watsa could be due to keenness of several fishers to deploy a fishing gear with a variety of mesh sizes to exploit fish of varied body sizes to boost fish landings. FAO (1980) reported purse seines as poli (1.0–1.5 cm) and 'atsiki no ye' (unspecified mesh size). Later, Doyi (1984) identified poli with a mean mesh size of 1.3 cm, watsa (5.0–6.0 cm) and 'achiki na oye' (2.5–3.0 cm) as purse seines. A critical look at 'Atsiki no ye' and 'achiki na oye' indicates that these fishing gears are the same type of purse seine but with different spellings. Considering the mesh sizes of 'Atsiki no ye' and 'achiki na oye', they can be equated with the modern-day poli-watsa.

Our results also suggest that fishers hardly use ali to exploit sardinella these days, although the gear was historically dominant. Prior to the introduction of purse seines in the waters of Ghana in 1959, ali existed as a traditional gear (FAO, 1980). It is a multifilament net constructed from cotton which makes it more expensive than set net, a monofilament net made of nylon (CRC, 2013). Ali becomes heavy whenever it is wet, thereby making its utilization difficult for small canoe users versus a set net which is not only light in weight but efficient in catching fish. From these accounts, it is probable that many fishers in the gill net fishery sector are no longer interested in using ali. From this study, the longest net was encountered in the set net fishery, despite the use of small canoes in this sub-fishery. As indicated earlier, the inexpensive and light nature of the set net possibly encourage the fishermen to construct longer nets for their fishing activities.

The study also revealed that a wide range of fishing vessels with different sizes are utilized in the sardinella fishery. Most of these vessels are powered by outboard motors. Although these findings confirm the reports of Doyi (1984), Akyeampong et al. (2013) and Dovlo et al. (2016), some of the fishing vessels which had lengths of about 20–24 m appear to be larger in size than those previously observed in the artisanal fishery. The increase in the size of canoes in fishery could be a way to employ more hands to boost fish production. Crew size and depth of fishing location usually depend on the size of the fishing vessel and large vessels normally carry more fishers to deeper waters to harvest fish in Ghana (Dovlo et al., 2016). In this study, the majority of fishers in the purse seine fishery who were noted for using powered large fishing vessels (<15 m) fished in deeper waters and thereby spent more time to harvest and land their catch. In contrast, gill net fishers, characterized by a small crew size, mostly used small canoes to harvest their catch in relatively shallow waters, spending few hours to carry out their fishing activities. In the beach seine fishery, the canoe crew made up of paddlers (in vessels without outboard machines), net-releasing crew, swimmers, and the "horseman" (captain) are in charge of setting the net in coastal waters. Prior to setting a beach seine, one wing of the net is left on the shore whilst, in the setting process, the other wing is brought to the shore by the swimmers to initiate the hauling process (Kraan, 2006). From this account, it is obvious that canoes are not used throughout the fishing operation in the beach seine fishery but needed to facilitate the net setting procedure. The use of canoes for carrying fishing nets to sea during the setting process accounts for the medium sizes of canoes in the fishery.

4.2. Catch composition and sexual maturity

Our results also suggest *S. maderensis* mature sexually at a total length (TL) of 15.2 cm whereas *S. aurita* mature at a total length of 14.7 cm in the coastal waters of Ghana. The L_{mat} for *S. maderensis* in this work is less than Osei's (2015) findings. Some other reports on length at sexual maturity (L_{mat}) exist for round sardinella in Ghana's coastal waters: 15 cm fork length (FAO, 1990); 16.7–17.1 cm (Quaatey and Maravelias, 1999). By implication, the lengths at sexual maturity of the two species of sardinella in our study are relatively smaller than those reported previously. Several studies have shown that intense fishing quickens sexual maturation in fish (Law and Grey, 1989; Diekmann and Heino, 2007; Jørgensen et al., 2007; Sharpe and Hendry, 2009; Marty and Rochet, 2014; Hunter et al., 2015). As a strategy to withstand fishing pressure, heavily exploited fish stocks mature early to contribute through reproduction to sustain their population (Wootton, 1998). Until now, fish stocks including sardinellas have been subjected to heavy exploitation in Ghana (Lazar et al., 2016). Hence, the shortened period of sexual maturation exhibited by sardinellas in Ghana could be attributed to an ecoevolutionary response by the fish to withstand the intense fishing pressure exerted on the fish stocks, but determining this mechanism is out of the scope of our study.

Length–frequency distributions of fish landings can be used as an indicator of overfishing, particularly in data-poor contexts (Froese, 2004). If exploited fish stocks are dominated by fish above length at maturity, the fishery is likely to be sustainable. But if fishes being landed are primarily below length at maturity, it is a good indication that overfishing is occurring (Froese, 2004). On this basis, the sardinella fishery of Ghana is unsustainable given that the exploited sardinella are presently dominated by immature fish. The predominance of juveniles as evidenced in the modal lengths which are generally less than L_{mat} for each species implies that the fishermen are using fishing gears with undersized mesh sizes to exploit the sardinella stocks. Meanwhile, we have shown that many of the juveniles are caught by poli, poli-watsa, beach seine and set net whose mesh sizes are relatively smaller compared to ali and watsa gears. It is therefore imperative to stringently regulate the mesh sizes of fishing nets to limit the landing of juveniles in the sardinella fishery of Ghana.

Our findings also reveal that most of the *S. aurita* are landed in the purse seine fishery (sum of catch landed by users of poli, watsa and poli-watsa) whereas more *S. maderensis* are landed in the gill net fishery (sum of catch landed by users of set net and ali). *S. aurita* mostly winters at depths of 50–80 m off central Ghana, although this fish has been described as a highly migratory species (Zei, 1962; Koranteng, 1989; Brainerd, 1991). On the contrary, *S. maderensis* is less migratory and inhabits coastal waters of depths up to 50 m (Whitehead, 1985). We have also shown that *S. maderensis* prefers waters of 5–24 m in depth whereas *S. aurita* preferably dwells in waters of depths 20–34 m. Hence, the high catch composition of *S. aurita* in the purse seine nets (usually deployed in deep waters) and of *S. maderensis* in the gill net (used in shallow waters) could be explained by the distribution of the two species in the coastal waters. The higher proportion of *S. aurita* in the poli-watsa landings could be due to high occurrence of the poli-watsa in the fishery and the wide ranges of mesh sizes the net possesses. The catching properties of both poli (mesh size ≤3.0 cm) and watsa (mesh size >3.0 cm) possessed by poli-watsa likely explains the bimodal size distribution of *S. aurita* in the landings. Thus, the net panel with small mesh sizes, which is a characteristic of poli, catches more juveniles and could be restricted by managers. The higher proportion of *S. maderensis* in the set net landings could be ascribed to the high frequency of set net in the gill net fishery as well as high efficiency of the net.

Efforts in gathering data on sardinellas from the industrial fishery sector in Ghana proved futile due to difficulties in accessing the fishers at the Tema Fishing Harbor. As a result of this, information on the sardinella fishery with respect to the industrial fishery was excluded from this paper. Nonetheless, a one-month preliminary survey conducted in 2017 using sardinella catches from the industrial fishery through "Saiko fishing" (transshipment) revealed that adult individuals of *S. aurita* were being exploited in the sector. These individuals constituted a small fraction as bycatch. It is imperative to note that other small pelagic fish (e.g., horse mackerels) are exploited in addition to sardinellas as bycatch in the industrial fishery.

4.3. Conclusion

Six kinds of fishing gears, namely poli, watsa, poli-watsa, ali, set net, and beach seine were recorded among the artisanal and semi-industrial fleets of the sardinella fishery of Ghana. These gears fall broadly into purse seine (poli, watsa and poli-watsa), gill net (ali and set) and beach seine categories. Purse seines are differentiated based on mesh sizes as follows: poli ≤3.0 cm; watsa >3.0 cm; poli-watsa had a combination of poli and watsa mesh sizes. The difference between the two kinds of gill nets are based on the nature of the net material: ali (multifilament cotton material); set net (monofilament nylon material). Poli-watsa significantly constitutes the preponderant fishing gear in the sardinella fishery. About 96% of the fishing vessels are motorized in the sardinella fishery.

Management measures are urgently needed in the sardinella fishery of Ghana. We found sardinella landings were predominately composed of juveniles that have yet to become sexually mature, and thus believe overfishing is occurring. Whereas purse seines are catching more *S. aurita,* gillnets are harvesting more *S. maderensis*. Differences in our findings and previous assessments of the fishery highlight the need for periodic assessments to guide policy-makers and managers in their decision-making. For management and conservation purposes, it is recommended that further research should focus on how management actions such as mesh size regulation can promote sustainable exploitation of the sardinella stocks in Ghana.

CRediT authorship contribution statement

Evans K. Arizi: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft, Project administration. **Jeremy S. Collie:** Writing – reviewing and editing. **Kathleen Castro:** Conceptualization, Writing – reviewing and editing. **Austin T. Humphries:** Conceptualization, Methodology, Writing – reviewing and editing, Supervision, Project administration.

Declaration of competing interest

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

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Appendix A. Supplementary data

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