Estimating tag-reporting rates for Atlantic tropical tuna fleets using coincidental tag return and tag seeding experiment data

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Abstract

One of the most important biases to consider in tagging capture-recapture data for stock assessment studies is the proportion of reported tags among the actual recaptures, i.e., the tag-reporting rate. In this study, we used the model developed by Kimura (1976) and adapted in a Bayesian framework by Carruthers et al. (2015) to estimate the reporting rates for thirteen Atlantic Ocean tuna fleets using coincidental tagging data and catch data disaggregated by species, school-type (Fish Aggregating Device and Free Swimming Schools), location and time. The method was applied on recaptures and tag seeding experiments conducted during the Atlantic Ocean Tropical Tuna Tagging Program (AOTTP) of the ICCAT (International Commission for the Conservation of Atlantic Tunas). Tag seeding consists of secretly planting tags on fish by observers onboard fishing vessels to estimate how many tags are found during later stages (landing, processing, etc.) and reported to scientific authorities. Our results showed that the tag-reporting rate was as large as 84.70% (80.58% – 88.39%) for the European Union purse seiner fleet (Spain and France) but decreased for several surface fleets from 72.79% (67.49%-77.77%) for the Spanish baitboats (operating off Senegal or in Canary islands) to 22.83% (15.26% - 31.24%) for the Ghanaian mixed purse seiner-baitboat fishery. Overall, we conclude that given the very low reporting rate for several important fleets operating in the Atlantic Ocean, it is crucial to account for the reporting rate estimates to avoid highly biased results in future stock assessment using tagging data.

Keywords: Tag reporting rate, Tag seeding experiments, Bayesian analysis, Tropical tuna, Atlantic Ocean.

Highlights

- The reporting rate of the "observed" (European purse seiner) fleet was estimated at 84.70% from tag seeding data.

- The tag-reporting rates for the others twelve fleets were estimated by using coincidental tagging data and catch data disaggregated by species, school-type (FAD, free school, location and time.

- Estimates of the other fleets inferred from the reporting rate of the European purse seiner fleet were lower and ranged from 22.83% to 72.82%.

1. Introduction

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Tagging programs remain valuable sources of information for research on highly migratory species (HMS). Since the “Rio de Janeiro conference” in 1966, ICCAT has been responsible for coordinating research on Atlantic tuna and the regional management of its fisheries (Carroz and Roche, 1967). As part of this mission, ICCAT has implemented several tagging programs in the Atlantic Ocean over the years. However, most of these programs were limited to one species, and for practical reasons, they were not carried out on an Atlantic Ocean basin-wide scale. The long-awaited project of an Atlantic Ocean basin-scale tagging program started in June 2016 under the "Atlantic Ocean Tropical Tuna Tagging Program (AOTTP)". The AOTTP objective is to improve the estimation - derived from capture-recapture data - of key parameters in stock assessment, namely growth, natural and fishing mortality, movement, and stock structure. From 26 June 2016 to 28 December 2020, 120 679 fish were tagged using conventional, internal electronic and chemical (OTC) tags. As of 29 July 2021, 17 669 tags have been recovered, implying an empirical recapture rate (assuming 100% reporting) of 14.64%. The main target species of AOTTP were the three principally harvested tropical tunas (skipjack, *Katsuwonus pelamis*; yellowfin, *Thunnus albacares* and bigeye, *Thunnus obesus*). Assessing exploitation and mortality rates with AOTTP's tagging data requires a good estimate of the proportion of recaptured tags that are returned, i.e. the tag-reporting rate (Hillary et al., 2008). However, the rate of fisher underreporting is usually unknown.

Several methods have been used to estimate the tag-reporting rate. Some include the use of tagging data alone, angler or port surveys, high reward tagging, and observer programs in multi-component fisheries with a 100% reporting rate in one component (Pollock et al., 2002, 2001). However, these methods assume spatio-temporal invariance of the reporting rate and 100% reporting of all fish recovered from a portion of the fishery, which can be considered major assumptions (Berger et al., 2014). On the other hand, the tag seeding experiments estimate tag reporting rates for the fishery components that conform to the experimental tagging plan (gear, fleet, landing location, etc.). Tag seeding consists of secretly planting tags in fishers' catches by observers onboard fishing vessels to verify that the tag is found during later stages (landing, processing, etc.) (Hearn et al., 2003). However, sometimes tag seeding is compromised, or seeding experiments cannot be conducted for all fleets operating in the tagging area to infer an overall reporting rate. In such situations, we can proceed another way by defining an observed fleet whose reporting rate is largely known and better controlled.

The concept of estimating all the fishing operators' reporting rates by using the knowledge of one operator's reporting rate (i.e., the “observed fleet”), developed initially by Kimura (1976), was extended by Carruthers and McAllister (2010) to a Bayesian estimator that operates on data disaggregated in time, space, and size of the species. This method is divided into three steps: (1) selection of the observed fleet and calculation of the reporting rate associated with this fleet from seeding experiments, (2) construction of comparison strata of the observed fleet's catch data and recaptured tags with that from the other fleets and (3) inference of the reporting rate of the other fleets from the reporting rate of the observed fleet. In this study the observed fleet is the European purse seiner fleet (France and Spain flags) operating in the Atlantic Ocean. The other fleets' reporting rate estimation is done by comparing the catches and recaptures made simultaneously in the same strata by these fleets and the observed fleet (coincidental tagging data). Carruthers et al. (2015) used time, space and tuna size factors to construct these strata.

In our case, we based strata construction on time, space and school type factors. The school types considered were unassociated schools (i.e., free school; or not associated with structure) where large yellowfin tuna dominate, and schools associated to floating objects, mainly drifting fish aggregative devices (dFAD), attracting skipjack and juvenile bigeye and yellowfin. Indeed, there are different sizes of fish by school type, and reporting rates would be expected to vary by size (Hearn et al., 1999; Pollock et al., 2002), so "it is essential to consider fleet fishing strategies as a source for heterogeneity." It is important to note that the choice of the school type variable versus the size variable is related to the reliability and quality of the catch at size data available for this study.

Therefore, this study estimates the tag-reporting rates of the major surface fleets (i.e., purse seine, hook and line, and baitboats) operating in the Atlantic Ocean that have recovered at least thirty tags during the AOTTP. Small-scale artisanal fleets and longline fleets, which report low recaptures, were not included in the analysis.

2. Materials and methods

2.1. Theory

As mentioned in the Introduction section, Kimura (1976) developed a method to infer the unknown tag-reporting rate of a commercial fleet from an observed fleet with a known tag-reporting rate. By defining an observed fleet (obs) for which we have simultaneously the amount of fish caught (C_{obs}) and the number of tags recovered (T_{obs}) in a given spatio-temporal stratum, the following relationship can be established:

$$\lambda_{\mathrm{com}} = \frac{T_{\mathrm{com}} C_{obs} \lambda_{obs}}{T_{obs} C_{\mathrm{com}}} \quad (1)$$

where T is the number of tags, C is the number of fish caught, and the subscripts *obs* and *com* refer to the data of an observed fleet assumed to have a known reporting rate of λ_{obs} and a commercial fleet with unknown reporting rate λ_{com}.

For the sake of generalization and to be able to use this method to infer the tag-reporting rates of other fleets that do not overlap with the observed fleet in a given spatio-temporal stratum, we can rephrase it in terms of mark rate *m* (the probability of catching a tag given a fish is caught) .

$$m = \frac{T_{obs}}{\lambda_{obs} C_{obs}} = \frac{T_{com}}{\lambda_{com} C_{com}} \quad (2)$$

and therefore:

$$T_{\mathrm{com}} = m\, \lambda_{\mathrm{com}}\, C_{\mathrm{com}} \quad (3)$$

We then assume that tagged fish are fully mixed in each stratum (see discussion section for more details on the tag mixing assumption).

Note that where λ_{obs} is known, for any strata in which T_{obs} and C_{obs} are reported, *m* is informed. Any fleet that reports T_{com} and C_{com} in the same strata may be assumed to be operating on the same population of marked fish of mark rate *m*. It follows that these coincidental observations inform the reporting rate of the commercial fleet. If reporting rates can be assumed constant over time and space, this commercial reporting rate will then serve to inform other fleets' reporting rates with coincidental data (even if they do not overlap directly with the observed fleet). In this way, commercial reporting rates flow from the observed fleet through a network of mark rates and overlapping tag recovery observations. In this study, the observed fleet is composed of French and Spanish purse seiners for which there are independent tag seeding data with which to estimate the tag-reporting rate.

The tag-reporting rate of the observed fleet can be quantified from tag seeding data by assuming a binomial probability of reporting a seeded tag (Carruthers and McAllister, 2010):

$$P(R \mid \lambda_{obs}, S) = \binom{S-1}{R} \lambda_{obs}^{R} (1-\lambda_{obs})^{S-R} \qquad (4)$$

where S is the number of seeded tags and R is the number of seeded tags reported by the observed fleet. For any strata ***s***, the tags reported by a fleet f can be assumed to be distributed according to the negative binomial distribution:

$$P(T \mid C, \lambda, m) = \prod_f \prod_s \binom{C_{f,s}-1}{T_{f,s}} \left(\lambda_f m_s\right)^{T_{f,s}} \left(1-\left(\lambda_f m_s\right)\right)^{C_{f,s}-T_{f,s}} \qquad (5)$$

In this study, a stratum (see "Strata considered" section for more details on strata construction) is a division in time, space and fishing mode (FAD vs free school) for which a population of fish can be assumed to have the same mark rate ***m***. For the commercial fleets, reporting rates were assigned a uninformative beta(1,1) prior. In this analysis, we used the same beta prior for the mark rate of each stratum. Using the Gibbs sampler, we used a Bayesian statistical approach to estimate reporting rates distribution with Markov Chain Monte Carlo (MCMC) simulation. The MCMC was undertaken using R 3.6.3 (R Development Core Team, 2020), the package ‘R2WinBUGS’ (Sturtz et al., 2005) and WinBUGS 1.4 (Lunn et al., 2000) with three chains of 50 000 iterations and a ‘burn-in’ of 5 000 samples. In addition, the R packages ggmcmc (Fernández-i-Marín, 2016) and coda (Plummer et al., 2006) was used to process the MCMC simulation obtained from WinBUGS and assess the convergence of the MCMC algorithms.

2.2. Presentation and pre-processing of the study data

From 26 June 2016 to 28 December 2020, 120 679 fish (tropical tuna) had been tagged (during AOTTP) using both conventional, electronic and chemical (OTC) tags, of which 41 015 (36.53%) were yellowfin, 46 989 (41.85%) were skipjack, and 24 217 (21.62%) were bigeye. As of 29 July 2021, 17 669 tags concerning the three tropical tuna have been recovered, of which 8 423 were yellowfin, 3 576 were skipjack, and 5 021 were bigeye. Data missing key information at recapture (i.e. gear type, fleet code, date or position) were removed from the analysis. We considered fleets that recaptured at least 30 tags during the AOTTP and tuna tagged with a conventional tag (yellow spaghetti tag) according to the flag and fishing gear type. We split the data according to the gear type, i.e. purse seine catch and recapture data vs other gears (baitboats and handline) catch and recapture data.

Catch and fishing effort statistics for each species by area (1x1 degree squares by month for purse seiners, 5x5 degree squares by quarter for baitboats and handlines), gear, flag, raised to the total landing of Atlantic fishing fleets were extracted from the ICCAT website. Indeed, the spatio-temporal data called "Task 2" used in this analysis, which in general area incomplete, are raised to the total annual catches reported in "Task 1" by each ICCAT contracting party (CPC) and assumed to be complete. These spatio-temporal datasets were used as the data source to calculate the catch rate $\boldsymbol{m}$ (See equation 2).

Since the purse seine catch and effort statistics of the tropical tuna fishery operating in the Atlantic Ocean are only available through 2019, we selected the purse seiners capture-recapture data that occurred through 31 December 2019. Likewise, since the other fleets' catch and fishing effort data raised to total landings are only available through 2018, we selected the baitboats and handline capture-recapture data that occurred through 31 December 2018. This preprocessing allowed us to obtain 12 288 recaptures, representing 72.19% of the initial data.

A tag seeding experiment had been conducted on board some fleets and some unloading locations. Scientific observers or voluntary skippers secretly tagged some tunas before the fish were placed in the vessel's well. The probability of detecting these seeded tags was comparable to those used in an actual tagging operation. After preprocessing the tag-seeding data, there were 338 tags seeded on the French and Spanish purse seiner fleet for the three target tuna species (Yellowfin, Bigeye, and Skipjack).

2.3. Definitions of fleets for which reporting rates were estimated

We initially planned to estimate the tag-reporting rate of 15 fleets (fleets that recaptured at least 30 tags during the AOTTP) according to the flag and fishing gear type. Unfortunately, two of them, i.e. the Ivorian artisanal fleet and the Brazilian baitboats, did not overlap well with the observed fleet, making it impossible to use this method to estimate their reporting rate (see **Fig.Sup 1** to **Fig.Sup 4**). Furthermore, we initially intended to estimate other gears reporting rates, such as some longlines operating in the Atlantic Ocean. However, we could not do that due to poorly documented catches and small areas of operation of these fleets (e.g., the networks of anchored FADs in the Ivorian EEZ or catches concentrated near the coast). For all of these reasons, it is difficult or impossible to estimate the tag-recovery rate of these fleets using this method. After all the validation and verification steps of the model's assumptions, we defined twelve fleets (in addition to the European purse seiner fleet), some of those as the result from the grouping of others (see **Table 1** for a complete presentation). The “BB_Dakar” and “PS_BB_GHA” represented the baitboat vessels of Spain, France, and Senegal based in Dakar-Senegal and the purse seiner and baitboat vessels of Ghana, respectively. For the Ghanaian fleet (composed of two different gears), the ICCAT tropicals working group concluded that the estimation of catch and efforts data should considered baitboat and purse seine in the same fleet segment (Chassot et al., 2016). Consequently, we put the two Ghanaian gears together in the same fleet (“PS_BB_GHA”). However, because more than 85% of Ghanaian recaptures are from purse seiners (see **Table 2** and **Table 3**) we performed then a sensitivity analysis to estimate the reporting rate for the Ghanaian purse seiner fleet alone (“PS_GHA”).

2.4. Strata considered

In the development of the methodology, selecting the observed fleet and estimating its tag-reporting rate using seeding data is followed by the construction of strata to compare the mark rates *m* between the observed fleet and the other fleets. Disaggregating the data into strata to estimate the reporting rate corrects some bias generated by assuming that the reporting rate is homogeneously distributed throughout the study area. Besides, this process significantly reduces the number of overlapping recaptures used to infer the other fleets' reporting rates. This phase is crucial because it is the basis of the reporting rates estimation with this method. For it to be useful, it is necessary to construct strata large enough to have data meaningful for analyses, but small enough to minimize potential bias. In addition, it is essential to know what spatio-temporal resolution is appropriate for comparing different fleets' return rates.

Table 1

The disaggregation of fishing fleets operating in the Atlantic Ocean for which individual reporting rates were estimated. We defined twelve ‘fleets’ (in addition to the Spanish and French “observed fleet”) according to different combinations of flags and gears. In some cases, these ‘fleets’ are grouping multiple flags or gear types; for example, the baitboat of Spain, France, and Senegal based in Dakar and operating off Senegal were aggregated under the term ‘BB_Dakar’.

* The Ghana PS fleet is used as a sensitivity approach to analyze Ghanaian PS and BB's pooling on the reporting rate estimate.

Flag	**Gear**	**Fleet code**	**Description**
Panama	Purse seiner	PS_PAN	Purse seiners of Panama
Salvador	Purse seiner	PS_SLV	Purse seiners of Salvador
Curaçao	Purse seiner	PS_CUW	Purse seiners of Curaçao
Guatemala	Purse seiner	PS_GTM	Purse seiners of Guatemala
Senegal	Purse seiner	PS_SEN	Purse seiners of Senegal
Cabo Verde	Purse seiner	PS_CPV	Purse seiners of Cape Verde
Brazil	Handline HL	HL_BRA	Handline vessels of Brazil
Ghana	Purse seiner	PS_GHA	Purse seiners (only) of Ghana*
Ghana	Purse seiner and Baitboat	PS_BB_GHA	Purse seiners and Baitboats of Ghana
Spain,France & Senegal	Baitboat	BB_Dakar	Baitboats based in Dakar Senegal
Spain	Baitboat	BB_SPA_CAN	Baitboats of Spain based in the Canary Islands
Portugal	Baitboat	BB_PRT	Baitboats of Portugal based in Madeira and Azores
Spain & France	Purse seiner	Ref_PS_FR_SPA	Purse seiners of Spain and France

Where possible, we added species and school type (which approximate the size-structure of the catch data) factors in the strata's construction. In the catch and effort data, sometimes the school type is missing or the variable itself does not exist for some fleets. When it was not possible to estimate the proportion of catches by school type, we simplified the calculation by removing the school type variable in the strata construction with the aim to compare them with the observed fleet. For most cases, the strata constructed are thus of the type: spatio-temporal structure*year*species*school type. To overcome the situations where catch and effort data have missing information for the school type variable, we considered some simpler models without the school type. In cases recapture (tagging) and catch data have missing values for the school-type variable, we used the known proportion of catches and recapture by strata and by school type to reallocate this data with missing values on school type (assignment based on averages). We estimated the tag reporting rates from these strata and tested the hypothesis that the tag reporting rate of the observed fleet is higher than those of the other fleets. This condition allowed us to validate the choice of the spatio-temporal structure or to use a larger resolution to obtain more consistency between the data of the fleet under consideration and those of the observed fleet. We proposed two other spatio-temporal structures for the purse seiners and one other structure for the baitboats. The base case model proposed ensures that the spatio-temporal strata construction depends on the species and the fishing mode. Situations that required data restructuring, distribution of recaptures without school type information, and simplification of strata construction (strata with catch data without defining school type) were addressed to ensure the estimation of the tag-reporting rate of the 12 fleets. The final models used for the estimation of each tag reporting are specified in the result section.

2.5. Convergence of the MCMC algorithms (Gelman and Rubin’s diagnostics tools)

The Markov Chain Monte Carlo (MCMC) algorithms are widely used to fit complicated statistical models in situations where the traditional estimation techniques are challenging to apply. However, it is difficult to determine the algorithm's convergence, because it is not a scalar quantity to a point but a distribution to another distribution. Therefore, MCMC diagnostic tools are needed for deciding the convergence of Markov chains to stationarity. There are many MCMC diagnostics tools in the literature, but we used the Gelman-Rubin diagnostic tools (parameters and plot) in this paper. Gelman and Rubin's (1992) approach to monitoring convergence is based on detecting when the Markov chains have forgotten their starting points by comparing several sequences drawn from different starting points and checking that they are indistinguishable. There are many ways to compare parallel sequences. The most obvious approach is to look at overlaid traceplots and see if the two sequences can be distinguished. A quantitative approach is based on the analysis of variance. The Gelman-Rubin diagnostic measures whether there is a significant difference between the variance within several chains and between several chains by a value called "scale reduction factors". The gelman.diag function in the R package coda gives the scale reduction factors for each parameter. A factor equal to one means that between-chain variance and within-chain variance are equal; larger values mean that there is still a notable difference between chains. Convergence is achieved when the scale reduction factor is below 1.1. The R package coda's gelman.plot function shows the development of the scale-reduction over time (chain steps), which is helpful to see whether a low chain reduction is also stable.

Table 2

Total nominal catch of fish (tons) and recaptures numbers by fleet, average recapture rate and simple reporting rate for purse seiner. The average recapture rate is the number of tags recaptured per tons of fish caught. Assuming a single mixed strata, an approximate point estimate of reporting rate can be calculated for the seven purse seiner fleets ('Simple reporting rate estimate') by multiplying their recapture rate by the assumed reporting rate of the observed fleet (84.95%; 290 tags seeded, 247 reported) and dividing this by the recapture rate of the observed fleet.

Fleet code	Catch (tons)	Number of recaptures	Average recapture rate	Simple reporting rate estimate (%)
PS_PAN	41036.5	443	10.79	85.34
PS_SLV	86443.2	554	6.4	50.66
PS_CUW	1100063.4	724	6.57	52
PS_GTM	46883.8	65	1.38	10.96
PS_SEN	113640.7	1975	17.37	137.4
PS_GHA	178580.7	379	2.12	16.77
PS_CPV	37449.3	90	2.40	18.99
Ref_PS_FR_SPA	371491.9	3990	10.74	84.91

Table 3

Total nominal catch of fish (tons) and recaptures numbers by fleet, average recapture rate and simple reporting rate for baitboats. The average recapture rate is the tags recaptured per tons of fish caught. Assuming a single mixed strata, an approximate point estimate of reporting rate can be calculated for the five other fleets ('Simple reporting rate estimate') by multiplying their recapture rate by the assumed reporting rate of the observed fleet (84.95%; 290 tags seeded, 247 reported) and dividing this by the recapture rate of the observed fleet.

Fleet code	Catch (tons)	Number of recaptures	Average recapture rate	Simple reporting rate estimate (%)
PS_BB_GHA	227351.4	402	1.76	10.99
BB_Dakar	34127.5	1948	57.08	354.8
BB_SPA_CAN	17524	545	31.09	193.30

BB_PRT	16506.8	335	20.29	126.15
HL_BRA	65634.1	197	3	18.65
Ref_PS_FR_SPA	274012.9	3745	13.66	84.95

3. Results

The data structure allowed us to estimate two types of modelling procedure (i.e., omitting catch data without declared school type vs reallocation of the catch with unknown school type based on known proportions by school type) with two types of strata construction in each modelling option. The specification-retained strata by fleet are presented in **Table 4**. Reporting rate estimates in this study are detailed in **Table 4** and illustrated in **Fig. 1** and **Fig. 2**.The analysis of the Gelman Rubin diagnostics (**Table 5** and **Fig.Sup 7)** ensured that convergence was achieved for all models. The posterior estimates of reporting rates varied widely among the different fleets. The effective sample size (ESS) used to draw posterior distributional conclusions was approximately 4 500 by chain (mean ESS). The ESS is the equivalent number of independent samples that would contain the same posterior accuracy as the correlated samples from an MCMC. Based on tag seeding experiment data, the reporting rate of the EU purse seiner fleet was estimated to be 84.72%. The mean reporting rate estimates of the twelve other fleets were between 22% and 72%. The Ghanaian fleet composed of baitboats and purse seiners showed the lowest reporting rate. The sensitivity analysis showed no differences between the reporting rate of purse seiners alone and purse seiners combined to baitboats, and reinforced the advice to consider these two gears in the same fleet.

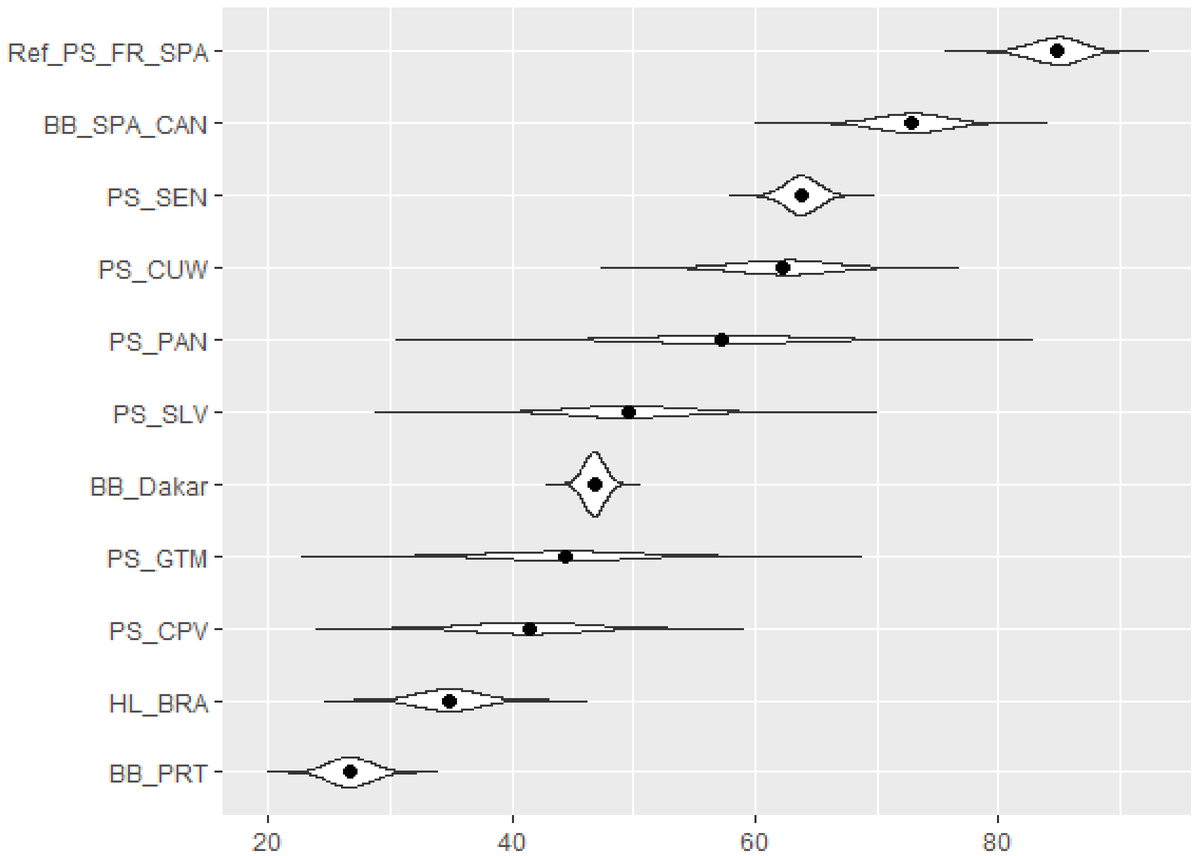

Fig. 1. MCMC posterior probability and 95% credible intervals for the estimated reporting rates of the 11 fleets (the Ghanaian fleets are presented in figure 2). The central range depicted by a solid black violin is the 50% probability interval. The most central range is the 95% (97.5 - 2.5%) credible intervals.

Table 4

Posterior probability distributions of AOTTP reporting rates (percentages) and structure of the stratification used in each case for different tropical tuna surface fleets operating in the Atlantic Ocean. sd: standard deviation.

		MCMC posterior probability and credible intervals				
Fleet code	**Models components (variables)**	2.50%	50%	97.50%	***Mean***	sd
PS_PAN	School-type; specie; year & [1° x Month]	44.93	57.37	69.50	***57.29***	6.31
PS_SLV	School-type; specie; year & [1° x Month]	40.83	49.62	58.17	***49.62***	4.39
PS_CUW	School-type; specie; year & [1° x Month]	54.77	62.37	69.39	***62.28***	3.70
PS_SEN	School-type; specie; year & [5° x Bimonthly]	61.18	63.81	66.42	***63.81***	1.34
PS_CPV	School-type; specie; year & [10° x Quarter]	33.10	41.34	50.12	***41.12***	4.36
PS_GTM	School-type; specie; year & [10° x Quarter]	33.91	44.35	55.54	***44.49***	5.47
BB_Dakar	School-type; specie; year & [5° x Quarter]	45.15	46.76	48.38	***46.76***	0.82

HL_BRA	Specie; year & [20° x Semester]	30.26	34.87	39.61	***34.88***	2.37
BB_SPA_CAN	Specie; year & [20° x Semester]	67.49	72.85	77.77	***72.79***	2.65
BB_PRT	Specie; year & [20° x Semester]	23.49	26.73	30.26	***26.77***	1.72
PS_GHA	School-type; specie; year & [5° x Bimonthly]	20.77	28.23	36.72	***28.35***	4.07
PS_BB_GHA	School-type; specie; year & [5° x Quarter]	15.09	22.51	31.11	***22.69***	4.10
Ref_PS_FR_SPA	Directly obtained from tag seeding data	80.74	84.78	88.39	***84.72***	1.96

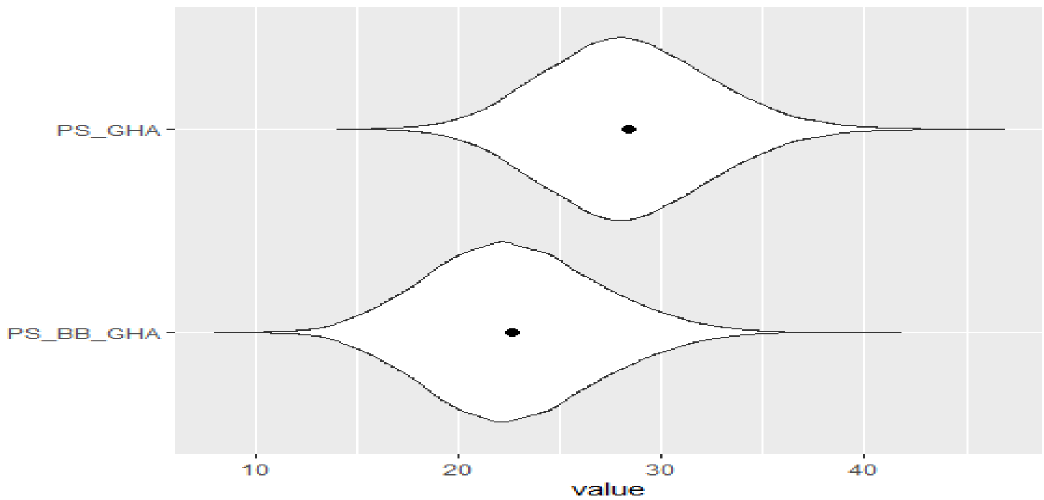

Fig. 2. MCMC posterior probability and 95% credible intervals for the estimated reporting rates of the Ghanaian fleet, depending on whether we consider the purse seiners only or the mixed purse seine and baitboat fishery. The central range depicted by a solid black violin is the 50% probability interval. The most central range is the 95% (97.5 - 2.5%) credible intervals.

Table 5

Gelman-rubin convergence diagnostics (Convergence rule: parameter < 1.1)

Parameters	Point estimate	Upper Confidence interval
PS_PAN	1.001	1.000
PS_SLV	1.000	1.000
PS_CUW	0.999	1.001
PS_SEN	1.000	1.000
PS_CPV	1.000	1.001
PS_GTM	1.000	1.001
BB_Dakar	0.999	1.000
HL_BRA	1.000	1.000
BB_SPA_CAN	1.000	1.001
BB_PRT	1.000	1.001
PS_GHA	1.000	1.000
PS_BB_GHA	0.999	1.000
Ref_PS_FR_SPA	1.000	1.001

Multivariate potential scale reduction factor	**1.002**

4. Discussion

This study aimed at estimating the tag-reporting rate of the main surface fleets catching tropical tunas in the Atlantic Ocean, based on a theoretical approach proposed by Kimura (1976) combined with a Bayesian method proposed by Carruthers and McAllister (2010). The approach is to infer the tag-reporting rate of other fleets from an observed fleet for which we can have a relatively good estimate of its tag-reporting rate. Estimating the reporting rate is a requirement for the use of tagging data. It is crucial to understand the difference in reporting rates between fleets to estimate correcting factors for better-estimated crucial parameters for stock assessments such as natural or fishing mortality, species movement and stock mixing rates.

The observed fleet in this study was the European purse seiner fleet composed of Spanish and French vessels, for which the reporting rate was estimated at 84.72% from tag seeding data (**Table 4**). Based on this estimate, we were able to estimate the tag-reporting rate of 11 other surface fleets operating, at least partially, in the same spatio-temporal strata than the European purse seiner fleet. The Spanish baitboats from Canary Island or purse seiners from Curaçao and Senegal exhibited larger reporting rates than the Ghanaian fleet or Portuguese baitboats (from Madeira and Azores). The differences observed (more than 25%) between European purse seiners and the same purse seiners registered under the flags of Cape Verde and three Latino- American countries (i.e., Panama, El Salvador and Guatemala) are surprising as all these purse seiners belong to Spanish tuna companies. There is no clear explanation for this difference, but we suspect it may be due to the different landing locations of these fleets. Indeed purse seiners registered under these flags may have a larger proportion of landings in Mindelo (Cape Verde), as well as in Tema/Takoradi (Ghana), than the European fleet (Spain and France) mostly landing in Abidjan (Cote d'Ivoire). This could suggest an additional effect of the landing place to the reporting rate, as evidenced by Hampton (1997) in the Pacific ocean. Such results underline the need to investigate the potential variables that could describe the heterogeneity of reporting rates and, consequently, the possibility of considering them in the analysis. For example, following the estimates made in this document, it would be essential to initiate other analyses to know which variables in the strata construction or other parameters, such as the tag type and the landing location, are the most important in describing reporting rate heterogeneity. However, we could not carry out such analyses because we did not have adequate data, such as tag seeding data covering many of the studied fleets and catches data by landing location. It is relevant to notice that more than 90% of the tags used during the AOTTP and all the tags used during the seeding experiments were conventional tags. It would be interesting for future tagging programs to collect more adequate data to perform these analyses.

Notice that in this study, the model includes the tag reporting rate of the observed fleet as an estimator and not as a distribution. That is why the concerned fleet's result variance is not always larger than the observed fleet variance. Future work could develop an integrated approach to model the reporting rate such that the variance of the observed fleet is maintained for all other fleets. Otherwise, as Brooks and Deroba (2015) showed, the variance of the observed fleet estimator is not carried forward to subsequent estimators (i.e., the other fleets).

It must be stressed that the tag-reporting rate estimated from the tag seeding data was made under the strong assumption that it remained homogeneous for this fleet over the entire study period and spatial extent. Indeed, all the analyses carried out in this study were based on several assumptions: (1) tags are distributed homogeneously over the spatial and temporal scale of comparisons among fleets (i.e., at the resolution of the estimated mark rates "m"); (2) reporting rates remain constant over time among species and are the same in areas beyond spatio-temporal comparisons; (3) catches are accurately reported (with consequence on the estimates as showed by Carruthers et al., 2015). Moreover, our method assumes that the tagged fish are mixed throughout the release and fishery areas. This means that the fish released from a relatively small region mix rapidly over a much broader region of interest, so tagged and untagged fish are equally likely to be captured by commercial fisheries. Thus, the results obtained are meaningful only under these assumptions and cannot be interpreted or validated outside of them. However, we are aware that several studies have shown that tag-reporting rates vary over time. Hampton (1997) showed a temporal dependence of the reporting rate in a tagging program, and Hillary (2008) found that the reporting rate could change from year to year with the example of the Indian Ocean EU purse seiner fleet whose reporting rate changed from 2004 to 2007. However, there were insufficient tag seeding experiments data throughout the duration of the AOTTP to expand the analyses.

Another crucial phase in the modelling is the strata construction. Hearn et al. (1999) identified potential biases in aggregating return rates and catches without considering size classes. We would have liked to address this issue, but the difficulty of having size data available and appropriate for this study did not allow us to look at this aspect. However, we compensated for this by including the school type variable in the construction of the strata. Today, it is evident that fishing under dFADs (and other aggregating structures: oil platforms, anchored FADs, school associated with the tagging vessel, etc.) is different from fishing free schools. Besides, large yellowfin dominate free schools when dFAD schools mainly comprise skipjack and juveniles of yellowfin and bigeye. However, the school type variables related to catch data and tag recovery position is not free of bias. Indeed, the catch and fishing data are, in most cases, reported by national scientists or estimated by the ICCAT secretariat. Consequently, these data may contain uncertainties (e.g., misreporting, inadequate sampling, etc.) and present challenges to resolve. A challenge in the construction of the strata concerns the spatio-temporal distribution of the data. Previous studies using this method have proposed several structures and compared the difference in results to evaluate the impact of the spatio-temporal structure on the estimates of the tag-reporting rate. We selected five strata with a monthly 1x1 squares degree to a semi-annual (January - June and July - December) 20x20 squares degree. Unfortunately, the capture-recapture data contained errors in many key covariables of our study, school type, recapture positions (latitude and longitude), and dates (month and year), which reduced the available data for analysis. In some cases, we proposed methods to correct these (such as comparing species at release to species at recapture) and removed them from the data used whenever possible. All of this pre-processing resulted in only 72.19% of the original recapture data.

Finally, tag reporting rate estimates obtained from the AOTTP data are considerably higher than those observed in the Indian Ocean (Carruthers et al., 2015). Indeed, an average of the estimated tag-reporting rates (of the 11 other fleets) weighted by the recaptures yields 52 return tag out of 100 recaptured tags. Again, this value is considerably higher than the 15 tag returns out of 100 recaptured tags found in the Indian Ocean by Carruthers et al. (2015). Notice that these rates are not directly comparable because the fleets considered by Carruthers et al. (2015) were more heterogeneous than those in this study. Indeed, their work included longlines and artisanal fishing gears whose reporting rates are low. Nevertheless, a simple comparison of tag seeding results shows that the RTTP and IOTTP observed fleet's tag reporting rate was larger than those of the AOTTP estimated in this study.

Knowing fleet reporting rates is essential to using tagging data in fisheries research. Therefore, it is fundamental to correct the tagging database to account for uncertainties in the tag reporting rate and other factors before introducing tagging information into stock assessment models. Berger et al. (2014) suggested a number of correction procedures for this purpose. The quality or reliability of input data used to estimate the tag reporting rate, i.e. seeding experience, release recovery data, and catch data affect our ability to monitor and interpret estimation of reporting rates. A reasonable estimation of tag reporting rates begins with collecting reliable data. The relatively low number of seeding experiments, the unbalanced nature of the dataset coverage by observer fleet through time, and some missing information on the recovery data during AOTTP are some limits of this study. However, its results remained crucial for using AOTTP tagging data in future stock assessments.

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.

CRediT authorship contribution statement

S. AKIA: Conceptualization, Methodology, Software, Validation, Visualization, Investigation, Writing - original draft.

M. Amande: Conceptualization, Supervision, Writing - review & editing, Supervision.

D. Gaertner: Conceptualization, Validation, Writing - review & editing, Supervision, Funding acquisition, Project administration.

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