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FISHING ACTIVITY OF TUNA PURSE SEINERS ESTIMATED FROM VMS DATA AND VALIDATED BY OBSERVERS' DATA

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SUMMARY

In the lack of direct estimate of tuna abundance, the French tropical tuna fleet of purse-seiners provides a way to monitor the tuna stocks particularly through the calculation of Catch per Unit of Effort (CPUE). The objective of this study was to analyze the individual track of purse seiners with the aim to identify which part of the searching behaviour should be used to perform the fishing effort. In this context, Vessel Monitoring Systems (VMS) data are useful to analyse the different fishing activities of a purse seiner at a small scale (i.e.. stop, track and cruise), generally embedded into the concept of fishing effort. A state-space model (run in a Bayesian framework) was applied to speeds and turning angles from Vessel Monitoring Systems (VMS) data, to identify the different "states" of the fishing behaviour of a purse seiner over a fishing trip. Then a threshold was fitted to distinguish the activities "fishing" and "stop" without fishing (from the "still" state), "tracking" (from "meander"), and "cruising" (from "straight"). On a subset of VMS data corresponding to observers' data, some differences of fishing efforts between fishing on free-swimming schools and schools associated with FAD (Fish Aggregating Devices) are highlighted.

RÉSUMÉ

Etant données les difficultés d'estimation directe de l'abondance de thon, la flottille française de thoniers senneurs tropicaux offre la possibilité de surveiller les stocks de thon, particulièrement grâce au calcul de Capture par unité d'effort (CPUE). L'objectif de cette étude était d'analyser la trajectoire individuelle des thoniers senneurs, dans le but d'identifier quelle parties du comportement de recherche doivent être utilisées dans le calcul de l'effort de pêche. Dans ce contexte, les données de Vessel Monitoring Systems (VMS) sont utiles pour analyser les différentes activités de pêche d'un thonier senneur à fine échelle (c'est-à-dire arrêt, recherche active, route-recherche), généralement inclus dans le concept d'effort de pêche. Un modèle à espace d'état (avec une approche bayésienne) a été appliqué aux vitesses et angles de changement de direction issus des données de Vessel Monitoring Systems (VMS) pour identifier les différents états du comportement de pêche d'un thonier senneur pendant une marée. Ensuite un seuil a été ajusté pour distinguer les activités de « pêche » et d' « arrêt » sans pêche (à partir de l'état « immobile »), « recherche active » (à partir de « sinueux »), et « route-recherche » (à partir de « tout droit »). Sur un sous-jeu de données VMS correspondant aux données Observateurs, certaines différences d'effort de pêche entre bancs pêchés sur Bancs Libres et ceux pêchés sur bancs associés aux DCP (Dispositifs de Concentration de Poisson) sont mises en évidence.

RESUMEN

A falta de estimaciones directas de la abundancia de túnidos, la flota atunera tropical francesa de cerqueros proporciona una forma de hacer un seguimiento de los stocks de túnidos, especialmente a través del cálculo de la captura por unidad de esfuerzo (CPUE). El objetivo de este estudio es analizar la trayectoria individual de los cerqueros con el fin de identificar qué parte del comportamiento de búsqueda debería usarse para calcular el esfuerzo pesquero. En este contexto, los datos de los sistemas de seguimiento de buques (VMS) son útiles para analizar las diferentes actividades pesqueras de un cerquero a pequeña escala (es decir, parada, búsqueda activa y navegación-búsqueda), generalmente incluidos en el concepto de esfuerzo pesquero. Se aplicó un modelo estado-espacio (ensayado en un entorno Bayesiano) a

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las velocidades y ángulos de cambio de dirección de los datos del Sistema de Seguimiento de Buques (VMS) para identificar los diferentes "estados" del comportamiento de pesca de un cerquero durante una marea. Posteriormente se ajustó un umbral para distinguir las actividades "pesca" y "parado" sin pescar (del estado de "inmóvil"), "búsqueda activa" (de "sinuoso") y "navegación-búsqueda" (de "directo"). Sobre un conjunto de datos de VMS correspondientes a los datos de observadores, se destacan algunas diferencias de los esfuerzos pesqueros entre la pesca sobre banco libre y sobre bancos asociados con DCP (dispositivos de concentración de peces).

KEYWORDS

Catch/effort, CPUE, fishing behaviour, purse seining, fishing effort,
logbooks, tropical tuna species, Bayesian model, trajectories analysis, VMS data

1. Introduction

In the lack of direct estimates from fishery-independent sources, such as scientific surveys, catch per unit of effort (CPUE) of European tuna purse-seiners operating in the Indian Ocean and in the Atlantic Ocean (mainly from Spain and France), is used as one of the major index of abundance in tuna stock assessments. Up to now, the nominal fishing effort used to perform CPUEs is expressed as the time spent to search for tuna schools, i.e. the daylight time after omitting inactive time (i.e., setting, running from port to fishing areas, etc). Nominal fishing effort is then standardized accounting for different factors, such as the characteristics of the vessel, the season and the fishing area (Soto *et al*., 2009).

Even if standardised CPUEs are useful to follow the demographic trends of exploited populations, the use of directly observed CPUE as an index of abundance remains problematic and alternate indices remain looked for. In the case of the tuna purse seine fishery for which the detection of schools depends upon visual clues, the individual searching path of a vessel may be used to determine which proportions of the fishing day are effective in terms of fishing effort (Polacheck, 1988). Since 2000 the EC tuna purse-seiners are equipped by Vessel Monitoring Systems (VMS). Thanks to a general agreement with French tuna owner companies and the French Administration of Fisheries, French tropical purse-seiners' VMS data are available for scientific research, since VMS data provide accurate information on the hourly positions of the vessels.

The general purpose of this study is to benefit from VMS data to improve the definition and estimation of fishing effort, and to generate new proxies for the tuna abundance. However, VMS data depict the individual trajectory of a vessel without giving information about their fishing activities (**Figure 1**). We selected four activities, namely fishing, stopping, tracking (active searching), and cruising (searching without appearances of tuna) and estimated the time spent in each of them using a Bayesian Markovian model based on the speeds and turning angles provided by hourly VMS data. Although, the problematic is the same for the purse seine fishery operating in the Atlantic Ocean, for convenience reasons, only VMS and observers' data from the Indian Ocean were used in this study.

2. Material

2.1 VMS data

Since 2000, the European Commission legislated that all European fishing vessel longer than 24 meters should be equipped with a Vessel Monitoring System (VMS) (and then all vessels longer than 15m, in 2005). The Global Positioning System (GPS) positions of the vessels were registered every hour and transmitted on shore by satellite (Argos or Inmarsat). Being GPS positions, the data were accurate (error smaller than few tens of meters) and regularly recorded every hour. Speeds (in knots) and turning angles (in radians) between consecutive positions were readily calculated from VMS data. The data used for this study were collected from the French purse-seiners based in the Seychelles islands, targeting tropical tuna species: yellowfin tuna (*Thunnus albacares),* skipjack *(Katsuwonus pelamis),* and bigeye tuna *(Thunnus obesus*) in the Western Indian Ocean (14 vessels in 2006, 18 vessels in 2007, with a total catch around 100 000 tons per year). Given the shoaling behaviour of tropical tunas and given the fact that fishers base their decision to fish on visual detection of tuna schools, fishing activity occurs at day. Consequently only the daytime parts of the individual trajectories were then used. Starting and ending time of the day were deduced from the date and the latitude and longitude of each GPS position through an ad hoc routine to automatically select the daylight VMS data (**Figure 1**).

2.2 Observers' data

The scientific observers' program conducted in the French purse-seiner fleet operating in the Indian Ocean is being undertaken in the framework of the European Data Collection Regulation. This regulation specifies that 10% of the trips have to get an observer on board. From November 2005 to the end of 2007 only 11 trips (corresponding to 301 days at sea and 265 sets) were available for the analysis. Observers on board recorded the position of the vessel every hour, or each time a change in speed or in turning angle (cap) occurred. The beginning and the ending time of each fishing operation were also reported as well as the fishing mode (i.e., non-associated school or free-swimming school and FAD school). It should be stressed that these two types of fishing modes are developed in the Atlantic and the Indian oceans since the development of FADs fishing operations in the early 1990s (Ariz *et al*., 1999; Hallier and Parajua, 1999).

A subset of VMS data, corresponding to observers' data, was extracted with the objective to tune some of the model parameters and, more importantly, to validate the model outputs before its application to the entire data set. It also allowed exploring if the behaviour of the vessel prior to fishing could be used to discriminate between free-swimming sets and FAD sets.

3. Method

3.1 Estimation of activities on the VMS trajectories

The model, for which a thorough description can be found in Walker and Bez (submitted) [3], proceeds in two phases.

First, any hourly segment (step) of the trajectories was assigned to one of the three movement states defined for this study. The model consisted in a state-space model (Buckland *et al.* 2004, Royer *et al.* 2005, Patterson et al., 2008) where movement's states were assumed to follow an order one Markovian process. Although this framework has already been applied in other ecological issues (Morales *et al*., 2004, Jonsen *et al*., 2005), this is the first application to VMS data. States were inferred in a Bayesian framework (Gelman *et al*., 2004) knowing both vessel speeds and turning angles. Estimates corresponded to the state having the maximum a posteriori probability. The rationale behind the selection of the three states was the following. First, we expected a purse seiner to move quickly through abundance-poor areas. These "*cruising"* phases were associated to large speeds and to turning angles being predominantly around 0° (**Figure 2**). On the opposite, within areas where tuna schools are abundant, skippers try to track schools. In these "*tracking*" phase, apparent hourly speeds are expected to be smaller on average and turning angles should be widely distributed over the full circle. Finally, vessels can remain "*still*" for a while (fishing, school observations, engine break down, etc).

Second, thanks to observers' data, stillness steps were attributed one of the two possible main activities compatible with the absence of movement, namely "*fishing*" and "*stopping*" (**Table 1**). The "*fishing*" activity was attributed to steps where fishing was the dominant estimated activity, whereas "*stopping*" corresponded to a waiting time near a free-swimming school or near a FAD. Stops are required either to maintain electronic equipments located on FADs or to evaluate the effective presence of fishable schools. Long stops are sometimes due to technical break-downs and damages, although skippers try as much as possible to postpone the immobilization of the vessel until the night. Stops were thus considered as part of the searching operations and contribute to the fishing effort.

We thus ended up with four possible activities (**Figure 3**). Prior studies (Pella 1969, Pella and Psaropulos 1975, Gaertner *et al*., 1999) have described the sequence of successive fishing activities of a tuna purse seiner over a cruise. However they mainly concerned the detailed chasing and fishing processes which were not compatible with the behaviour components that were made available by hourly VMS data. It was thus not possible to rely on the former vocabulary developed by these authors and we fixed a new glossary.

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[3] Walker E., and Bez N. (submitted). A pioneer validation of a state space model of vessel trajectories (VMS) with observers' data. Ecological Modelling.

The quality of the outputs of the model was finally evaluated thanks to the observers' data (field truth). 97% of the fishing sets declared by observers were detected by the model. However, some sequences (e.g. three fishing sets of two hours each separated by only a quarter of an hour) were viewed as only one long sequence of six fishing steps.

In order to more precisely quantify the differences between the true fishing sets and the estimated ones, we also compared:

- The statistical distributions of the sets durations (hourly rounded)
- The temporal patterns of fishing and non fishing activities depicted by both time series.

For the latter, we used simple and cross variograms which allow elucidating the dominant temporal patterns in each series and if these patterns are concomitant in both series.

Dealing with binary variable $1(x) = \begin{matrix} 1 & \text{if fishing} \\ 0 & \text{if not} \end{matrix}$

the variograms can be interpreted in terms of probabilities (Rivoirard, 1994):

$$\gamma(t) = \frac{1}{2}E\left[\left(1_x - 1_{x+t}\right)^2\right] = \frac{1}{2}\left(P\left[1_x = 0 \text{ and } 1_{x+t} = 1\right] + P\left[1_x = 1 \text{ and } 1_{x+t} = 0\right]\right)$$

Assuming symmetry, this reduces to:

$$\gamma(t) = P\left[1_x = 0 \text{ and } 1_{x+t} = 1\right] = P\left[1_x = 0 \mid 1_{x+t} = 1\right] \cdot P\left[1_{x+t} = 1\right]$$

Assuming stationarity, i.e. assuming that the probability to fish is well approximated by the overall mean

$$P\left[1_{x+t} = 1\right] = P\left[1_x = 1\right] = p_1$$

we finally get that:

$$\gamma(t) \# P\left[1_x = 0 \mid 1_{x+t} = 1\right]$$

i.e. that the variogram is proportional to the probability to be fishing knowing that *t* hours before (or after) this was not the case. After "a while", the condition gets no longer influence and the variogram flattens to the product of probabilities, i.e. the variance. Variograms are fully analogous to Fourier transforms except that they decomposed the signal over time periods rather than time frequencies.

Cross-variograms (analogous to co-spectrum) are defined by

$$\gamma_{\text{OBS,VMS}}(t) = \frac{1}{2}E\left[\left(1^{\text{OBS}}{}_x - 1^{\text{OBS}}{}_{x+t}\right)\left(1^{\text{VMS}}{}_x - 1^{\text{VMS}}{}_{x+t}\right)\right]$$

They quantify the common patterns present in the two signals. In the present case, if estimations were perfectly equal to the truth, all the simple the cross-variograms would be equal.

3.2 Components of the fishing activities

To analyse the components of the fishing activities, the heterogeneity among the vessels is highlighted in the box plots of the distances covered in the activities "tracking" and "cruising", for the time spent in the four activities. The searching effort (as the time spent in the activities 2, 3 and 4 in each spatial square of 0.25° by 0.25°) is also mapped at a fine spatial scale, and compared to the maps of the fishing sets.

As mentioned in the Introduction section, the current calculation of fishing effort for the tropical purse-seiners is defined as the number of daylight hours after removing (1) the "inactive" time spent in sets (it is admitted that during the set the vessel is not searching for tuna schools) and (2) some hours dedicated to technical repairs or cruising to or from the harbour to the fishing grounds. The time devoted to the fishing sets is deduced from the number of sets and the associated catch of the set reported on logbooks (a simple linear regression between the catch of the set and the duration of the set has been estimated regularly from observers' programs). As a consequence we proposed to consider here the hours preceding a fishing set (Allen and Punsly, 1984), and then to evaluate among these "pre-fishing" hours how many are spent in the four activities.

4. Results

4.1. Distances and time spent in the activities

The distances covered in the VMS steps in "cruising" and in "tracking" by quarter from 2006 to 2007 showed the heterogeneity within the vessels at a quarter scale (**Figure 4)**. There is evidence that the mean distance in cruising (2660 n.m.) is lower than the mean distance in tracking (3540 n.m.). The pattern within each year is similar for both activities: the distances increased from quarter 1 to 4 for cruising, whereas, for tracking activity, the distances increased only to quarter 3, then decreased in the fourth quarter. The highest heterogeneity in the covered distances concerns the tracking activity during the quarter 3 and 4 (in 2006 and 2007).

The cumulated time in the activities depicted the same pattern than for distances (**Figure 5)**. However, the average time spent in tracking (385 hours) is quite twice higher than the time spent in cruising (210 hours) and in stop (200 hours). The time spent "tracking" is more heterogeneous between vessels than observed for the other two activities.

The distances covered and the durations spent within each sort of activity have been calculated for 5 areas in the Western Indian Ocean (**Figure 6**). The distances covered presented the same pattern for 2006 and 2007, with highest distances covered in North-West Seychelles, and secondarily in South-East Seychelles and Somalia areas (**Figure 7**). However, the heterogeneity within vessels is more important in 2006 than in 2007. The time spent tracking is the largest particularly in NW Seychelles (**Figure 8**), whereas the durations are very heterogeneous within vessels.

4.2. Temporal structure of the activity "fishing"

For the observers' time series, the strongest pattern, i.e. the one that explains 90% of the overall variability of the fishing/non-fishing switch, was three hours (**Figure 9**). This corresponded to sequences of three successive steps with the same value (either 0 or 1). Knowing the fisheries, this has to be interpreted as the dominant duration of a fishing set (series of three consecutive ones). This pattern was common to both time series. It was however particularly salient in the simple variogram of the observers' data and in the cross variogram, indicating that it was concomitant to both time series. Two extra temporal structures happened to be present in all the simple and cross variograms, namely:

- a three days pattern showing that the conditional probability to fish kept a memory over three days; batch of three days of fishing sets did occur
- a hole effect of 13 to 14 hours; this pattern reflected the fact that fishermen have the strong habit to realise sets on log-school early in the morning, i.e. a night apart from each others.

The time series of the model outputs got an extra structure compared to these ones. To quantify precisely this extra structure, we modelled the empirical variograms using only spherical models (the periodic spikes being excluded from the modelisation) and an automatic procedure based seeking for minimum square errors. While the variogram for the observers' data happened to be:

$$\gamma_{\mathrm{OBS}}(t) = 0.1 \cdot \mathrm{sph}(h/2.6) + 0.01 \cdot \mathrm{spherical}(h/26)$$

The best model for the VMS derived data was:

$$\gamma_{\mathrm{VMS}}(t) = 0.088 \cdot \mathrm{sph}(h/3.1) + 0.033 \cdot \mathrm{spherical}(h/7.2) + 0.044 \cdot \mathrm{spherical}(h/44)$$

Apart from the fact that the dilution of the patterns estimated by the VMS was expected (slight increase of the range of the strongest pattern; from 2.6 to 3.1 hour), the main difference between the patterns of the two time series was thus a structure of 7 hours accounting for 20% of extra variance. This supports the idea that some

(20%?) of the succession of two sets have been considered as one single set of 6 hours or so by the estimation procedure.

The cross structure being equal to that of the simple variogram of the observers' data leads to consider that:

$$1^{\mathrm{VMS}}(\mathrm{x}) = 0.33 \cdot 1^{\mathrm{OBS}}(\mathrm{x}) + 0.18 \cdot \varepsilon(\mathrm{x})$$

where the error is temporally independent from the observers' data but gets a structure of 7 hours. The physical interpretation of such a noise corresponded to two consecutive sets.

4.3 Components of fishing effort

As mentioned previously, the current fishing effort is expressed as the total number of daylight hours minus the number of inactive hours (e.g., dedicated to fishing sets, etc.). Thus this calculation takes into account the hours of searching before the sets and these after the sets. The idea here is to consider only hours of search that precede every set. For every set, among the hours (of the same day) preceding the set, the proportion of hours spent in the activities fishing, stop, tracking, and cruising was estimated/calculated (**Figure 10**). Most of the time, the proportion of time spent in cruising, stop or fishing before a set was very low, in contrast to the proportion of time spent in tracking.

Every month, the total of fishing hours and of effort hours has been counted by 0.25° *0.25° square (**Figures 11** and **12)**. It should be stressed that few cells are empty because no vessel visited it. From these maps it was evidenced that VMS data allow mapping fishing actions and effort distribution with a high accuracy.

4.4 Difference of effort components for sets on free-swimming schools and sets on FAD schools

From the subset of the VMS data corresponding to observers' data, the two main fishing modes (free-swimming schools versus associated schools with FAD) were attributed to every fishing step. The number of fishing steps occurring at every hour of the day is represented for Free sets and FAD sets in **Figure 13**. In the early morning, fishing hours were more dedicated to FAD sets than for free schools sets, and then the proportion of FAD sets compared to the total number of sets decreased all along the day. In contrast, fishing hours ending on free schools sets were quite constant all along the day.

The components of the effort were considered also, when calculating the proportions of hours (preceding the sets, the same day) spent in each activity, but the histograms were built distinguishing the types of sets (free schools and FAD schools). Contrarily to the results obtained on the whole fleet and without distinction between fishing modes, it can be seen that the proportions of hours spent in stopping or tracking before a set were quite high, although the percentage of time spent in fishing or cruising were often low **(Figure 14)**.

5. Discussion

Building abundance indices from commercial CPUEs remain problematic for many reasons: non-proportionality between CPUEs and abundance, such as hyperdepletion and hyperstability (Hilborn and Walters 1992, Harley *et al.*, 2001, Polacheck, 2006), changes in fishing power (Fonteneau *et al.*, 1999) or in fishing grounds (Walters, 2003) over the years, etc. Even if these criticisms remain valid at a global scale, improvements in the definition of individual fishing effort, and specifically the determination of the proportion of active versus inactive time, can be obtained from information on small-scale activities.

As far we are concerned, there were many applications of VMS data in different fishery studies (Bertrand *et al.*, 2005, Witt *et al.*, 2007, Mills *et al.*, 2007) but none focussed on the determination of the different movement states of a fishing trip. The model on VMS data used in the present study has been validated on the activities "fishing" versus "no fishing", on the subset of VMS corresponding to observers' data. The misdetection rate which was obtained on the steps was about 10%, and the rate of under-detection on the sets was about 3%. It was showed a difference in searching behaviour of the vessels when they are fishing either on free schools or on FAD schools. These analyses required to be continued, because some variables indicating obviously the discrimination between sets on free schools and on FAD schools may consist on additional information used as a prior in the model.

6. Conclusion

VMS data are very profitable concerning the accuracy and exhaustiveness of the data, but require some statistical developments to make them usable for a thorough interpretation of fishing effort. The application of the Bayesian model allows us to distinguish two types of "searching" behaviours: the tracking and the cruising activities. VMS data are a valuable source of information for performing the fishing effort exerted on tropical tuna purse-seiners but require developing some methods adapted to this new type of fishing information.

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Table 1. Definition of the dominant states and activities per step. Discrimination between effective fishing and various elements contributing to prospecting.

			Dominant state per step				
			1	2	3		
			Still	Meander	Straight		
Dominant activity per step	1	fishing	x			Fishing	Recorded by observers. Coverage: 10% of the fleet
	2	stop	x			Non fishing. Components of fishing effort	Not recorded by observers.
	3	tracking		x			
	4	cruising			x		

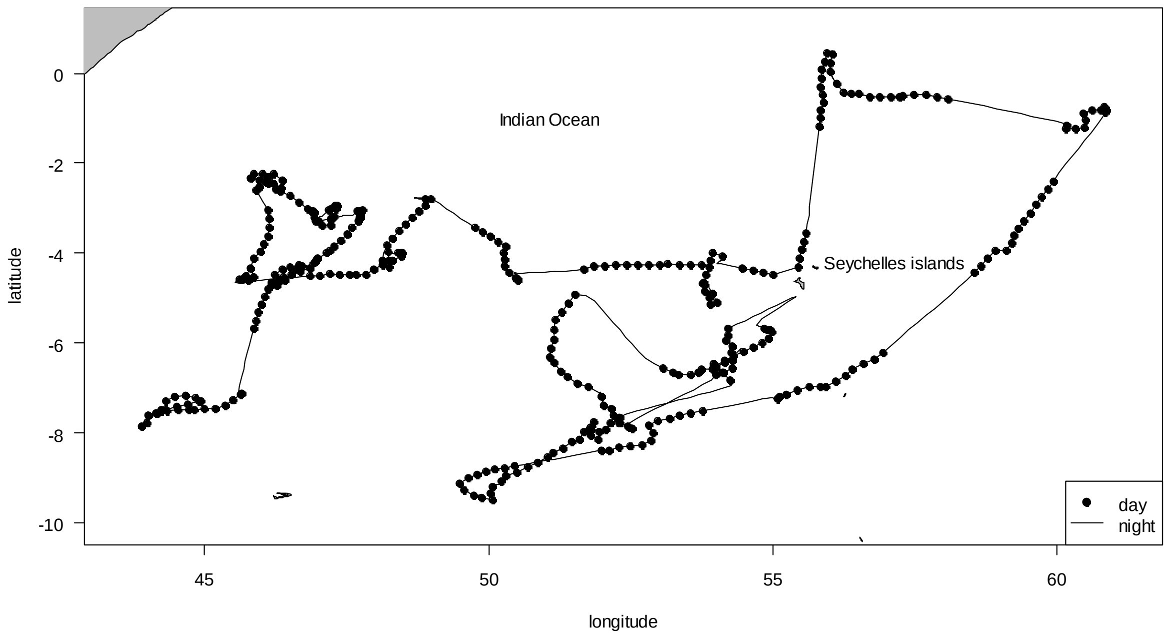

Figure 1. Example of a trajectory of a tuna purse seiner during a fishing trip from VMS data. Continuous line represents activity at night; dotted line represents daily activity.

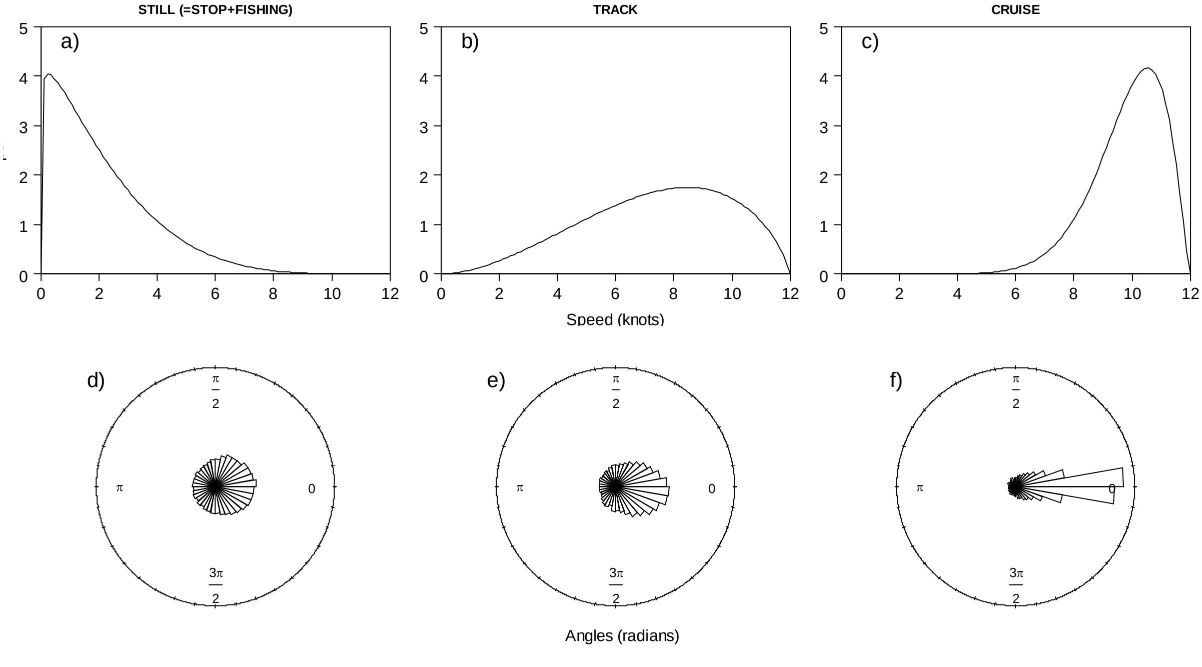

Figure 2. Distributions of speeds (a, b, c) and turning angles (c, d, e) for the three estimated states (cruising, tracking, still) from the Bayesian model.

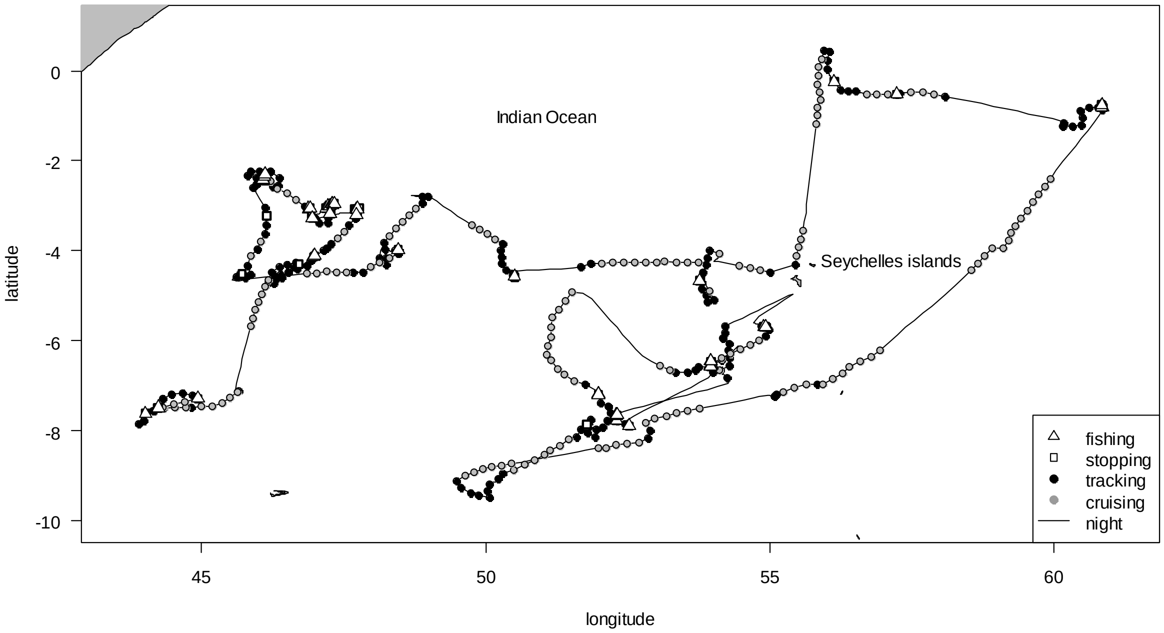

Figure 3. Example of trajectory of a tuna purse-seiner with the four activities estimated on daily VMS positions from the Bayesian model.

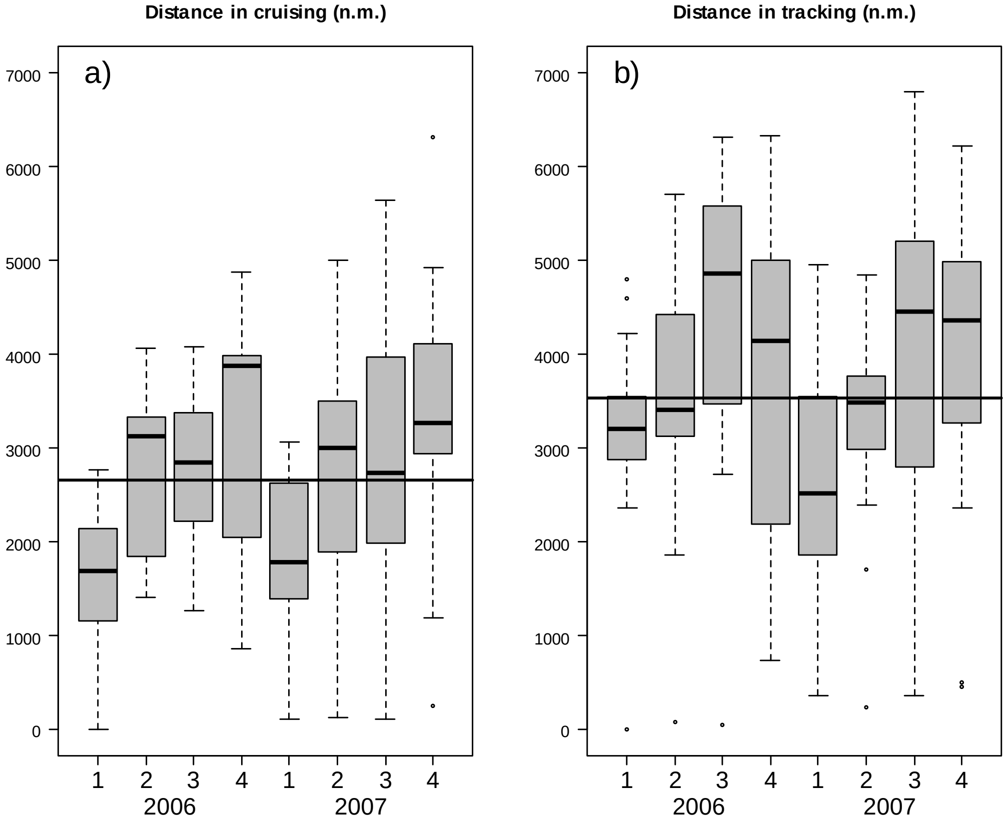

Figure 4. Cumulated distances (in nautical mile) during the activities "cruising" (a) and "tracking" (b) calculated for every quarter in 2006 and 2007 (all vessels' VMS). The horizontal lines represent the mean distances for each activity for the two years. The quarter 1 is from January to March, the second one from April to June, the third one from July to September, and the fourth one from October to December.

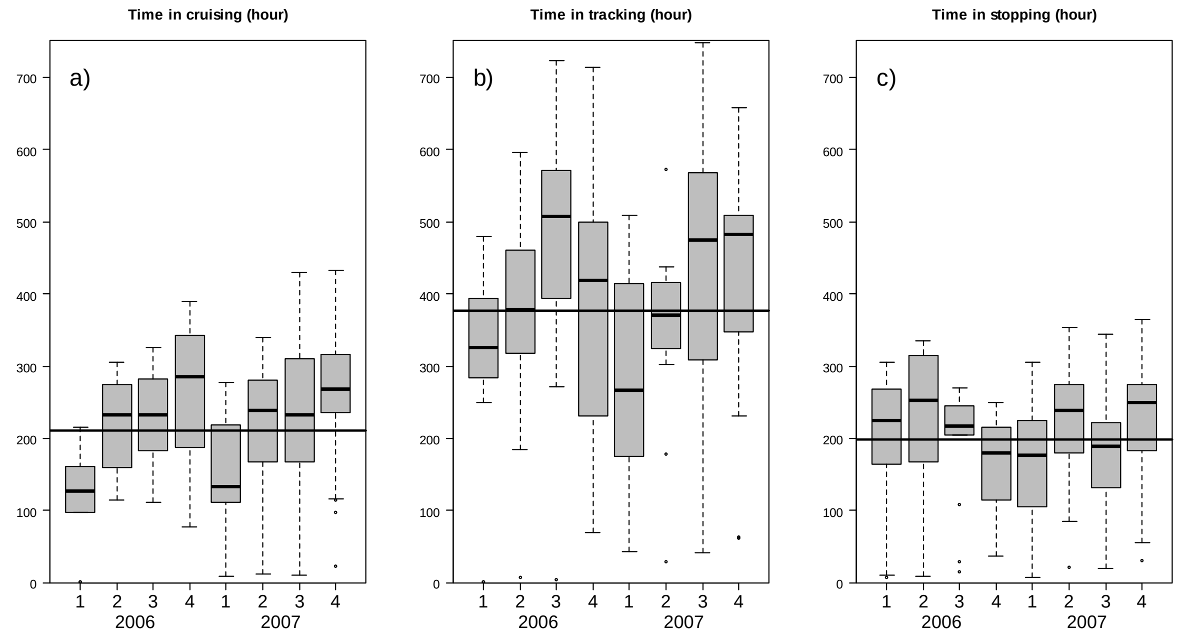

Figure 5. Cumulated time (in hour) in the activities “cruising” (a) and “tracking” (b) and “still (stopping+fishing)” (c) calculated for every quarter in 2006 and 2007 (all vessels’ VMS).

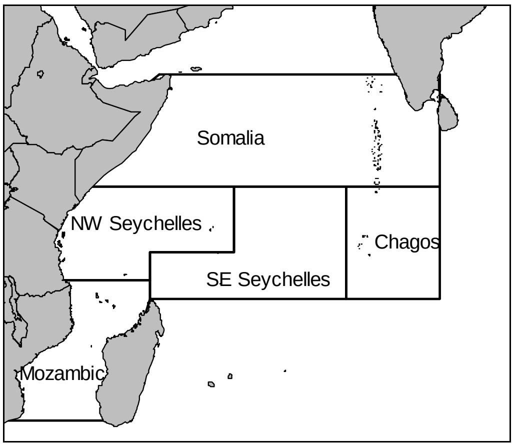

Figure 6. Areas of the West Indian Ocean.

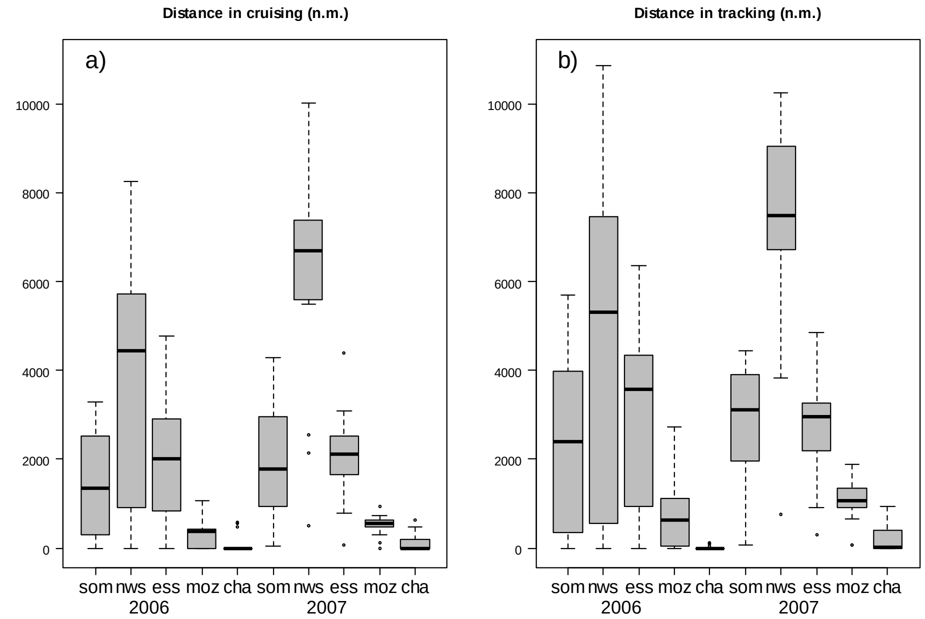

Figure 7. Cumulated distances (in nautical mile) during the activities "cruising" (a) and "tracking" (b) calculated for every area in 2006 and 2007 (all vessels' VMS). The areas are the Somalia, North-West Seychelles, East-South Seychelles, Mozambic channel, and Chagos areas defined in Figure 6.

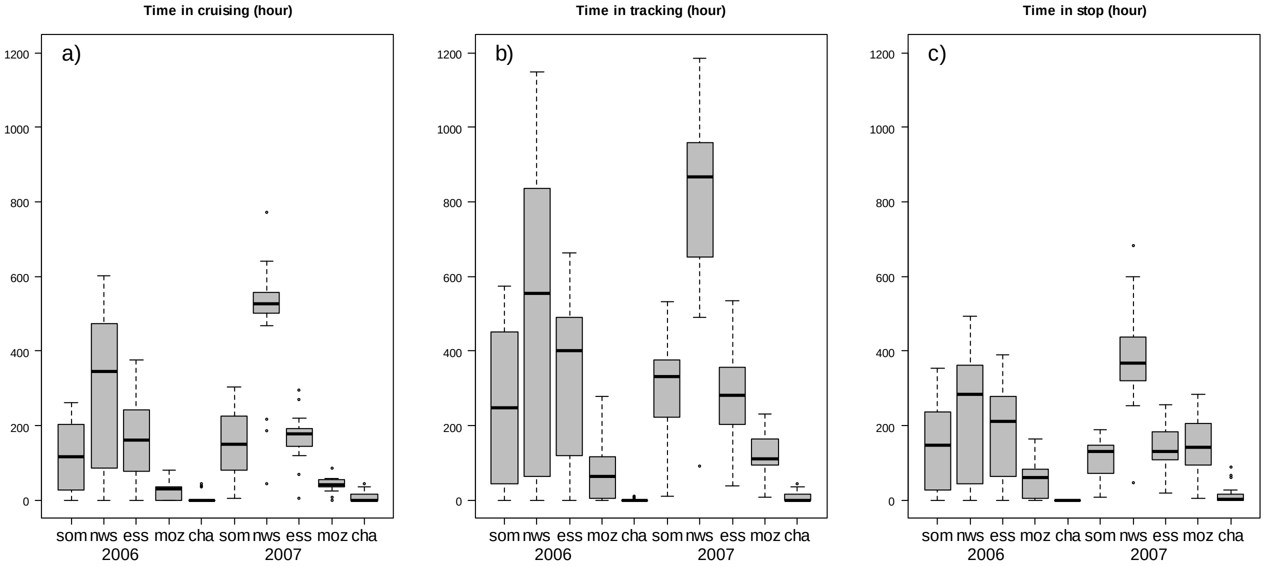

Figure 8. Cumulated time (in hour) in the activities "cruising" (a) and "tracking" (b) and "still (stopping+fishing)" (c) calculated for every area in 2006 and 2007 (all vessels' VMS). The areas are the Somalia, North-West Seychelles, East-South Seychelles, Mozambic channel, and Chagos areas defined in Figure 6.

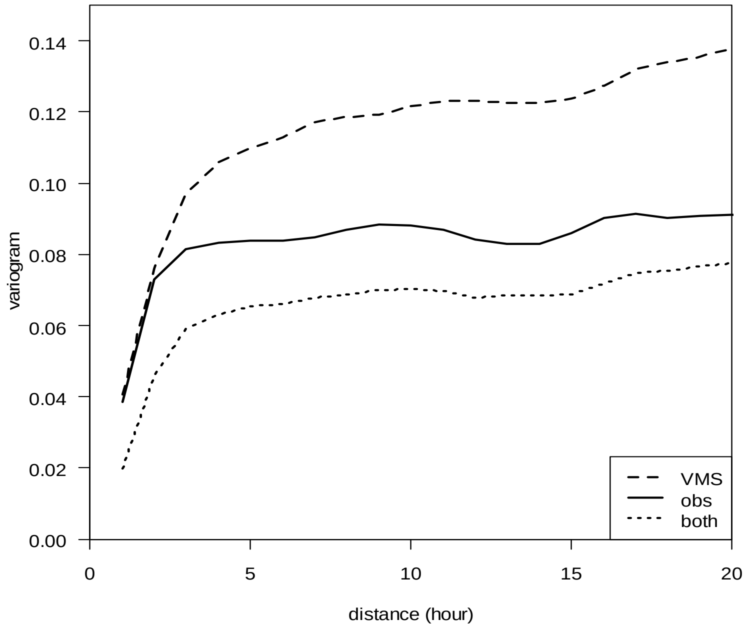

Figure 9. 1D Variograms and cross-variogram for the steps in fishing.

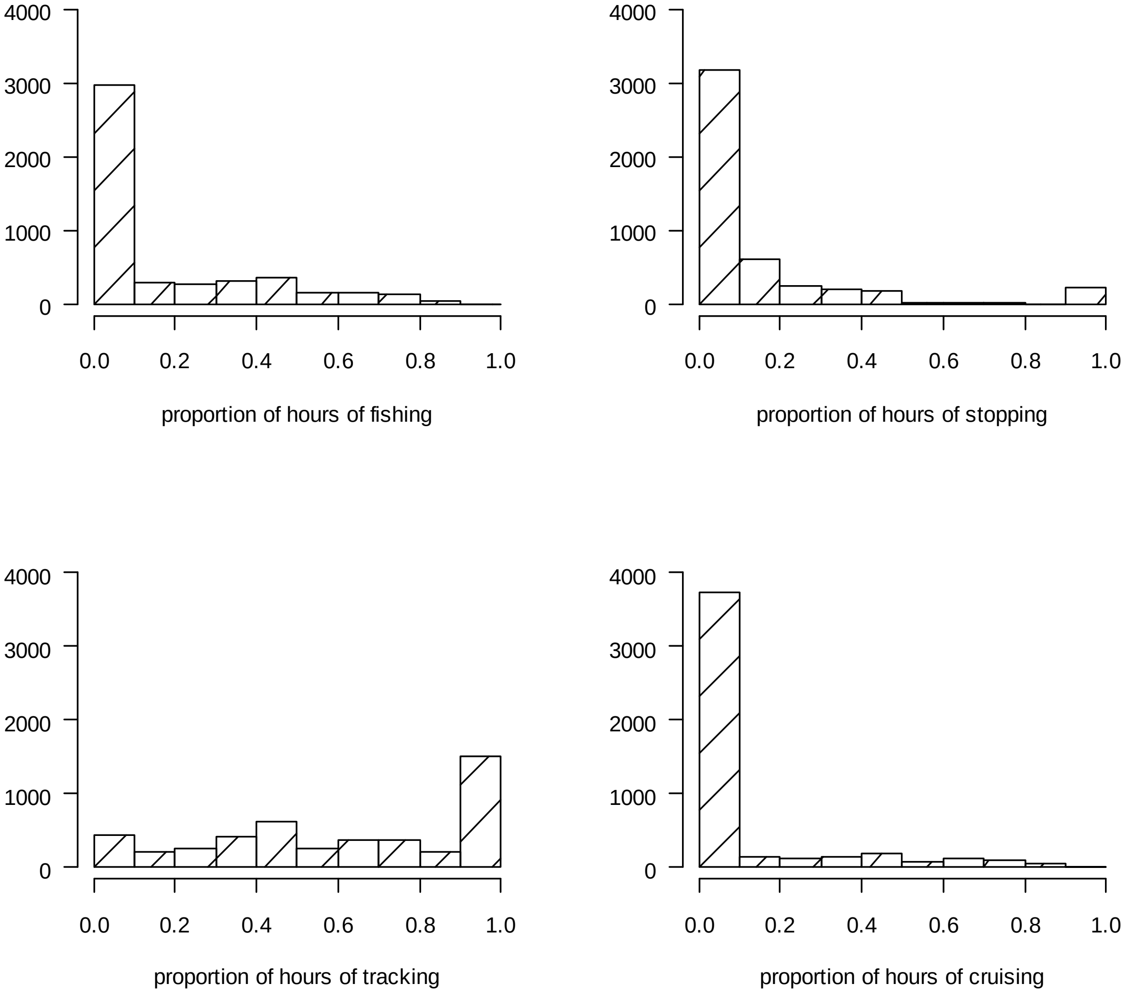

Figure 10. Proportion of hours before a fishing set (and in the same day), spent in the four activities.

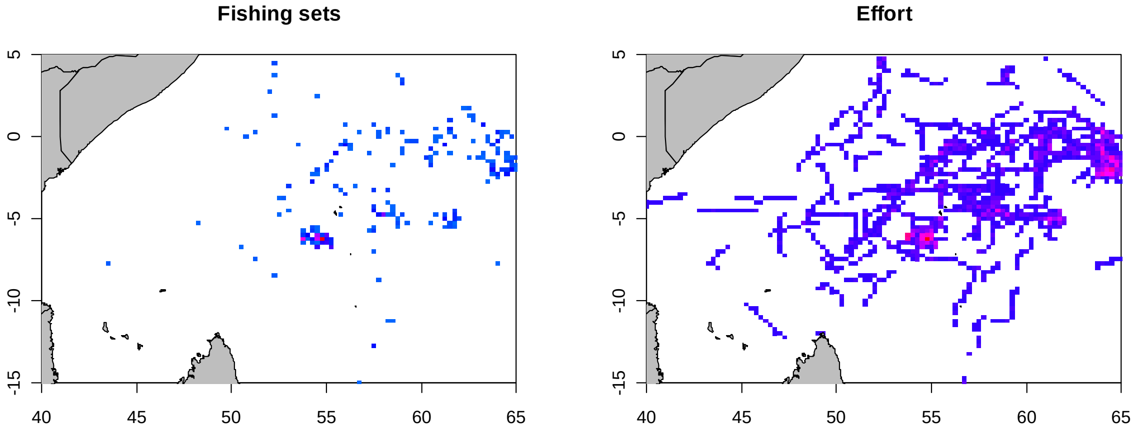

Figure 11. Example of spatial repartition of the fishing hours and of the effort hours at the scale of 0.25° by 0.25°, for November 2006 (high number of hours in red, low number in blue, no vessel presence in white).

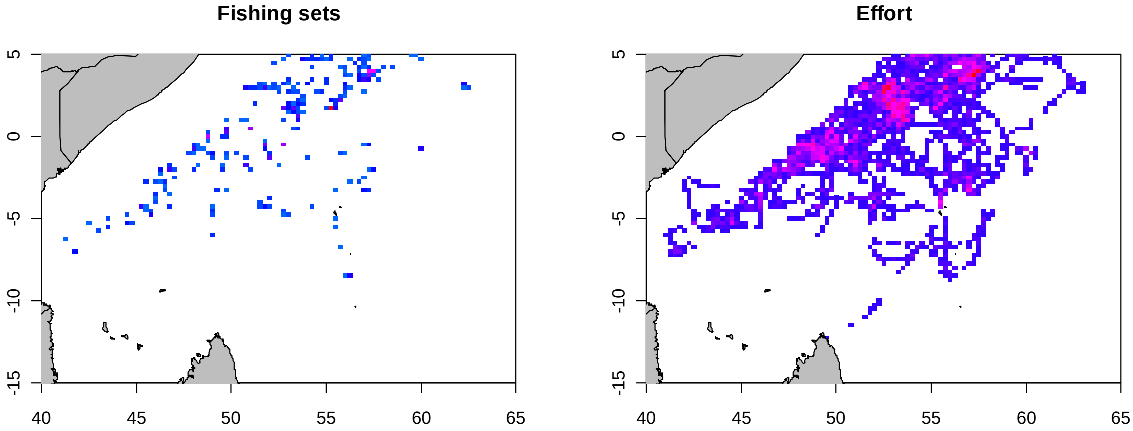

Figure 12. Example of spatial repartition of the fishing hours and of the effort hours at the scale of 0.25° by 0.25°, for August 2007 (high number of hours in red, low number in blue, no vessel presence in white).

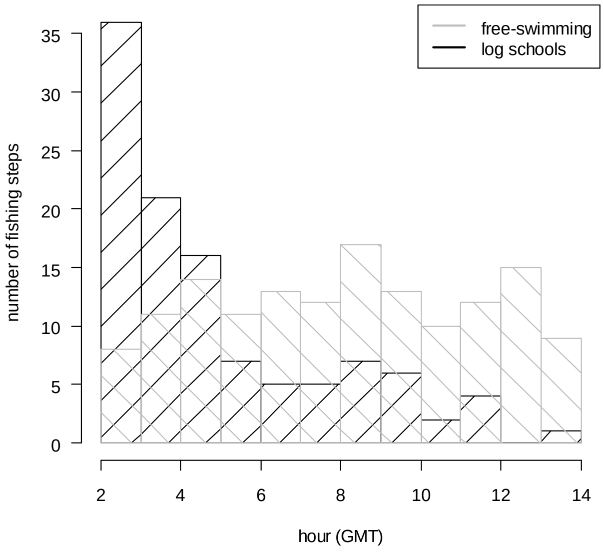

Figure 13. Hours of daylight with steps in fishing (free schools or FAD schools).

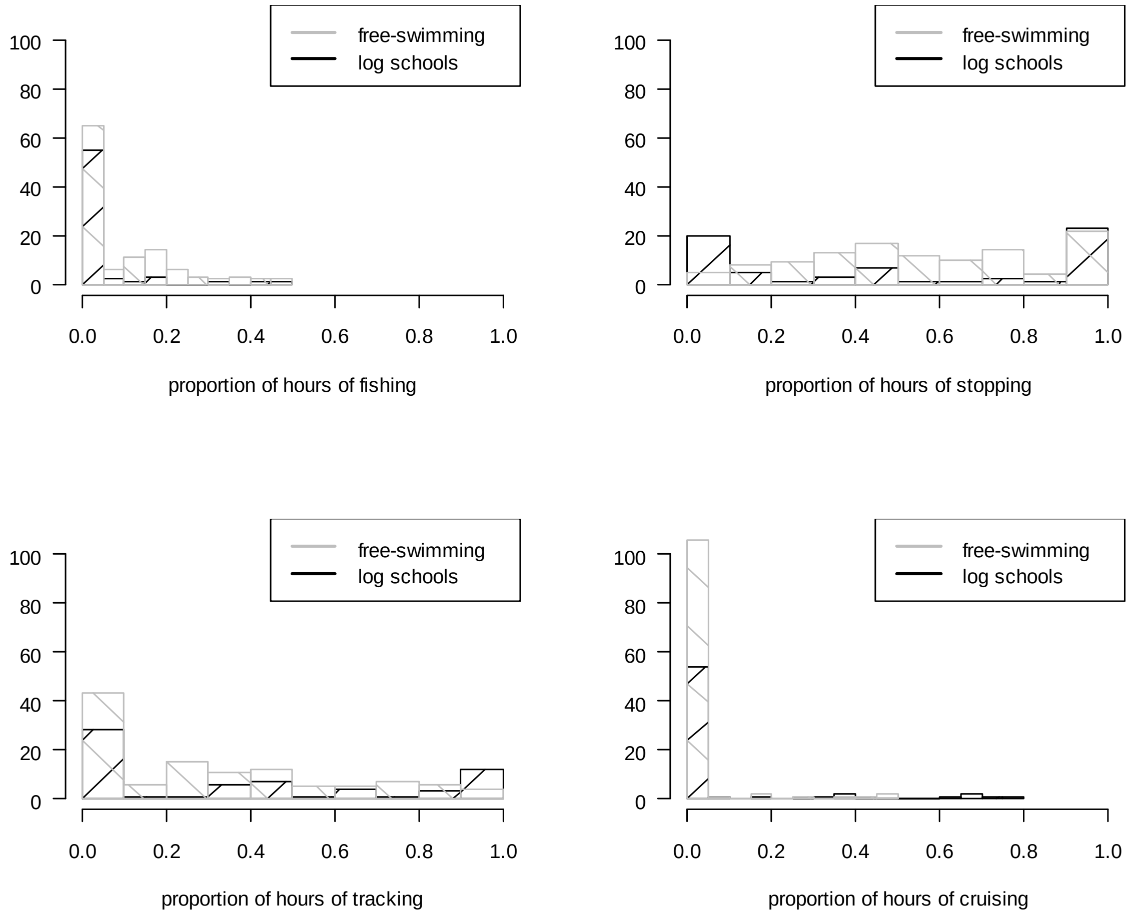

Figure 14. Proportion of hours before a fishing set (and in the same day), spent in the four activities, for the two types of sets (sets on free schools and on FAD schools).