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Original Article

A framework for mapping small-scale coastal fisheries using fishers' knowledge

Marc Léopold[1,2]*, Nicolas Guillemot[1,3,4], Delphine Rocklin[1], and Cheryl Chen[5]

[1]*IRD (Institut de Recherche pour le Développement), U227 COREUS2, BP A5, 98848 Nouméa Cedex, New Caledonia*
[2]*Fisheries Department of Vanuatu, Private Bag 9045, Port-Vila, Vanuatu*
[3]*Université Européenne de Bretagne, UMR 985 Agrocampus Ouest/INRA, 65 rue de Saint-Brieuc, CS 84215, 35042 Rennes, France*
[4]*Koniambo Nickel SAS, Environment Department, BP 679, 98860 Koné, New Caledonia*
[5]*Ecotrust, Marine Planning Program, 721 NW 9th Avenue, Suite 200, Portland, Oregon 97211, USA*

Corresponding Author: tel: +678 533 3340; fax: +687 264 326; e-mail: marc.leopold@ird.fr

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Collecting spatial information on fisheries catch and effort is essential to understanding the spatial processes of exploited population dynamics and to manage heterogeneously distributed resources and uses. The use of fishers' knowledge through geographical information systems (GISs) is increasingly considered as a promising source of local information on small-scale coastal fisheries. In this paper we describe the first framework for mapping entire small-scale coastal fisheries using fishers' knowledge on catch size and fishing effort. Four mangrove and coral reef fisheries targeting invertebrates or finfish in New Caledonia (southwest Pacific) were mapped following a five-step framework: (i) stratified random sampling of regular fishers; (ii) collection of fishers' knowledge of fishing areas, fishing effort, and catch size through map-based interviews; (iii) data integration into a spatial geodatabase; (iv) statistical extrapolation of fisher data to the fishery scale; and (v) mapping of catch, effort, and catch per unit effort (CPUE) for each fishery using a GIS overlay procedure. We found evidence that fishers' knowledge supplied precise and accurate quantitative and spatial information on catch size, fishing effort and CPUE for entire fisheries. Fisheries maps captured the fine-scale spatial distribution of fishing activities in a variety of ways according to target taxa, gear type, and home ports. Applications include area-based marine conservation planning and fishery monitoring, management, and governance. This integrated framework can be generalized to a large range of data-poor coastal and inland small-scale fisheries.

Keywords: fisheries mapping, fishers' knowledge, map-based interviews, participatory GIS, small-scale coastal fisheries, spatial fisheries management.

Introduction

Fisheries research has progressively implemented sophisticated spatially explicit technologies to understand the spatial processes of exploited populations and to manage heterogeneously distributed resources (Wilen, 2004). Much work has been done to account for the natural spatial variability of exploited fish populations and incorporate georeferenced commercial catch data into models for stock assessment and fishing dynamics. However, these research instruments are mainly dedicated to large-scale demersal and pelagic fisheries, while worldwide small-scale fisheries disproportionately lack a substantial knowledge base (Jacquet and Pauly, 2008). According to the FAO (2008), it is estimated that ~50 million of the 51 million fishers worldwide are engaged in small-scale fisheries. Furthermore, small-scale fishers produce nearly half of the world's fish with the majority of these fishers either partially of wholly fishing for subsistence (Berkes *et al.*, 2001). Small-scale fisheries are typically defined by the utilization of low technology gear and vessels, and target a wide variety of species for local markets and/or subsistence and recreational purposes. Despite their commonly artisanal nature, they are now assumed to be very significant worldwide and, in some cases, generate a greater pressure on coastal resources than the pressure resulting from commercial fisheries (Dalzell, 1996; Cooke and Cowx, 2004). In addition, demographic and economic growth and the continuous increase in fishing power have enhanced overexploitation risks of inshore resources, as observed in the Pacific (Hunt, 2003).

Observational information on small-scale fisheries is often scarce and insufficient to conduct robust analyses to inform appropriate management measures (Johannes, 1998; Zeller *et al.*, 2006). For example, on-board geolocation equipment providing spatial fishing information is widely used in developed countries (e.g. Begossi, 2001; Stelzenmüller *et al.*, 2008) but remains uncommon in most small-scale fisheries. An intrinsic complication to collecting representative quantitative and spatial fishing data is the informal and heterogeneous nature of small-scale fisheries. Furthermore, small-scale fishing practices are embedded in often complex and diverse social systems such as local customary sea tenure practices and cultural values of the marine environment that can play an important role in spatial fishing patterns and practices (Olson, 2005; Berkes, 2008). Indeed, spatially explicit information that incorporates this human dimension is crucial as fishery management increasingly implements area-based management measures such as marine reserves or multi-use marine spatial plans.

In this context, new approaches to fisheries research have promoted the integration of fishers' knowledge into conservation planning and fisheries management through the use of geographical information systems (GISs). Fishers' local knowledge is increasingly considered as a promising source of local information (Neis *et al.*, 1999; Jones *et al.*, 2008) and of spatial data in particular (St Martin, 2004; McCluskey and Lewison, 2008). GIS tools have been used in a number of fisher surveys in the last decade, mainly in describing the value or importance of fishing areas (Scholz *et al.*, 2004; Aswani and Lauer, 2006; Wheeler *et al.*, 2008) and the spatial patterns of fishing effort (Anuchiracheeva *et al.*, 2003; Aswani and Lauer, 2006; Richardson *et al.*, 2006; Hall and Close, 2007; Daw, 2008; De Freitas and Tagliani, 2009; Hall *et al.*, 2009; Forcada *et al.*, 2010; Weeks *et al.*, 2010). In these research efforts fishers were asked to locate their main fishing areas or spots, either using visual support (latitude/longitude grids, topographical maps, bathymetric charts or aerial pictures) or referring to travel time and direction. Mapping catch estimates over local fishing grounds was only recently achieved by combining spatial data on fishing effort gained in fisher interviews with biological scientific data (Hall *et al.*, 2009) or fisheries data available from official catch records (Scholz *et al.*, 2011).

In available studies however key informants or the most productive fishers were preferentially sampled due to logistical or methodological constraints. As interviews were not randomly performed, statistical bias may result from any extrapolation of sample data at the fishery level. In particular, obtaining representative data at the fishery level was challenging due to the qualitative and segmented nature of fishers' maps and the small sample size of most surveys. Consequently fishing data generated by the available interview-based methods cannot be generalized to characterize fishing effort and catch of entire fisheries. This limitation weakens the significance of map outputs for the spatial management of these fisheries (McCluskey and Lewison, 2008).

This paper aims at filling this methodological gap and formalizes the first interview-based framework for mapping entire small-scale coastal fisheries. Generalizing the protocol of Close and Hall (2006) for the collection and use of local knowledge, the framework provides guidelines to collect and process fishers' knowledge of catch size and fishing effort at the fishery level through map-based interview surveys, statistical inference, and the use of GISs. This framework has been used in four case studies in New Caledonia (Southwest Pacific) including various harvesting activities targeting both finfish and invertebrates and operating at different geographical scales. The implications in terms of reliability, application and generalization of the framework for the spatial management of small-scale coastal fisheries and conservation planning are also presented.

Material and methods

Case studies

The study was performed in the New Caledonia archipelago (Southwest Pacific). The population (246 000 inhabitants) is multicultural and distributed in urban areas (70%) and over 341 small traditional Melanesian villages (30%). The main island of the country, the Grande Terre, is surrounded by a 1600 km long, discontinuous barrier reef with highly diverse and shallow (0–40 m depth) reef and lagoon formations over a 22 200 km^2 area (Figure 1). Mangroves extend alongside the west and north coast over 360 km^2. These environmental conditions together with human development over the last century have shaped artisanal small-scale fisheries, which are of economic and socio-cultural importance to local people. These artisanal small-scale fisheries encompass a large range of customary, subsistence, recreational and commercial practices that are also tied to socio-economic and cultural norms, as in most Pacific island countries.

Four small-scale coastal fisheries were studied from 2004–2008 to test the methodological framework across differing geographical scales, resources, fishing use patterns, and social contexts (Figure 1 and Table 1).

The first case study focused on a mud crab (*Scylla serrata*, Portunidae) fishery located in the northwest area of the Grande Terre. The survey area covered 170 km^2 of mangrove area, soft bottom flats and sea grass beds. The fishery was primarily operated by traditional Melanesian fishers (mostly women) who collected mud crabs by hand by checking burrows, using their catch for household consumption and local market (Dumas *et al.*, 2012).

The second case study concerned a multispecies finfish fishery composed of 312 small fishing boats in the Northwest Lagoon (760 km^2) of Grande Terre. Most fishing boats were operated for recreational or subsistence purposes using a large range of fishing

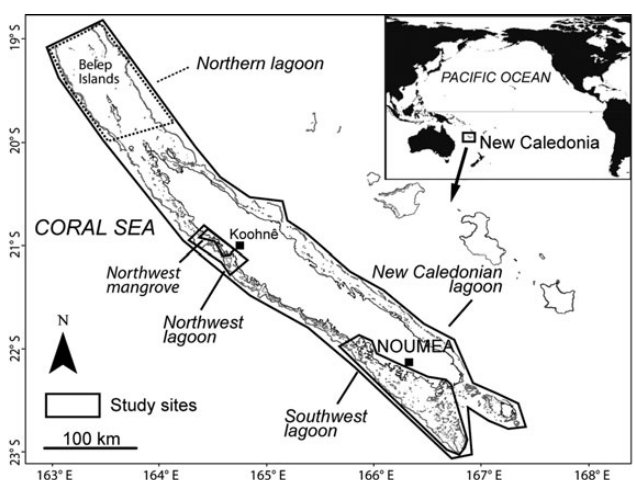

Figure 1. Location of the four study sites for reef finfish (Northwest Lagoon, Southwest Lagoon, and whole New Caledonia Lagoon) and mud crab (northwest mangrove) fisheries in New Caledonia (South Pacific).

Table 1. Characteristics of the four case studies in New Caledonia (South Pacific).

Sites	Survey characteristics					Fishery characteristics						Mapping process		
	Survey period	Survey area (km^2)	Number of inhabitants	% in urban areas	% in Melanesian villages	Target species	Fishing gears	Fishing units[a] Total	Fishing units[a] Sample	Catches[b] ($t\ year^{-1}$)	Fishing effort[b] ($trip\ year^{-1}$)	Map support	Scale of paper maps	Resolution of fishery maps (km^2)
Northwest mangrove	May 2006 – June 2006	170	2 100	37%	63%	Mud crab (*Scylla serrata*, Portunidae)	Hand, pots	172	98 (57%)	88 ± 26 (30%)	10,730 ± 2,810 (26%)	Aerial pictures	1:25,000	0.04
Northwest Lagoon	Sept 2007 – Nov 2007	760	9 600	87%	13%	Reef finfish	Gillnet, handline, speargun	312	146 (47%)	169 ± 8 (5%)	7,720 ± 460 (6%)	Satellite picture	1:130,000	0.22
Southwest Lagoon	Nov 2004 – Oct 2005	4 800	151 000	98%	2%	Reef finfish	Gillnet, handline, speargun	3 940	532 (14%)	1,140 ± 90 (8%)	28,800 ± 1,250 (4%)	Nautical charts	1:770,000	0.86
New Caledonia Lagoon	Nov 2004 – Oct 2008[c]	22 200	209 000	88%	12%	Spanish mackerel (*Scomberomus commerson*, Scombridae)	Trolling, speargun	520	123 (24%)	165 (na)	4,720 (na)	Satellite picture	1:100,000	10

Survey sites were characterized by the survey period, their geographical extent, the total population size and its distribution in urban areas and Melanesian villages. Fisheries characteristics included target species, fishing gears, number of fishing units (total, sample), and estimated annual catch and fishing effort of the year prior to survey. The mapping process was characterized by the type and scale of the map supports used to outline fishing areas during fisher interviews, and the spatial resolution of fisheries maps. The latter was defined by the surface of the cells of the grid that was used to standardize fishery map representations (see *Material and methods* for details). na = not available. Source for main gears, fishing area, fishing units, catch, and fishing effort: this study. [a]Fisher households (mud crab fishery) or boat owners (finfish fisheries). [b]The width of the 95% confidence interval is indicated both quantitatively and relatively to the total estimate (in parenthesis). [c]Three consecutive surveys were conducted and totalled a 16-month period.

gears (gillnet, speargun, handline) and targeted a large diversity of reef species (Guillemot *et al.*, 2009).

Both surveys were conducted to anticipate fisheries management issues in the next decade, as a major nickel-mining complex in the area has been generating fast socio-economic changes since 2005. The mining complex will trigger a significant demographic change, new market opportunities for marine products, and environmental disturbances in both the lagoon and mangrove areas. Commercial and recreational practices are thus expected to intensify in the midterm and to possibly induce local overexploitation and user conflicts.

The third case study focused on the recreational finfish fishery in the Southwest Lagoon (4800 km^2) to explore the spatial and social patterns of this developing fishery. This site was located close to Nouméa, the capital of New Caledonia, which is the most densely populated area and the economic centre of the country. This large, multispecies and multigear fishery involved 3940 boats (Jollit *et al.*, 2010).

The fourth case study focused on the Spanish mackerel (*Scomberomorus commerson*, Scombridae) fishery across the entire lagoon of Grande Terre (22 200 km^2). This emblematic species is targeted by 520 recreational and commercial fishing boats across the country. The main commercial fishing area involves 24 fishing boats around the Belep islands in the Northern Lagoon. Three consecutive surveys were conducted to collect data at the country scale.

Data collection and analysis framework

Protocols for the collection and use of key informants' knowledge using GISs have been described by Close and Hall (2006) and Scholz *et al.* (2011), among other authors. In this paper, we generalize their approach to entire small-scale coastal fisheries and provide examples of map uses for fisheries management and conservation planning. Specifically a five-step integrative framework has been developed for collecting, analysing, and mapping fisher-based knowledge of fishing effort and catch at the fishery level (Figure 2).

Step 1: Stratified random sampling of fishers

For each case study, a stratified random sampling design was implemented to obtain a robust representation of each fishery. The sampling design slightly differed between the case studies.

In the finfish case studies, outboard powered vessels were considered as the relevant sampling units, since they contributed most to fishing power and fish catch in coastal waters. We used both official registers and direct counting at landing sites, wharfs and ports to determine the number of operating fishing boats (Guillemot *et al.*, 2009; Jollit *et al.*, 2010). The sampling design involved two-way stratification according to fishers' home ports and activity. The second-level strata (i.e. fishing activity) were defined *a posteriori*. They consisted of boat length-classes in both multispecies case studies (Guillemot *et al.*, 2009; Jollit *et al.*, 2010) and fishers' fishing intensity (low and high) in the Spanish mackerel fishery.

In the mud crab case study, households were considered as sampling units, as most mud crab fishers do not own a boat and usually pool their catch at the household level. In Melanesian villages, mud crab fisher households were directly determined through a preliminary survey conducted in the communities. In urban areas, the number of households involved in mud crab fishing was estimated through official population census data and random sampling. The sampling design involved a one-way stratification that consisted of fishers' communities.

Sample size was determined by the survey costs and time constraints of each case study. It ranged from 98 fishing units (57% of

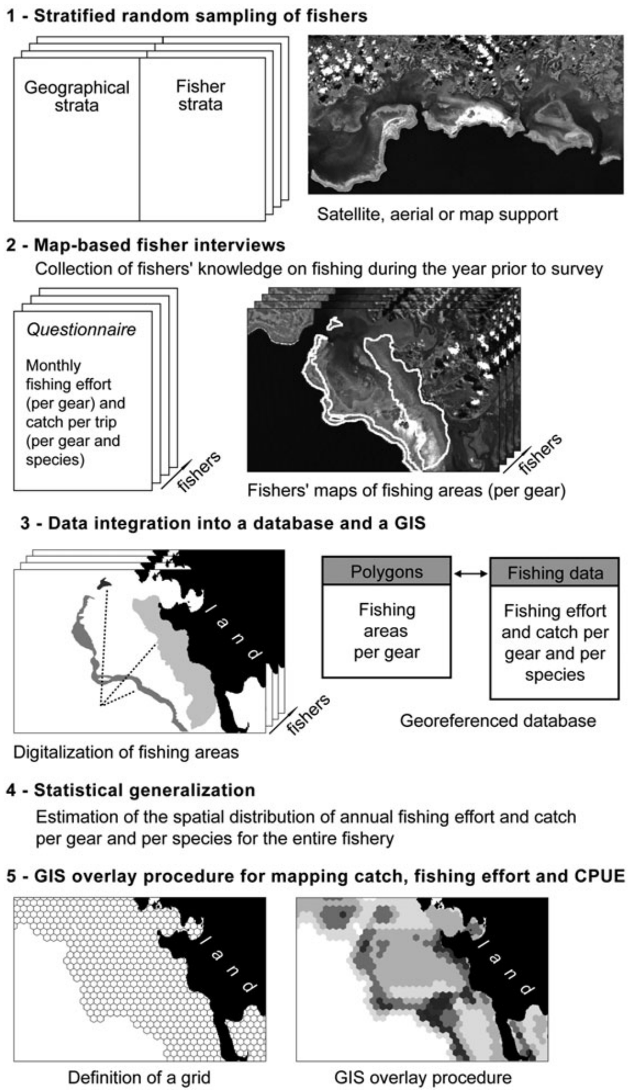

Figure 2. Five-step integrated framework for mapping small-scale coastal fisheries using fishers' knowledge: (i) stratified random sampling of fishers; (ii) collection of fishers' knowledge on fishing effort, catch, and fishing areas through map-based interviews; (iii) data integration into a database and a geographical information system (GIS), (iv) statistical generalization for estimating the spatial distribution of effort, catch, and catch per unit of effort (CPUE) for the entire fishery; and v) GIS overlay procedure for mapping fishery indicators using ESRI© ArcGis 9.2. See *Material and methods* for details.

the total) in the mud crab fishery to 532 fishing units (14% of the total) in the southwest finfish fishery (Table 1).

Step 2: Collection of fishers' knowledge of fishing effort, catch, and fishing areas through map-based interviews

In-person map-based fisher interviews were carried out at home ports when fishers returned from sea or at their living places following the practical recommendations by Close and Hall (2006) concerning interview techniques. Boat owners and a household's most active fisher were interviewed in the finfish and mud crab case studies, respectively, to eliminate the risk of multiple counting of fishing trips.

Closed-ended questions were used to collect quantitative data regarding perceived fishing effort (number of fishing trips in a month) and catches per fishing trip (i.e. CPUE). Fishers declared either the average perceived CPUE or the perceived percentages of occasions when their CPUE approximated each of several levels (e.g. 20% of the time 9 kg trip^{-1}, 60% of the time 20 kg trip^{-1}, and 20% of the time 35 kg trip^{-1}). In the latter case the mean catch per trip was recalculated proportionally to the percentage of each CPUE level (i.e. 20.8 kg trip^{-1} in the above example). Effort and catch data were detailed by fishing gear (gillnet, speargun, handline, trolling) and by species. Vernacular names referring to monophyletic (family and single genus or species) or polyphyletic (groups of similar-looking species) taxonomic groups were used. Interviews were kept as short as possible and lasted from 20 min to 2 h depending on the complexity of the fishers' activity.

Data from fisher interviews were collected for each month of the year prior to the interview date with questions on the most recent fishing trips and then working backwards. The recall period was bound by public landmark events (Christmas holiday). This recall technique aided the short-term memory of fishers and has been shown to enhance data accuracy (Bernard *et al.*, 1984; Bradburn *et al.*, 1987; Brennan *et al.*, 1996).

Spatial data of the location of fishing activities was also collected during interviews. Fishers were asked to detail their respective fishing areas for each gear type they utilized. For this purpose, geographical support was provided using colour satellite Landsat 7 TM pictures (1:100 000–1:130 000 scale), aerial photographs (1:25 000 scale) or nautical charts (1:770 000 scale). Fishers outlined their fishing areas on map hard copies according to natural features, coastal geomorphology (e.g. rivers, estuaries, flats, reefs, mangrove edges), and localities previously identified as relevant references (Close and Hall, 2006).

Step 3: Integration of fishers' knowledge into a geodatabase

Monthly catch size for each fisher was estimated by multiplying monthly fishing effort and mean catch per trip per species and per gear type. Monthly catches and fishing effort were then summed up to obtain annual catches (c) and fishing effort (f) per species and per gear type, respectively. All fishing areas were digitized into GIS vector polygons (p). When a fisher used a given gear type in several fishing areas, a homogenous distribution of fishing effort (f) and the catch per unit of effort ($CPUE$) was assumed across these areas. Annual fishing effort and catch per species and per gear type were, therefore, assumed to be distributed proportionally to the surface of each fishing area (S_p) [Equations (1)]. Both assumptions were based on the observation that small-boat fishers repeatedly visited the same areas, ranging from small- to middle-sized areas (i.e. km scale). These polygons (p) and associated attributes [annual fishing effort (f_p) and catch (c_p) per species and per gear] were aggregated into a one-layer multifishers geodatabase.

$$f_p = f^* S_p \Big/ \sum_p S_p \text{ and } c_p = f_p^* CPUE \qquad (1)$$

Step 4: Statistical generalization for estimating fishing indicators for entire fisheries

Quantitative sample data was processed according to the stratified random sampling design of each case study using common inference procedures (e.g. Guillemot *et al.*, 2009; Jollit *et al.*, 2010). The annual catch and fishing effort per species and per gear type were estimated for each sampling stratum ($\hat{C}_{st}$ and $\hat{E}_{st}$, respectively) and for the entire fishery.

Fishing activities were not extrapolated to areas that were not mentioned by the interviewed fishers. The relative importance of each fishing polygon in the fishery in terms of fishing effort and catch per species and per gear type was determined as follows. For each gear type, the estimated fishing effort of each sampling stratum ($\hat{E}_{st}$) was divided by the total fishing effort of the sample fishers in this stratum (f_{st}). We then weighted observed effort in each fishing polygon (f_p) by this ratio to obtain the extrapolated value of the fishing effort in this polygon ($\hat{f}_p$). The same procedure was followed to determine the extrapolated value of catch of each fishing polygon ($\hat{c}_p$) from the catch observed in this fishing polygon (c_p), the estimated catch in the associated sampling stratum ($\hat{C}_{st}$), and the total catch of the sample fishers in this stratum (c_{st}) [Equations (2)]. The extrapolated values of annual catch ($\hat{c}_p$) and fishing effort ($\hat{f}_p$) per species and per gear type constituted two new GIS attributes of the fishing polygons.

$$\hat{f}_p = f_p{}^*\hat{E}_{st}/f_{st} \quad \text{and} \quad \hat{c}_p = c_p{}^*\hat{C}_{st}/c_{st} \tag{2}$$

Step 5: GIS overlay procedure for mapping fishery indicators

As many fishing polygons overlapped, the fishing polygon layer was overlaid with a grid of hexagonal cells following a GIS overlay procedure derived from Goñi *et al.* (2008) to produce raster-like maps and thus facilitate map interpretation. For each fishing gear and each species, the extrapolated values of annual catch ($\hat{c}_p$) and effort ($\hat{f}_p$) of each fishing polygon were first assigned to cells proportionally to the fishing polygon area (S_p) that intersected in each cell ($S_{p,k}$)[Figure 3 and Equations (3)]. The within-cell estimates of catch ($\hat{c}_{p,k}$) and fishing effort ($\hat{f}_{p,k}$) corresponding to each fishing polygon were then summed among all polygons to obtain the value of total catch ($\hat{c}_k$) and fishing effort ($\hat{f}_k$) within each cell, respectively [Equations (4)]. Cell surface ranged from 0.04 to 10 km^2 (Table 1) resulting from a compromise between the geographical extent of fisheries (from 170–22 200 km^2), the scale of fishers' maps (from 1:25 000–1:770 000), and the expected precision and accuracy of map representations. Cell surface and shape were specified to build the appropriate grid using the ESRI© ArcGIS 9.2 "*Analyse par maille*" tool available online at ESRI© France Resource Center [URL http://ressources.esrifrance.fr/outil_creat_analys_mailles.aspx (last accessed 12 December 2013)].

$$\hat{c}_{p,k} = \hat{c}_p{}^*S_{p,k}/S_p \quad \text{and} \quad \hat{f}_{p,k} = \hat{f}_p{}^*S_{p,k}/S_p \tag{3}$$

$$\hat{c}_k = \sum_p \hat{c}_{p,k} \quad \text{and} \quad \hat{f}_k = \sum_p \hat{f}_{p,k}. \tag{4}$$

Spatial estimates of catch and fishing effort in each cell were expressed per surface unit (km^2 or ha) on the basis of cell surface, producing indices of catch and fishing effort per unit of surface (CPUS index in kg ha^{-1} year^{-1} and EPUS index in number of fishing trips ha^{-1} year^{-1}, respectively). A ratio estimate of spatial catch per unit of effort ($SC\hat{P}UE_k$ in kg fishing trip^{-1}) was then calculated in each cell following Walters' (2003) recommendations [Equation (5)].

$$SC\hat{P}UE_k = \hat{c}_k/\hat{f}_k \tag{5}$$

Uncertainty of quantitative and spatial data

Although the local cultural and socio-economic context was carefully considered in each case study prior to and during interviews to improve accuracy of map-based data, both intentional and accidental errors may induce uncertainty of fisheries maps (Close and Hall, 2006; Kimerling *et al.*, 2009). The precision and accuracy of quantitative and spatial data derived from the framework was investigated through statistical and cartographic analyses.

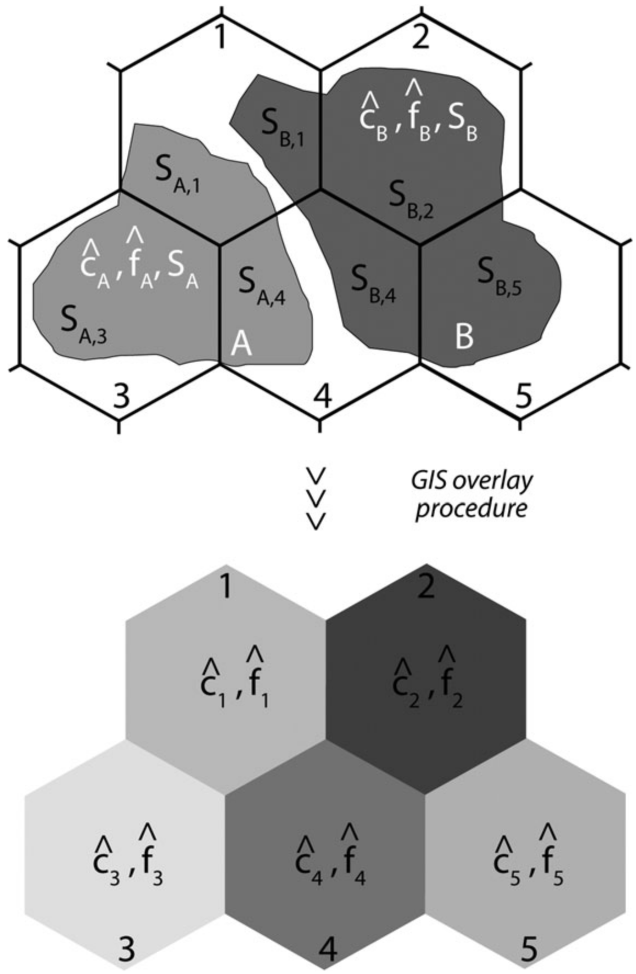

Figure 3. Application of the GIS merging procedure of the framework to two hypothetical fishing polygons, A and B, digitized from fishers' maps. This procedure uses a hexagonal grid for standardizing fishery maps of annual catch size and fishing effort per species and per gear. The extrapolated values of catch ($\hat{c}_A$ and $\hat{c}_B$) and fishing effort ($\hat{f}_A$ and $\hat{f}_B$) of fishing polygons are summed proportionally to their area (S_A and S_B) that intersects in each cell of the grid ($S_{A,1}$, $S_{A,3}$... and $S_{B,1}$, $S_{B,2}$...) to estimate catch ($\hat{c}_1$, $\hat{c}_2$...) and fishing effort ($\hat{f}_1$, $\hat{f}_2$...) for each cell (1, 2,...5), respectively. See *Material and methods* and Equations (3) for details.

The spatial stratification of interview surveys accounted for potential territory uses and coastal resource heterogeneity that could impact fishing patterns across the fisheries (e.g. Simón *et al.*, 1996) and bias extrapolations. Large sample sizes and stratified sampling designs were used to increase precision of statistical estimations according to available literature and to improve representativeness of fishery maps (e.g. McCluskey and Lewison, 2008).

The precision of quantitative data was measured for each case study through the 95% confidence intervals of annual catch and fishing effort estimates assuming normal distributions of the estimated means following probability sampling theory (stating that the distribution of means of non-normal data approximates a normal distribution at large sample sizes) (Cochran, 1963;

Zar, 2010). Additionally, official statistics of catch and fishing effort were available for the commercial Spanish mackerel fishery in the surroundings of the Belep Islands, located at the northern part of the New Caledonia Lagoon (Figure 1). We used such records to investigate the accuracy of our interview data in that area. The official records of the 2006 catch and fishing effort of 18 fishers in the Northern Lagoon (75% of the fishery's total in that area) were compared with the data collected during the interviews of these fishers using the Wilcoxon matched pairs tests.

Given the large sample size and the spatial stratification of the surveys it was assumed that the fishing areas identified during interviews were spatially representative of the fishing grounds visited by all the fishers of the fishery, and that significant fishing grounds were not left out by fishers (Close and Hall, 2006; McCluskey and Lewison, 2008). The overall spatial precision and accuracy of fishers' maps in our case studies was taken into consideration through the mapping procedure to avoid falsely accurate representations of fishing activities and to produce realistic fisheries maps. First, fishing polygons were already approximations and generalized representations of real fishing areas compared with line and point features and were therefore assumed to incorporate potential spatial errors of fishers' maps (Close and Hall, 2006). Second, the scale of the pictures used by fishers to outline their fishing areas was adapted to the expected level of precision and map feature generalization of the spatial analysis (Campbell, 1991; Close and Hall, 2006). Third, the granularity of fisheries maps (i.e. the surface of the cells of the grid) further generalized the representation of fishing areas. Cells were of hexagonal shape to improve the accuracy of spatial indices and gradients compared with an equivalent square shape (Tirunelveli *et al.*, 2002).

Results

Spatial indicators of fishing effort, catch and CPUE

The total annual fishing effort and catch greatly varied between the four fisheries, ranging from 4720–28 800 fishing trips per year and from 88–1140 t per year, respectively (Table 1). The GIS procedure allowed for mapping the distribution of catch, fishing effort and CPUE per species and per gear type for each of the fisheries. Thematic spatial analyses were conducted according to target taxa, gears, and the geographical units derived from sample strata. The examples of maps of catch density, effort density and CPUE that were presented thereafter highlighted the outcomes of the framework. Moreover, we produced an atlas of fishing activities of the northwest finfish case study to illustrate the complete scope of possible maps (*Supplementary data*).

Fine-scale maps of effort density (EPUS index) allowed the visualization of the distribution of fishing pressure over fisheries, revealing general spatial gradients of fishing pressure, fishers' site preferences for each gear, and main targeted sites for each species. They also indirectly provided social interpretations of the non-random allocation of fishing effort over fisheries as exemplified by the northwest finfish case study (Figure 4). In this fishery, fishers from the northern and southern sectors did not outline any harvest zones in a 61 km^2 central sector that was only visited by Xujo Melanesian fishers (Figure 4d). These results suggested that the latter have efficiently enforced exclusive access over the waters surrounding their village. Travel distance and costs cannot explain such patterns in fishing effort, as fishers from the three geographical sectors may travel to further fishing grounds northwards or southwards from this central area (Figure 4a, b and c).

The CPUS index provided straightforward information on catch density for each species and each gear type. Maps of catch density were used to identify differences in catch between gear types and between species over the fishing grounds as well as spatial gradients of catch density. In particular, these maps highlighted the most productive areas for fisheries due to ecological and/or fishing factors regardless of the survey's scale. In the northwest site for example, areas with strong river influence (i.e. Temala and Vavuto Bays) were associated with the highest mud crab catch densities compared with coastal mangroves and flats, ranging from 140 kg ha^{-1} $year^{-1}$ to less than 1 kg ha^{-1} $year^{-1}$, respectively (Figure 5). In the Spanish mackerel fishery, maps showed that catch density was highly heterogeneous over the New Caledonia Lagoon. Only 4% of the whole lagoon area was actually visited by fishers, while the southwest and northern areas constituted the main fishing grounds of the country. Fine-scale patterns highlighted that catch density peaked at up to 53 kg ha^{-1} $year^{-1}$ in very restricted locations (e.g. reef passages, isolated reefs or islands) (Figure 6). Fishers exhibited a marked seasonality in activity in the southwest area, where most catches of Spanish mackerel occurred during the spawning season in November and December. Spatial and temporal patterns of fishing activity taken together suggested that fishers mostly targeted spawning aggregations in this area.

The SCPUE index complemented the information on catch and fishing effort densities by providing spatial information on catch rates for each species and each gear. Gear-specific data was required to account for the consistency of fishing efficiency and selectivity. Maps of CPUE were used to estimate gradients of resource abundance over the fisheries. The map of CPUE of the spangled emperor (*Lethrinus nebulosus*, Lethrinidae) was illustrated in the northwest site (Figure 7). This is one of the main New Caledonia emblematic finfish species and is fished using handlines only. We observed that catch rates were heterogeneously distributed over the lagoon area, ranging from 0–44 kg $trip^{-1}$, while the mean fishing yield was about 6 kg $trip^{-1}$. These strong differences in fishing yields may be explained by the ecological traits of the species (e.g. habitat preferences) and/or fishery impacts on resource abundance.

Precision and accuracy of quantitative and spatial data

The width of 95% confidence intervals of annual catch and fishing effort estimates ranged from 5–30% and 4–26% across surveys, respectively (Table 1). Lower precision was achieved in the mud crab survey compared with the finfish surveys, partly due to the smaller sample size used in the mud crab survey ($n = 98$) compared with others ($n = 123$–532).

Records and interview data on annual catch and fishing effort in the Spanish mackerel fishery of the Northern Lagoon of New Caledonia were not significantly different ($n = 18$, $p = 0.27$ and $p = 0.26$, respectively). Of the surveyed fishers, 61% and 39% over- and underestimated their annual catch compared with the records, respectively (Figure 8a). Records and interview data on annual catch were highly correlated (Pearson correlation coefficient, $r = 0.88$), although they differed more widely when catch records were low (i.e. <1 t). Total official annual landings reached 20.1 t in 2006, whereas fishers reported 23.7 t, resulting in a 17.8% overall overestimation (+3.6 t) compared with the records. Interview data on fishing effort showed similar patterns and was correlated with effort records ($r = 0.49$), although the correlation rate was lower than that observed for catch (Figure 8b). Overall 273 and 358 fishing trips (+31%) were recorded and reported by fishers, respectively. This deviation between interview

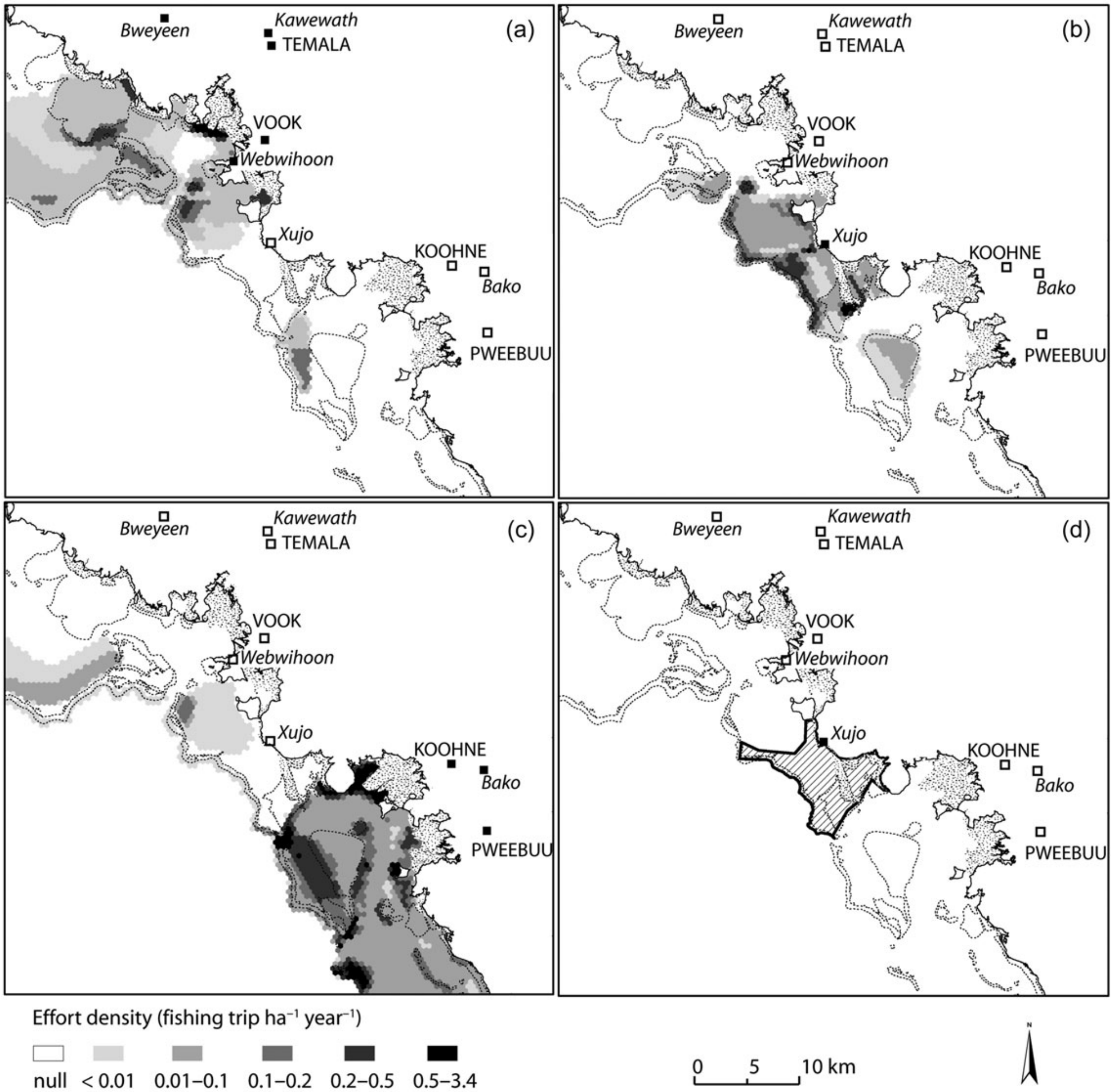

Figure 4. Distribution of estimated effort density (effort per surface unit) for reef finfish in the Northwest Lagoon of New Caledonia according to fishers' place of residence: Bweyeen, Kawewath and Webwihoon Melanesian villages, and Temala and Vook urban areas (**a**); Xujo Melanesian village (**b**); Bako Melanesian villages and Koohnê and Pwëëbuu urban areas (**c**). Xujo's exclusive fishing area derived from the three previous maps (**d**). Dotted lines = reefs, spotted areas = mangrove, uppercase letter = multicultural urban areas, lowercase letters = Melanesian villages.

data and records of fishing effort partly arose from a bias in the records. Unsuccessful fishing trips were not registered in the official statistics, which therefore underestimated the effective fishing effort. However, few outliers were observed, suggesting that some fishers likely misestimated their annual fishing effort (Figure 8b).

In some cases, intentional spatial errors were detected during interviews with a very small number of unwilling fishers who outlined their fishing areas with evident inaccuracy (e.g. the depth within the declared fishing area was well beyond the limits of gear use). Such errors generated biased fishers' maps that were excluded from the analyses. In other cases, accidental location errors were observed on the boundaries of fishing areas. These spatial errors were mainly attributed to the scale and detail of the pictures used by fishers to map their fishing areas. Our observations suggested that they likely reached 1–2 mm on paper maps in either direction, although this is difficult to quantify. Fishing grounds located far from the seashore, reefs or islets, or in open lagoons, were likely delineated with the lowest accuracy because fishers lacked reference points (i.e. landscape or seascape features) close to their fishing areas. For similar reasons, using high resolution colour satellite or aerial pictures provided more appropriate visual support to the fishers than nautical charts that symbolized natural features of significance for fishers and therefore likely decreased accuracy of

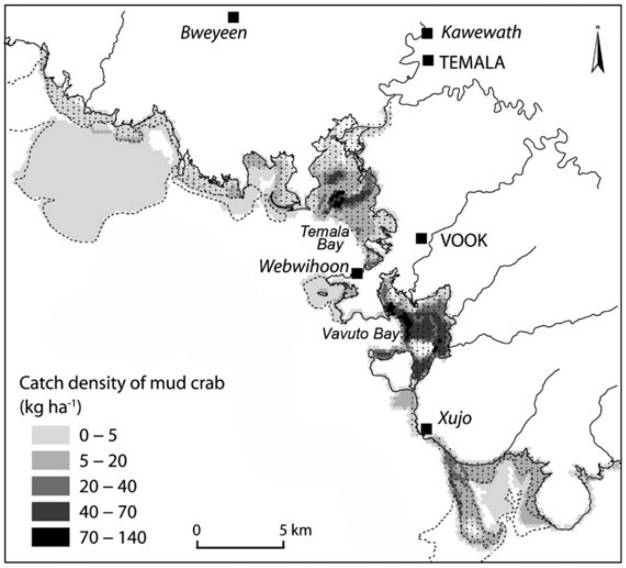

Figure 5. Distribution of estimated catch density (catch per surface unit) of mud crab (*Scylla serrata*, Portunidae) fishery in the Northwest Lagoon of New Caledonia. Lines = rivers, dotted lines = coastal reef flats, spotted areas = mangrove, uppercase letter = multicultural urban areas, lowercase letters = Melanesian villages.

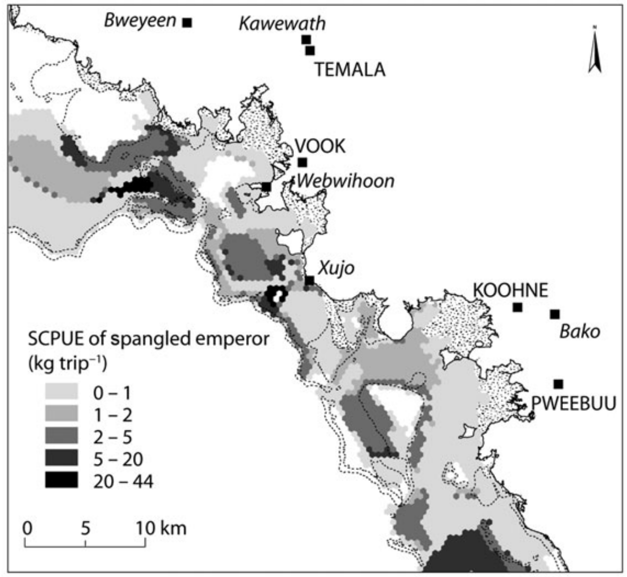

Figure 7. Distribution of estimated handline catches of the spangled emperor (*Lethrinus nebulosus*, Lethrinidae) per unit of fishing effort (SCPUE) in the Northwest Lagoon of New Caledonia. Dotted lines = reefs, spotted areas = mangrove, uppercase letter = multicultural urban areas, lowercase letters = Melanesian villages.

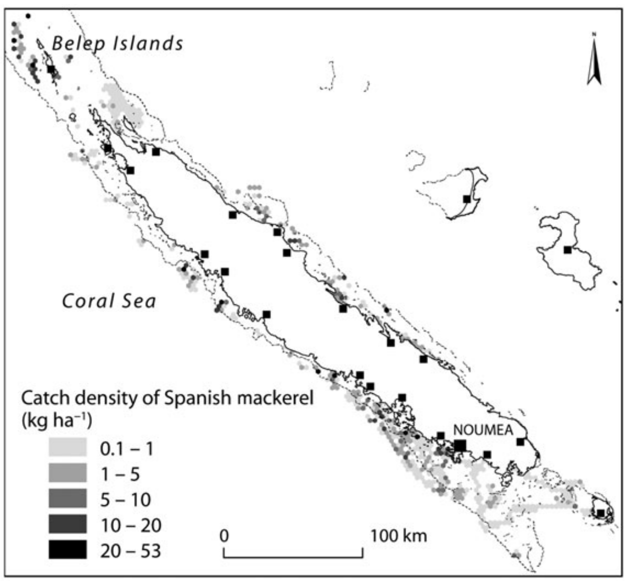

Figure 6. Distribution of estimated catch density (catch per surface unit) of Spanish mackerel (*Scomberomorus commerson*, Scombridae) fishery in the entire lagoon area of New Caledonia. Dotted lines = reefs, black rectangles = main urban areas.

fishers' maps. We also found that the accuracy of fishers' maps was higher when the spatial nature of fishing activities was rooted in marine tenure. For instance, the most accurate spatial representations were observed for the mud crab fishery due to the combination of several factors: location of fishing areas close to numerous landmarks, territorial practices, and use of high resolution aerial photographs.

Discussion

Reliability of fishers' knowledge

The reliability of the quantitative and spatial data collected during our fisher surveys was investigated using independent information. Previous empirical studies in medical and behavioural sciences suggested that informants' recall could be inaccurate for various reasons (Sudman and Bradburn, 1973). Accuracy of cognitive data appeared difficult to predict in social surveys (Romney and Weller, 1984), but it was observed that people tended to overestimate and underestimate the probability of unlikely and common events, respectively (Bernard *et al.*, 1984). As far as fisher surveys are concerned, this would mean that fishers likely overestimated the frequency of their most noteworthy catches, resulting in an overestimation of average catch per trip and consequently of the total annual catch. This likely occurred during our survey of the northern Spanish mackerel commercial fishery. However, no significant error was detected across fishers, and the measured overestimation rate of the fishery catch (+17.8%) appeared acceptable for fisheries management given the inherent variability of fishing activities and natural resources. Overall the large sample size of our fisher surveys led to reasonably high precision of fisheries catch and effort estimates. Additionally fish consumption patterns derived from national censuses were consistent with our estimations of finfish catch in the northwest and southern survey areas (Guillemot *et al.*, 2009; David *et al.*, 2010). These results suggest that fishers can provide accurate quantitative knowledge of their catch and fishing effort (e.g. Neis *et al.*, 1999; López *et al.*, 2003; Léopold *et al.*, 2004; Pinca *et al.*, 2012), although they should be confirmed by paired surveys of interview data and official records based on large fisher samples. Some recommendations also need to be considered for improving the reliability of fishers' data (e.g. White *et al.*, 2005; Moore *et al.*, 2010). We found that fishers felt comfortable with the aided recall techniques we used in our case

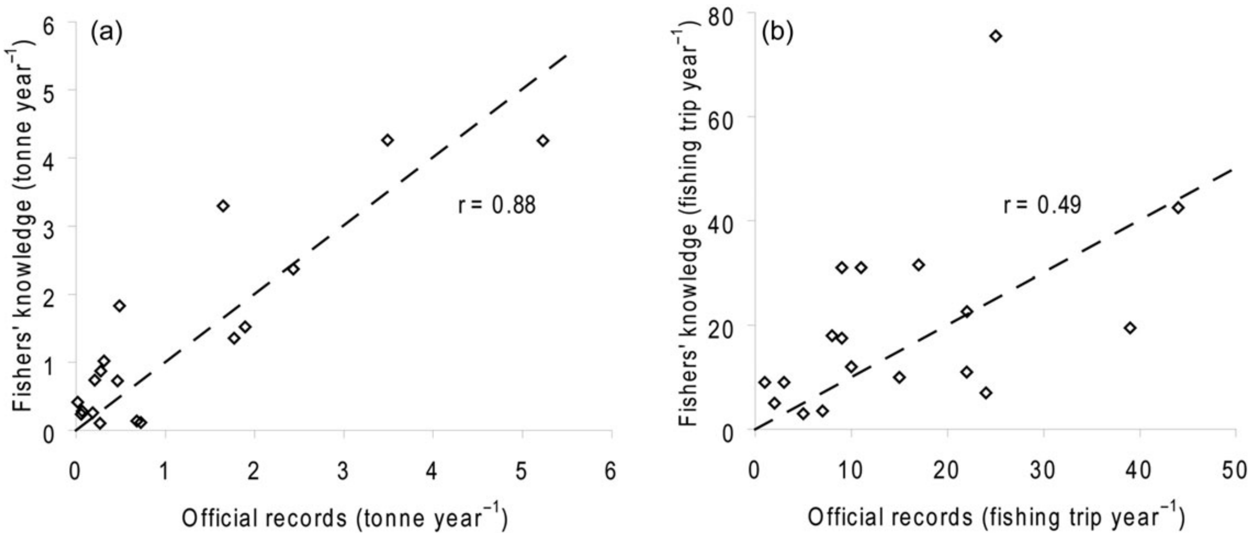

Figure 8. Relationships between fishers' knowledge and official records for annual catch (**a**) and fishing effort (**b**) of the Spanish mackerel (*Scomberomorus commerson*, Scombridae) fishery in the Northern Lagoon of New Caledonia in 2006. r = Pearson correlation coefficient, dotted lines: $y = x$.

studies. Fishing effort was measured in fishing trips, which is easy for fishers to use, however more specific units (e.g. fishers × fishing trips, fishing hours, net length) may be preferred for more detailed surveys. Providing preliminary information about the survey objectives and the future use of the fishing data was also critical for improving fishers' willingness to participate and thus the reliability of interview data. Potential bias has indeed been reported in monitoring and assessment surveys involving local communities (Silver and Campbell, 2005; Léopold *et al.*, 2009).

The hexagonal grid and the cell surface used for the fisheries maps handled fuzzy spatial representations of fisheries as a computational and cartographic approach to spatial uncertainty (Wang and Hall, 1996). The latter came from location error of fishing areas on fishers' maps that may be explained by the scale of the pictures used by fishers to outline their fishing areas and by the inherent vagueness of geographical boundaries of fishing grounds (Worboys, 1998). Our assumptions about effort and resource distribution across fishers' fishing areas may have also contributed to the imprecision of map representations. Asking the fishers to specify their annual effort and/or average catch per fishing trip for each fishing area would allow the depiction of spatial patterns of fishing activities and resource distribution more accurately (e.g. Scholz *et al.*, 2011). Nevertheless, the consistency between spatial catch density estimates derived from fisher interviews and independent biological observations of resource distribution was validated for both finfish and mud crab fisheries. Underwater visual censuses of fish communities in the northwest site detected significant negative impacts of the fishing pressure on fish biomass in the areas showing high CPUS (Guillemot, 2009). Conversely, the abundance and size of mud crabs (rather than the fishing effort) drove mud crab CPUS values which were not affected by fishing pressure, suggesting that the mud crab fishery was underexploited at the time of the survey (Dumas *et al.*, 2012). The spatial representativeness of the map products of both fisheries was likely improved by the high sampling rate used to survey these sites (47% and 57%) compared with the two other case studies (14% and 24%) given that fishing patterns were not generalized to areas that had not been visited by the interviewed fishers.

Key outputs and applications of map products

Filling the recurrent gap in reliable quantitative and spatial data on coastal fisheries and coral reef fisheries in particular, map products accounted for ecological, geomorphologic and human patterns for the full extent of our study fisheries at different geographical scales. These data products and the increased understanding of how coastal areas are being utilized by fishers contribute to fisheries management policy and conservation planning in various ways, as highlighted by our four case studies.

First, the fine-scale maps represented powerful tools for monitoring the spatial and temporal dynamics of fishing activities and their impacts on coastal resources. For instance spatial CPUE has been used as a proxy for the spatial distribution of resource abundance within a large geographical coverage to assess the biological outcomes of marine reserves (Stelzenmüller *et al.*, 2007, 2008; Goñi *et al.*, 2008) and to provide key criteria for the selection of sites and species for *in situ* resource monitoring programmes (Guillemot, 2009). Maps of catch density also constituted meaningful tools to monitor changes in the socio-economic impacts on fisheries by linking local economic, social and environmental features to commercial, recreational and subsistence fishing activities (Cinner *et al.*, 2009; Jollit *et al.*, 2010). Maps of catch and effort density may also be produced on a seasonal time-scale by adapting the statistical procedure to depict seasonality in activity. Specifically, monthly catches and fishing effort for each fisher may be summed up to obtain seasonal catches and fishing effort per species and per gear type, respectively, rather than on an annual basis.

Second, sites with high CPUE and catch density may represent priority conservation areas for maintaining fishery productivity and/or for protecting vulnerable species or life-cycle stages, such as spawning aggregations. Fine-scale CPUS and EPUS maps would facilitate the estimation of catch loss due to site-specific degradations of the marine environment (e.g. mining impacts, urban waste) and opportunity costs of establishing marine protected areas (Richardson *et al.* 2006; Ban *et al.*, 2009). Such maps have proved useful for determining spatially explicit conservation options (Scholz *et al.*, 2011; van de Geer *et al.*, 2013).

Third, EPUS maps displayed informal and tacit territory rules and allowed us to capture the fishery access regime and social seascape (St Martin and Hall-Arber, 2008). In particular, they identified potential sea-use conflicts in customary sea tenured systems. As in other insular countries in Oceania, local communities play an important role in the spatial determinism of fishing activities in New Caledonia, although public institutions give open access to all coastal waters. The extent to which different communities exhibited separated effort clusters at sea may be related to gear uses and/or marine tenure (Léopold *et al.*, 2010). Additionally, as a visual and cartographic tool, maps allowed sharing of information and enhanced the dialogue between users and public authorities. The participation of fishers in map production may strengthen their involvement in the decision-making processes affecting their practices (Jankowski, 2009).

The above applications of fisheries maps may not rule out the need for interdisciplinary approaches to the management of small-scale coastal fisheries. Specifically social and cultural information that contributes to understanding the fishers' and their communities' values and goals, as well as individual and collective preferences, has improved the feasibility of developing appropriate management in the survey sites (e.g. Léopold *et al.*, 2013a, b).

Generalization of the framework

The present integrated framework was specifically developed to inform data-deficient fisheries and did not rely on pre-existing or alternative data on fishing activities. Four small-scale subsistence, recreational and commercial coastal fisheries were included to embrace different geographical scales, resources, fishing use patterns, and social contexts. Standard statistical inference and GIS procedures were used to develop a generic framework and to facilitate its generalization. Very few assumptions were required about the structure of small-scale fisheries to use this framework. Site specificities included the presence of collaborative fisher communities and suitable natural conditions (i.e. landmarks and marine geomorphologic features). The framework, therefore, is designed to fit a large range of small-scale coastal fisheries in tropical and temperate waters both at sea and inland. More particularly, it has been strongly adapted to be implemented in developing countries where official records on small-scale fisheries are often incomplete or unavailable. It may also be used to complement lower spatial resolution commercial fishery statistics referenced to large statistical squares or latitude/longitude grids. Fine-scale maps, however, captured exploitation and management impacts that would not have been detected at a coarse resolution (Babcock *et al.*, 2005; Richardson *et al.*, 2006).

Such an approach (of combining official records and fisher interview data) has been developed by Scholz *et al.* (2011) using the Open OceanMap tool. The mapping procedure was based on the allocation of official catch records of a sample of voluntary commercial fishers to their respective harvest areas collected through interviews. Contrary to the integrated framework described in this paper, the Open OceanMap tool depends upon two different sources of knowledge for catch and effort data, respectively, and does not incorporate a generalization procedure for extrapolating sample data to the fishery level. Both limitations derived from the initial objectives of this tool have been addressed by our integrated interview-based approach. However embedding our framework in such a user-friendly computer tool would likely facilitate its implementation and spatial generalization. Computer tools that would process fishing data of the geodatabase and produce fisheries maps through pre-defined routines would be appropriate for agencies with little GIS and statistical expertise. Indeed, the statistical inference and GIS procedures associated with our framework would likely require technical capacities that typically may not be held by local managers, although map-based interview data may be collected by interviewers with little academic scientific education.

Conclusions

Following the approach used by Watson *et al.* (2004) for mapping worldwide commercial fisheries, this study formalizes the first framework for mapping entire small-scale coastal fisheries using only fishers' knowledge. Generalizing available survey methods, the integrated framework provides guidelines for collecting and processing fishers' knowledge on catch size and fishing effort at the fishery level through map-based interview surveys, statistical inference and the use of GISs. Despite the inherent limitations of interview data, the results show that the framework produces realistic spatial representations and precise map classifications of fisheries catch, effort, and CPUE using common measurements across the fisheries.

This framework is designed to offer new opportunities for characterizing small-scale coastal fisheries in such a way as to strengthen spatially sound management. More particularly, it aims to highlight the relevant scale for area-based fishery monitoring, management and governance.

Supplementary data

Supplementary data, including an atlas of finfish fishing activities in the northwest study area (New Caledonia, South Pacific), are available at *ICES Journal of Marine Science* online. It was produced using the integrated framework presented in this paper to illustrate the complete scope of possible fisheries map classifications.

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