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Monitoring the fishing process in the sea urchin diving fishery of Galicia

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The assessment and management of small-scale benthic fisheries requires attention to the spatial structure of stocks and patterns of effort allocation. Spatial information helps in the interpretation of fisheries data, and is required for designing spatially explicit management strategies, often prescribed in the case of benthic fisheries. Monitoring of boats with GPS, combined with port interviews, was evaluated as an approach to investigate the spatial pattern of fishing intensity and catch per unit of effort (CPUE) in the sea urchin (*Paracentrotus lividus*) diving fishery from Galicia, Spain. Fishing opportunities (FOs), relatively small regions of high fishing intensity, were identified and mapped at a fine scale. New FOs were first visited at an approximately constant rate. Concentration analysis shows that effort intensity was not uniformly distributed within FOs. CPUE did not exhibit a significant trend throughout the season, either at the scale of the aggregated fishery or within individual FOs. Catch per area and area covered per unit of diving time were inversely related, indicating that fishers stay longer in high-density patches. While abundance is the primary driver of effort allocation, other factors contributing to suitability were identified. Based on these results, we discuss realistic options for the monitoring of this and comparable fisheries.

Keywords: fishing effort, fishing intensity, Galicia, GPS, mapping, monitoring, *Paracentrotus lividus*, sea urchin, small-scale fishery, spatial.

Introduction

Small-scale benthic fisheries ("S fisheries"; Orensanz *et al.*, 2005) constitute a particular family characterized by the significance of spatial processes, including the complex spatial structure and dynamics of the stocks that they target, the heterogeneity and persistence of the location-specific effects of harvests, and the behaviour of fleets, particularly with regards to patterns of fishing effort allocation. The provision of scientific support for S fishery management may be challenging (Freire *et al.*, 2002). Fishery-independent assessments required by quota systems, for example, can be extremely expensive and logistically demanding (Freire and García-Allut, 2000; Parma *et al.*, 2003; Mundy, 2005). On the other hand, it is generally held that serial depletion and low spatial resolution constrain the information retrievable from fishery-dependent data, e.g. catch per unit of effort (CPUE; Keesing and Baker, 1998; Perry *et al.*, 2002). As a result, S-fisheries tend to be data poor (Prince, 2010). Because of the relevance of the spatial dimension for the dynamics of the stock and the behaviour of the fleet, and, most notably, for the nature of the incentives for conservation, it has often been claimed that spatially explicit options may be the most naturally suited to the management of S fisheries. Such options include territorial access privileges, rotation of the harvests, and permanent closures designed to protect the reproductive stock (Orensanz and Jamieson, 1998). The design of spatial harvesting strategies is less demanding than conventional quota-based approaches in terms of estimates of biomass and mortality; however, it requires spatially explicit information on the fishing process at scales finer than those generated by standard monitoring programmes (Keesing and Baker, 1998; Andrew *et al.*, 2002; Perry *et al.*, 2002).

One possible solution is to tap into the wealth of information generated by fishers themselves as a by-product of the fishing process. The distribution of fishing intensity (defined as the amount of fishing effort exerted per unit area), for example, should be informative about the distribution of target resources, and about the drivers of effort allocation. Fishing effort tends to concentrate in relatively small areas, defined by Branch *et al.* (2005) as "fishing opportunities" (FOs). The spatial location of FOs is determined primarily by resource abundance, but also depends on fishers' knowledge and on a number of factors: depth, exposure to weather, distance from port, resource quality, etc. In recent years, the increasing implementation of vessel monitoring systems (VMS) in industrial fishing vessels has generated abundant information about fleet behaviour, allowing identification of FOs and mapping of fishing intensity for a diversity of purposes (Harrington *et al.*, 2007; Mills *et al.*, 2007; Gerritsen and Lordan, 2011; Lambert *et al.*, 2012). In the case of artisanal fleets, GPS technology and data loggers offer an analogous opportunity (Marrs *et al.*, 2002; Buxton *et al.*, 2011).

Most studies on fleet behaviour have dealt with situations in which there are identifiable, discrete fishing events, as best exemplified by trawl or dredge hauls (e.g. Larcombe *et al.*, 2001; Marrs *et al.*, 2002; Branch *et al.*, 2005; Mills *et al.*, 2007). In those cases it is conceptually simple to investigate aspects of the fishing process such as the catch per unit of area effectively harvested, because the area swept by the gear correlates directly with fishing time. The discreteness of fishing events and the correlation between fishing time and area covered are lost in the case of hand-gathering and diving fisheries, in which search, probing, catching, and handling are well interspersed short-term events of a quasi-continuous ("fine-grained") process. Hand-harvesters are able to direct the search at even the smallest meaningful spatial scales, remaining longer at places of high density; measuring the "area effectively harvested" per unit of effort (e.g. 1 h of diving) is an elusive problem in such fisheries.

In this study, we utilize the case of the commercial diving fishery targeting sea urchins (*Paracentrotus lividus*) in Galicia (Freire and García-Allut, 2000; Andrew *et al.*, 2002; see the Supplementary material for further information) to (i) evaluate the merits of GPS-based monitoring for describing the fishing process at a fine spatial scale; (ii) assess patterns of distribution of fishing intensity and map FOs; (iii) analyse effort allocation within FOs, with emphasis on serial depletion; and (iv) investigate indicators of local density such as CPUE and catch per area during the fishing season. Finally, we discuss the observational scales relevant to understanding the fishing process and realistic options for monitoring commercial diving fisheries.

Material and methods

Study system

The coastal region of Galicia is partitioned into nine fishery administrative zones. Within each zone, fishers are organized in "confrarías", local organizations created with government support to co-manage fisheries within their allocated coastal sector. Regional management plans include regulations on seasons, maximum number of effective fishing days per year, hours of the day when fishing is permitted, size limits, and daily trip limits. The confraría of Lira, located within Administrative Zone V (Figure 1; see the Supplementary material), was chosen as a focal case study because it is well organized and it had made the largest contribution to sea urchin landings in the zone. The sea urchin trip limit for the 2006–2007 fishing season in this zone was of 100 kg per crew member, with a maximum of 300 kg per boat.

Fisheries data

Landing data by confraría, aggregated by boat, have been compiled by the fisheries authority back to 1997 and are publicly available (www.pescadegalicia.com). Data on number of trips and catch per trip for the fishing season 2006–2007 were voluntarily made available for this study by the confraría of Lira. When, as in the case of Zone V, a joint management plan involves more than one confraría, the catch landed in a confraría may originate in the historical territory of a different confraría. The spatial resolution of the data is low relative to the scale at which fleets identify and target FOs.

Field work

Subtidal sea urchins are targeted mostly by commercial hookah divers, which can legally operate down to a depth of 12 m. At the time of the study, the Lira-based sea urchin fleet was composed of four boats, ~ 6 m long and equipped with a compressor. Crews typically consist of a skipper and one diver, but one boat operated with two divers. While the diver is fishing, the boat either remains at the same location or drifts slowly following the diver, who can be tracked by the air bubbles on the surface. For safety reasons, the distance between the boat and the diver is kept to a minimum (1–2 m) except when fishing in shallow zones (<5 m), where the boat's draught would not allow for the boat and diver to remain so close together.

GPS devices (Garmin Geko model 201) were used to monitor the daily activity of the fleet. The season extended from 15 January to 30 April 2007, during which a total of 186 fishing trips were completed over 47 effective fishing days, from a total of 81 workable days (fishing is not allowed during weekends and holidays). Monitoring with GPS devices was conducted on 31 fishing days, starting on the 15th effective fishing day of the season (from 9 March to 30 April 2007; in what follows the "recorded period"), resulting in the recording of 67 boat tracks (Supplementary material, Table S1). Each track consists of the positions of the boat (longitude and latitude in UTM coordinates) during one daily fishing trip. The target polling frequency was 5 s ($n = 40$ tracks), but, due to technical problems, it was 1 min in 20 tracks, and fluctuated between 1 s and 10 min in 7 tracks (Supplementary material, Table S1). The accuracy of the GPS devices was <15 m root mean square (RMS). Participation in the study was voluntary, and the level of collaboration was variable among boats.

Daily fishing operations always started and ended at Lira's harbour, from where boats moved directly to the fishing grounds; we refer to the duration of travel between port and fishing zones, and among different fishing zones, as "travel time". The time during which divers remained underwater is defined as "diving time", equated with "effective fishing effort". Given the proximity between boat and diver, boat tracks corresponding to diving time were equated with diver tracks. Catches were hauled on board in mesh bags.

The crew of each boat was interviewed daily upon arrival at port to record information on catch weight, number of divers, mean diving depth, time spent diving, and catch location. When multiple locations were fished in a trip, data were recorded for each location separately. Divers pointed to fishing locations on nautical charts (scale 1:15 000). A sample of the catch was measured (maximum shell diameter, in mm; $n = 30$ individuals). Port interviews covered the entire fishing season; data from 153

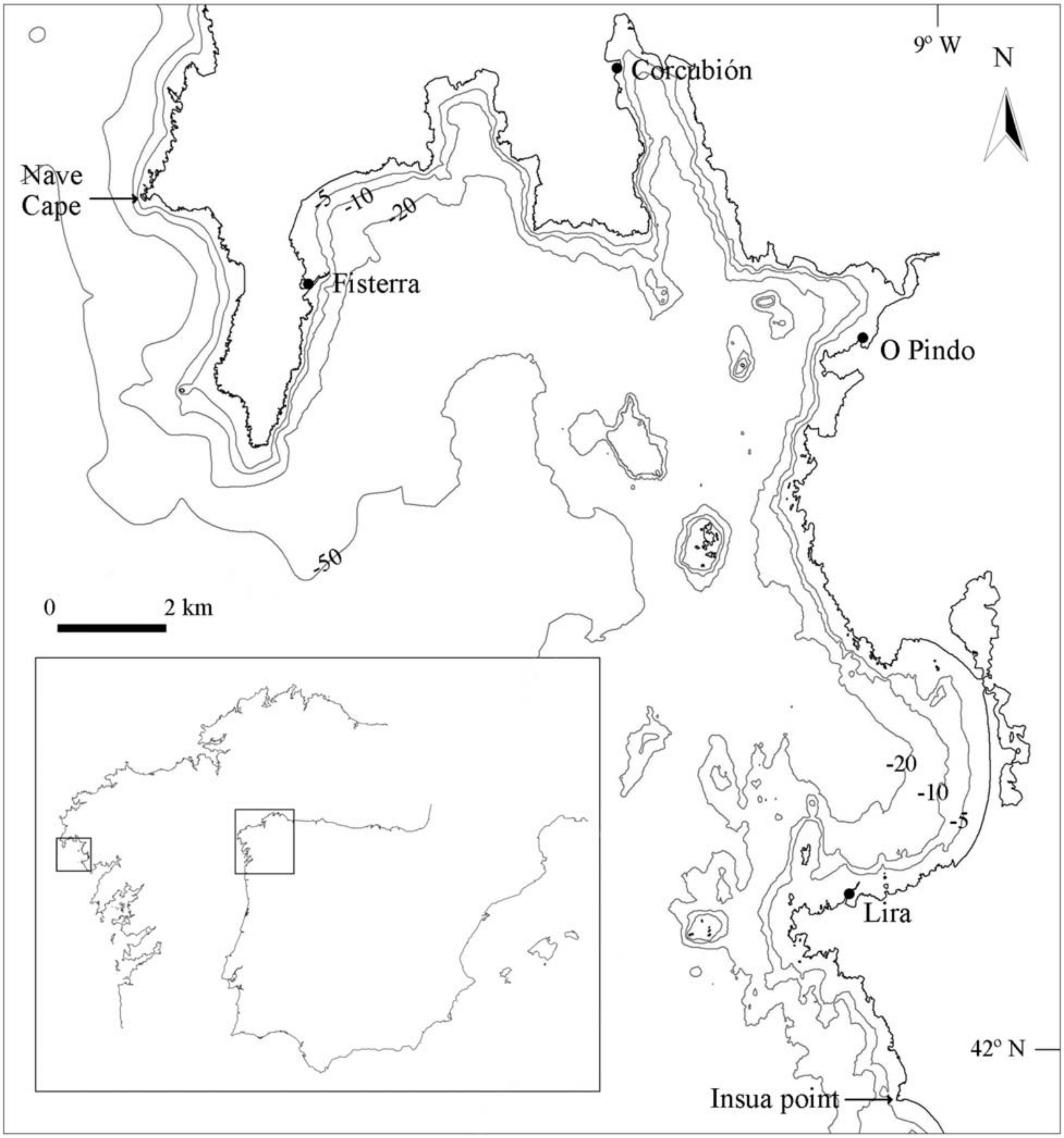

Figure 1. Study area and fishing harbours in Administrative Zone V. Cape Nave and Insua Point (to the North and South, respectively) bound the sea urchin fishing grounds in the zone during the 2006–2007 fishing season.

fishing trips (84% of the total) were recorded. The catch corresponding to trips not covered by port interviews were obtained from fish market records.

Data sorting and processing

GPS tracks were mapped using ArcView GIS 3.2 (Supplementary material, Figure S2) and classified into complete (when the entire diving period was recorded, 47 tracks) and incomplete (incomplete diving time information, 20 tracks; Supplementary material, Table S1). Out of the 47 tracks with complete diving time, 33 also had complete information on travel time. Incomplete tracks were the result of GPS user errors, a bad connection of the device, or battery replacement. GPS records located in the harbour were discarded.

Records were classified as "diving" or "travel" on the basis of boat speed. A cut-off level was determined from inspection of speed frequency distributions (see the Results). Boat speed was calculated as the lineal distance separating two consecutive records, divided by polling interval (5 s or 1 min), and expressed in km h^{-1}. Estimated speed and distance travelled are expected to differ between the two polling frequencies for two reasons. First, measurement error (GPS accuracy) is expected to inflate travelled distance at high polling frequency and slow speed (Palmer, 2008). Second, even in the absence of measurement error, trajectories are not straight during a dive; in consequence, the distance between two locations recorded with an interval of 1 min would be shorter than the corresponding distance calculated by adding the 12 segments recorded at 5 s polling intervals. These problems should not affect the estimation of effective fishing effort (diving time); consequently, all tracks were utilized to locate fishing areas and to analyse trends in effort. They could affect the estimation of spatial effort allocation; thus, for some of the analyses (see below), only 5 s polling data were used.

Identification of fishing opportunities

The potential area of suitable habitat available to the commercial sea urchin fishery, defined as rocky bottoms shallower than 12 m, was estimated using bathymetric data and information on substrate type extracted from nautical chart 926, Spanish Marine Hydrographic Institute. Within this area, we used clusters of GPS records classified as "diving" to define FOs, following Branch *et al.* (2005). FOs were identified using records from all trips, and each FO was assigned an identification number correlated to the time of first recorded harvest. Neighbouring FOs were deemed to be separate when the minimum distance between their records was >100 m. This criterion was based on our experience (Fernández-Boán, 2007) and on inspection of the data: the average distance between the start and end points of a visit to an FO was close to 100 m (see the Results). The depth range of each FO was estimated from a hydro-acoustic bathymetric survey (Sánchez-Carnero *et al.*, 2012).

The distance between an FO and the harbour of Lira was estimated as the mean distance travelled between the port and the FO in successive trips. The Euclidean distance between the centroids of the FOs, estimated as the mean of the UTM coordinates of the points, was used to group FOs in clusters. A hierarchical agglomerative clustering algorithm was applied using the complete linkage method (function HCLUST, R Development Core Team, 2011).

In order to compare fishing locations recorded by means of GPS and port interviews, we calculated the Euclidean distance between reported locations and the centroid of the FO visited by the same boat on the same day. When the number of FOs visited exceeded the number of locations identified in the port interview maps, we used the distance to the nearest FO.

Mapping fishing intensity

Fishing intensity was mapped following two approaches.

Discrete approach

Daily diving area and the area of each FO identified were estimated by superimposing a 5 m × 5 m grid on the 67 mapped tracks using ArcGis 9.2 software, and counting the number of GPS recordings per grid cell. A larger grid size, 15 m × 15 m, was used for comparative purposes. Grid sizes were selected considering the average distance between recordings: 2 m for the 5 s polling frequency and 11.4 m for the 1 min polling frequency. Daily diving area by boat and FO was calculated as the sum of 25 m^2 grid cells that contained at least one diving record (irrespective of polling interval). The total number of cells fished over all monitored trips was used to calculate the surface of each FO, defined as the "positive area" (Woillez *et al.*, 2007).

Continuous approach

The intensity of effective fishing effort within the largest FO (FO 7) was calculated by combining all GPS recordings classified as "diving" from 12 monitored visits to that FO. The intensity function was estimated using a fixed-bandwidth Gaussian kernel estimator (Diggle, 1985) implemented in the R package SPATSTAT (Baddeley and Turner, 2005) using a cell size of 25 m^2; the standard deviation was set to 6. The contour of the FOs and their area was determined using an intensity cut-off of 0.04 m^{-1}, equivalent to one GPS record per cell.

Concentration curves

The spatial distribution of fishing effort (number of GPS recordings classified as "diving" per grid cell) was examined using concentration curves (Orensanz *et al.*, 1998; Petitgas, 1998), which relate the cumulative distribution of effort intensity (for cells ranked from high to low effort) and the corresponding occupied area. Only tracks with 5 s polling intervals were considered (40 tracks). The "space selectivity index" (Ssp), defined as twice the area between the curve and the identity function, was used as an index of concentration (Petitgas, 1998).

Analysis of catch and effort data

Trends over the recorded period and differences among boats in daily diving time, area, and CPUE were tested by fitting linear models. Explanatory variables were fishing day (treated as continuous) and boat identification (treated as factor). The four boats were considered for evaluating differences in daily diving time, while only the two boats for which GPS recording was made at 5 s intervals were used for comparing daily diving area. A series of stepwise *F*-tests were conducted starting from the full model that included the interactions [boat × fishing day]. Pairwise comparisons between boats were done using *t*-tests with pooled s.d., applying Bonferroni's correction. Estimation of daily catch by FO was obtained from port interviews and market records when boats visited only one FO (29 tracks), or when catch in each FO was recorded separately in the port interviews (5 tracks). When a boat visited more than one FO in a day and only total daily catch was available from fish market records or port interviews (13 tracks), the total catch was apportioned to each FO in proportion to the diving time spent in the FO. The CPUE by FO was estimated only from complete tracks with known catches (32 visits to 14 FOs), i.e. excluding those estimated by apportioning the daily catch in proportion to diving time. Also excluded were eight visits corresponding to four tracks considered atypical due to changes in the usual number of divers. Statistical analyses were conducted using the R software, version 2.12.1 (http://www.r-project.org).

Results

Partitioning of fishing effort

As expected, speed during diving time estimated from tracks with a polling frequency of 5 s (average: 1.44 km h^{-1}, $n = 40$ tracks) was higher than that calculated with a 1 min polling frequency (average: 0.68 km h^{-1}, $n = 20$ tracks). Irrespective of polling frequency, alternation of travel (high speed) and diving (low speed) activity was generally apparent in plots of boat speed vs. time along a track (Figure 2). Based on inspection of speed frequency distributions, a cut-off point of 6 km h^{-1} was selected to differentiate between "diving" and "travel" speeds (Figure 3a). For a

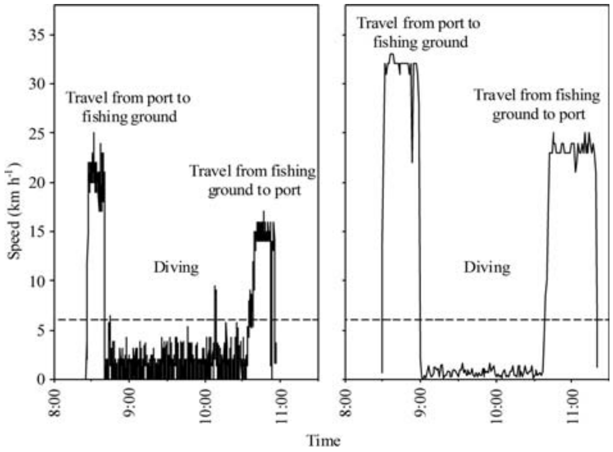

Figure 2. Speed (km h^{-1}) of Boat 1 during 2 d of the fishing season. Left: GPS recording with a polling frequency of 5 s (2 April 2007). Right: GPS recordings with a polling frequency of 1 min (23 April 2007). The horizontal dashed line corresponds to the 6 km h^{-1} cut-off speed used to separate travel from fishing activity.

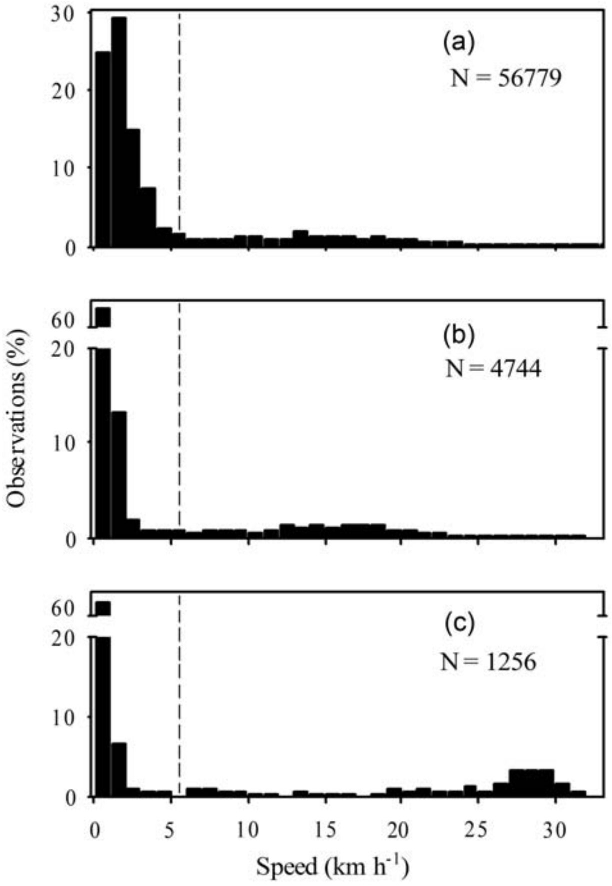

Figure 3. Frequency distributions of speeds calculated from the position of consecutive records. Top: Boat 2, 5 s polling frequency; middle: Boat 2, 1 min polling frequency; bottom: Boat 4, 1 min polling frequency. Vertical dashed lines indicate the cut-off speed (6 km h^{-1}) used to separate travel from fishing activity.

polling frequency of 1 min (Figure 3b, and c) a cut-off point of 3 km h^{-1} would have been better, but, as only 1.5% of the records had speeds between 3 and 6 km h^{-1}, for simplicity we used 6 km h^{-1} for all, regardless of polling frequency. Inspection of the results showed a few travel records that were erroneously classified as "diving" using this rule, and these were therefore reclassified. Those records originated when the boat was approaching or abandoning an FO (identified as a series of records with a straight course perpendicular or tangential to an FO), or slowing down in the presence of an obstacle. Boats travelled faster from port to the fishing grounds than during the return, when they were loaded with the catch (Figure 2). In cases where more than one FO was harvested on the same day, boats moved quickly between FOs.

On the basis of the tracks with complete travel and diving time ($n = 33$), average fishing time per boat (including travel and diving) was 3.10 ± 0.2 h d^{-1}, of which 2.16 h corresponded to diving time. The latter is comparable with the results obtained using all of the tracks with complete diving time (2.06 ± 0.74 h d^{-1}, $n = 47$). Average daily diving effort differed among boats ($F = 11.45$; d.f. = 3; $p << 0.01$, $n = 43$). The average daily effort exerted by Boat 2 [2.6 ± 0.14 (s.e.) h], the boat that operated with two divers, was close to 50% higher than that of the other boats (1.7 ± 0.11 h, pooled data), which did not differ among themselves. This result was consistent with Boat 2's 50% higher trip limit.

Estimated distance covered per diving time was shorter for low polling frequencies, as expected, because of trajectory tortuosity and measurement error. The average distance covered per visit to an FO was 2388 m (s.e. = 240 m, $n = 34$ visits) for tracks with a 5 s polling frequency, and 606 m (s.e. = 77 m, $n = 29$ visits) for those with a 1 min polling frequency. In contrast, there was little difference in the corresponding average Euclidean distance between the first and last record within an FO, which was 110.4 m (s.e. = 13.1 m) for a polling frequency of 5 s, and 94.6 m (s.e. = 14.2 m) for a polling frequency of 1 min.

Location, extension, and concentration of the identified FOs

A total of 35 FOs (Figure 4; Table 1) were identified. Total positive area (all FOs pooled) was 0.26 km^2, corresponding to 1.09% of the potential area (i.e. rocky bottoms shallower than 12 m). Most FOs were smaller than 1 ha (30 FOs); FO 7 was the largest, with an area of 5.54 ha (Table 1). Three FOs (1, 7, and 16) concentrated 46% of the effective fishing effort recorded; 19.5% corresponded to FO 7 alone. Cluster analysis grouped FOs into well-defined geographic clusters (Figure 4, bottom). Based on distance from port, most FOs belonged to three distinct strata (Figure 5a): 0–3 km (11 FOs), 5–7 km (16 FOs), and 16–20 km (7 FOs) (Table 1). Only one FO was in the range 8–15 km. FOs in the two groups closest to port contributed 79% of the catches and concentrated 77% of the total diving time of the period monitored. Most FOs were located in shallow zones, with a maximum depth of 5 m (25 FOs). Seven FOs had a depth between 6 and 10 m, and only three FOs were deeper than 10 m. FO 30 was located at 50 m depth according to the nautical chart; it was visited four times, with a total diving time of 3.1 h (Table 1). It is unlikely that harvesting could have been conducted at that depth, which suggests the possibility of a bathymetric feature not recorded in the cartography available.

The distance between fishing locations estimated by means of GPS and port interviews ranged from 48 to 3485 m. On 7 out of 16 fishing trips in which, according to the GPS data, several FOs

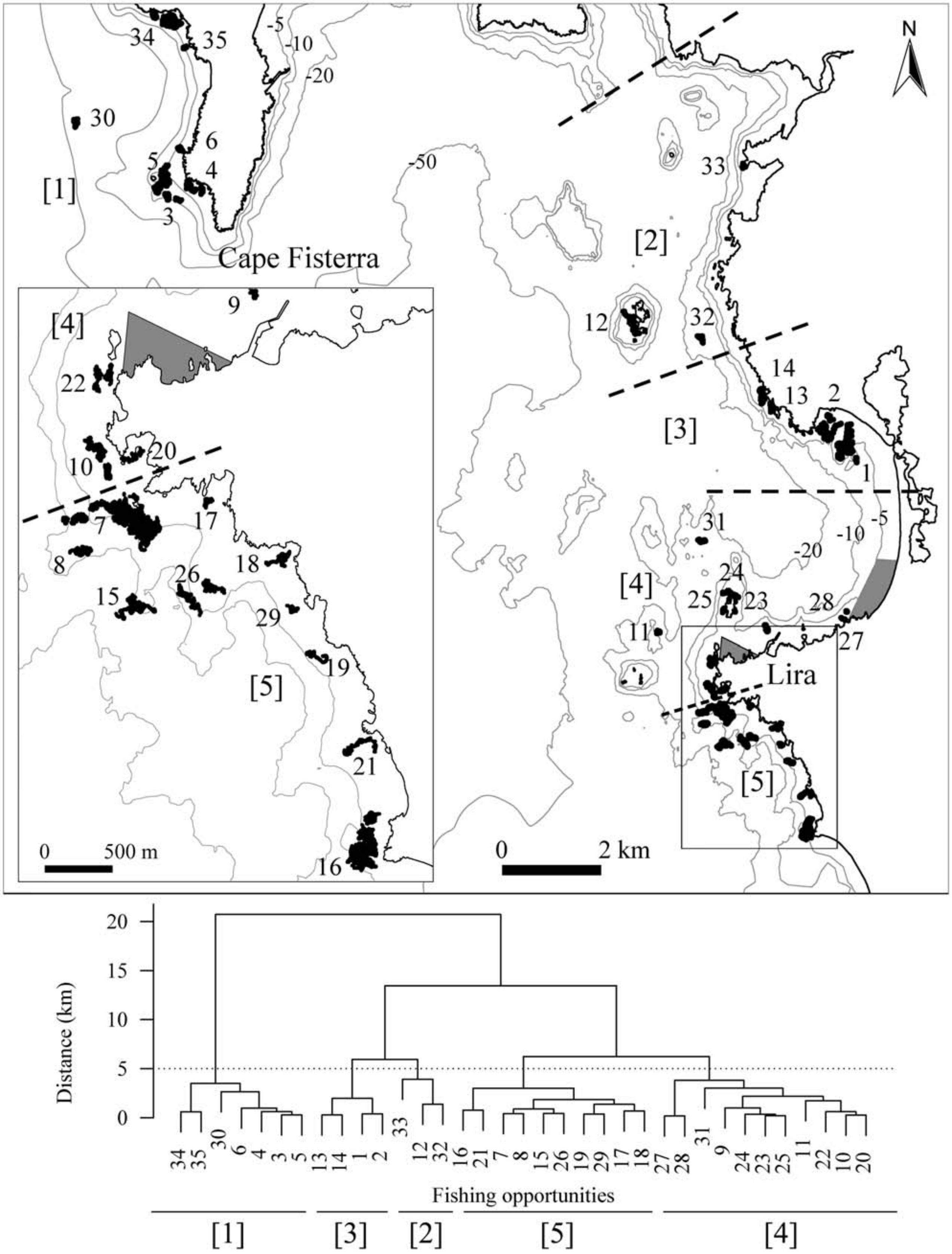

Figure 4. Top: fishing opportunities (FOs) identified in the study area, numbered in the order in which they were first visited during the recorded period. Bottom: cluster diagram of FOs (distance between centroids, in km); dotted line: cut-off point to define main clusters (numbers in brackets).

Table 1. General information on the FOs identified during the 2006–2007 fishing season.

FO	Depth (m)	Distance from port (km)	Visits	Positive area (m^2)	Diving time (h)	Concentration index (Ssp)	Catch (kg)
1	<5	4.3	8	24 725	13.2	66.0	1443
2	<5	4.7	3	7725	1.7	50.4	207
3	5–10	16.2	1	4075	1.7	49.3	150
4	<5	15.3	3	3075	2.4	25.7	315
5	5–10	15.7	7	23 475	10.6	50.5	1387
6	<5	16.5	1	1800	0.3	47.5	38
7	<5	4.5	12	55 350	24.0	49.6	2935
8	5–10	4.9	1	3775	0.6	41.0	71
9	<5	0.7	3	1825	1.2	53.8	285
10	<5	2.6	2	9425	2.9	49.3	357
11	5–10	2.9	1	1250	0.2	40.2	24
12	<5	6.9	4	10 325	5.6	50.7	677
13	<5	4.8	1	3525	1.0	47.6	120
14	<5	5.9	3	10 825	3.9	48.3	462
15	5–10	4.7	1	8050	1.9	47.8	450
16	<5	6.4	13	27 150	20.0	56.7	2640
17	<5	5.0	1	1450	0.5	48.8	59
18	<5	5.6	2	4250	2.2	59.4	338
19	<5	6.1	1	2175	0.4	40.9	46
20	<5	2.6	2	2225	2.3	–	160
21	<5	6.0	2	4225	2.4	–	297
22	<5	2.0	4	4100	3.9	–	766
23	<5	1.5	2	1775	1.3	53.2	133
24	<5	1.5	3	3575	2.0	–	237
25	<5	1.7	1	375	0.3	–	30
26	5–10	5.2	2	7775	1.6	35.7	195
27	<5	1.6	1	700	0.3	–	31
28	<5	1.7	1	450	0.2	–	30
29	<5	5.8	1	1125	0.3	–	39
30	>10	18.0	4	2400	3.1	–	383
31	>10	2.7	1	3100	0.9	42.6	160
32	>10	6.5	2	975	0.5	–	67
33	<5	10.8	1	775	1.0	–	126
34	<5	19.6	4	26 675	8.8	46.6	816
35	5–10	20.2	1	325	0.2	–	26

were harvested, fishers recorded a single location on the maps. Considering the magnitude of the errors and the size of the largest FOs, we conclude that locations recorded on port interview maps are not precise enough for a reasonable description of the spatial pattern of fishing intensity.

The use of the discrete and continuous approaches to characterize the pattern of allocation of fishing effort was illustrated with FO 7 (Figure 6). The two renditions of the pattern are comparable for any practical purpose. Fishing intensity tended to be highest towards the core of the region, fading at the periphery. The total surface estimated within the kernel contour corresponding to one count per cell (6.86 ha) was 24% larger than the surface estimated by simply counting the cells that contained at least one record (5.54 ha). This is a consequence of the kernel bandwith used (sigma = 6) which smeared the counts per cell eliminating all the internal empty cells observed in the discrete map (Figure 6, top). Concentration curves for the whole fishing area (positive area) show that ~80% of the records classified as "diving" were contained in 40% of the area (Ssp = 55.1%, Figure 7a). Concentration varied among FOs (Figure 7b), with FO 1 showing the most uneven distribution (Table 1). The pattern was not very sensitive to the two grids examined, as illustrated with FO 7 (Figure 7c). An increase in cell size from 25 to 225 m^2 resulted in a slightly lower concentration, but the change was not significant for any practical purpose.

Catch, effort, and CPUE

Differences in average daily catch among boats simply reflect trip limits imposed by regulation: 208.5 ± 3.1 kg d^{-1} for Boats 1, 3, and 4 (pooled), which had a 200 kg d^{-1} trip limit, and 316.0 ± 7.4 kg d^{-1} for Boat 2, which had a 300 kg d^{-1} trip limit. The daily diving time exerted by the four boats showed no significant trends over the recorded period (Figure 5b). All terms involving fishing day were dropped from the final model (F-tests not significant, $p > 0.56$). Daily diving area ranged between 1475 and 14 150 m^2, and no significant differences were detected either between Boats 2 and 3 (the only ones with complete tracks recorded at 5 s intervals; $F = 0.416$, d.f. = 1, $p = 0.527$, $n = 20$), or over the recorded period ($F = 0.19$, d.f. = 1, $p = 0.67$, $n = 20$).

The two highest CPUE values for a single trip (461.5 and 315.8 kg diver^{-1} h^{-1}) corresponded to the same boat and to FO 24, which was located at only 2 km from port; both were obtained towards the end of the season (days 41 and 42). This FO was visited four times by the same boat, but in the first two visits (on days 39 and 40) CPUE values were consistent with the average CPUE of the recorded period, and the tracks were comparatively longer and not

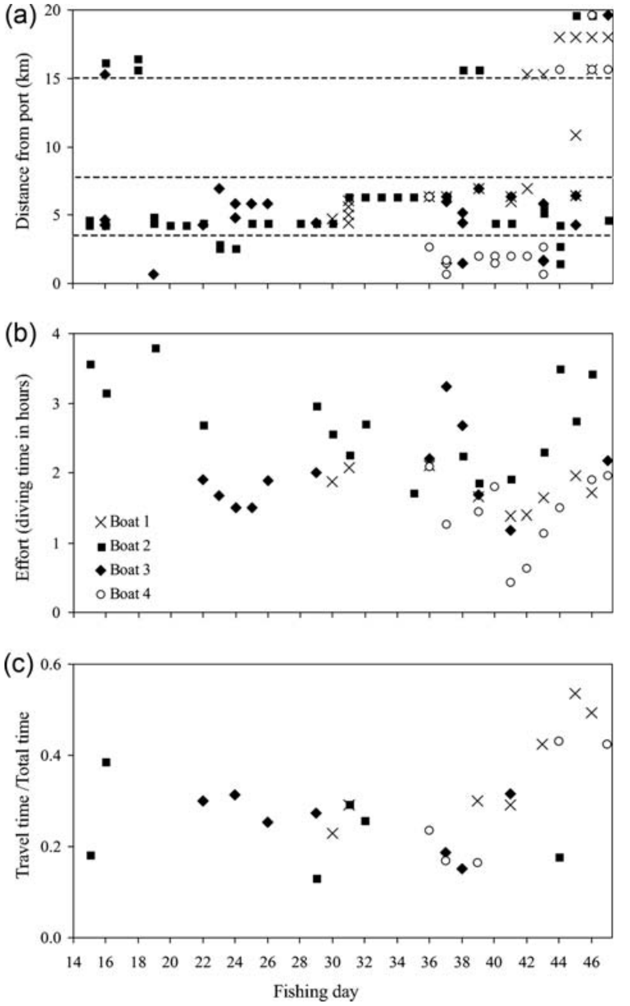

Figure 5. Patterns of effort allocation over the recorded period, by boat. (a) Distance from port (dashed lines separate groups of FOs defined by distance to port, see text); (b) effective fishing effort (diving time), in hours; (c) proportion of travel time as a fraction of trip duration.

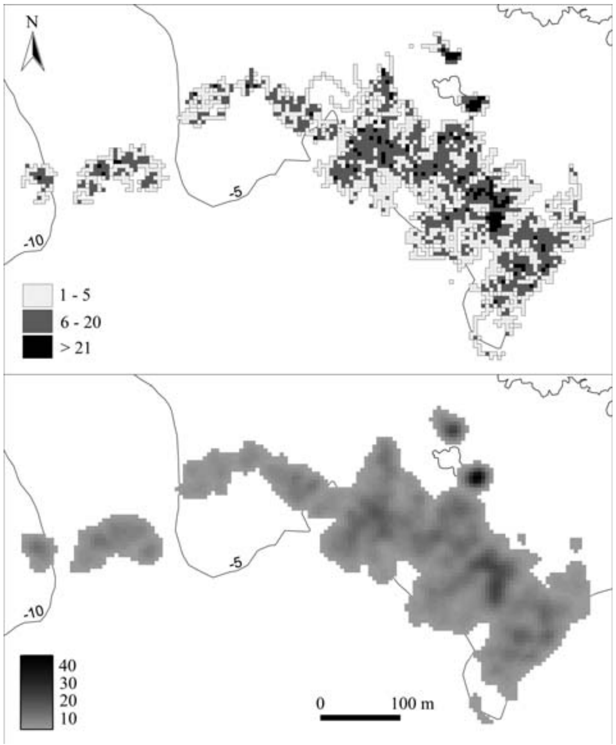

Figure 6. Distribution of cumulative fishing intensity within a fishing opportunity, illustrated with FO 7 (all tracks pooled). Top: discrete approach, number of GPS recordings per 25 m^2 cell. Bottom: continuous approach, intensity function.

overlapping with each other. The tracks of days 41 and 42 covered a small area and overlapped with each other. These two values (discussed later) were considered outliers and discarded for CPUE analysis. The analysis of CPUE over the recorded period indicated that neither the fishing day nor the boat, or their interaction, had a significant effect (Figure 8); all F-tests were non-significant ($p > 0.05$, $n = 30$). The overall average CPUE was 123.2 ± 5.4 kg $diver^{-1}\,h^{-1}$.

No trend was observed in CPUE in relation to the area fished per unit time (Figure 9a). In contrast, there was a non-linear decline in catch per area as the area fished per unit time increased (Figure 9b). In other words, when catch per unit area was high, fishers moved less.

The daily catch by boat and FO divided by the corresponding diving area varied between 0.018 and 0.231 kg m^{-2} (26 visits, 20 tracks), with a mean of 0.06 kg m^{-2}. Assuming an average weight of an individual sea urchin in the catch of 105.4 g (mean in the commercial catch for the 2006–2007 fishing season), this corresponds to an average of 0.57 individuals harvested per square metre.

While the cumulative catch per FO varied by a factor of 122 among FOs, the average CPUE based on visits with known catch (corresponding to 14 FOs) varied only by a factor of 2.3 (between 81 and 188 kg $boat^{-1}\,h^{-1}$). A linear relationship with a very high correlation was found between cumulative effective fishing effort (diving time) by FO and the corresponding cumulative catch ($r = 0.98$, $n = 14$), and between effort and the FO's positive area ($r = 0.96$). Cumulative catch per unit area, in turn, varied by a factor of 9.9, from 0.0189 to 0.187 kg m^{-2}, corresponding to a range of 0.18–1.77 sea urchins caught per square metre.

Fleet behaviour

During the recorded period, the daily activity of each boat was normally concentrated on a single FO (29 tracks), although it was not uncommon for boats to visit two or three FOs in a single trip (11 and 6 tracks, respectively); one of the trips visited four FOs in a single day. Twenty FOs were visited more than once during the recorded period (Figure 10; Table 1). Most FOs were harvested by only one boat (20 FOs), while only FO 16 was harvested by all boats (Figure 10). Each boat visited an average of 14 ± 3.8 FOs during the recorded period. The rate of addition of FOs to the pool of visited FOs during the recorded period was rather constant (Figure 10), with a slight tendency to a higher that average rate of addition at the beginning (days 14–26 of the fishing season). Average CPUE was not related to distance to port. Distant FOs, located between Capes Fisterra and Nave (northern boundary of the fishing zone), were harvested towards the end of the fishing season; 15 out of 21 visits took place during the last 6 d of the season. Correspondingly, the proportion of travel time increased

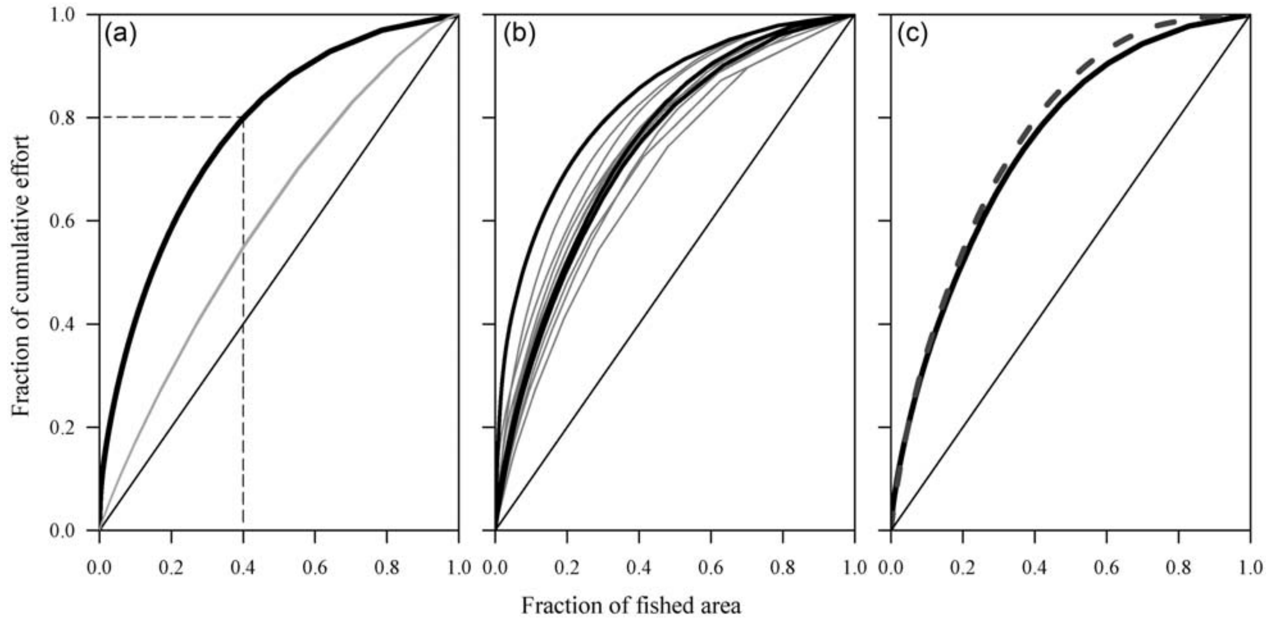

Figure 7. Concentration curves (records obtained with a polling frequency of 5 s). (a) All fishing opportunities (FOs) combined (25 m^2 cells): diagonal, uniform distribution of fishing effort; grey band, random distributions of fishing effort (100 simulated realizations); solid line, actual observations. (b) Same data as (a), FOs not pooled; thick lines highlight the three FOs that concentrated most of the effort (1, 16, and 7, shown in that sequence from high to low concentration). (c) FO 7, 25 m^2 cells (dashed line) and 225 m^2 cells (solid line).

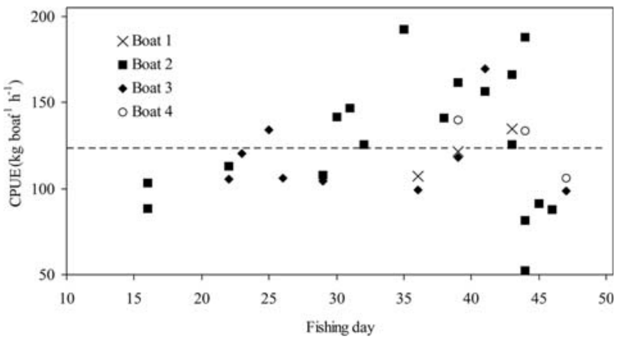

Figure 8. Trend of daily CPUE (kg $diver^{-1}$ h^{-1}) over the recorded period. The horizontal dashed line indicates the overall average.

towards the end of the season (Figure 5c). The shift to distant areas was not accompanied by an increment in CPUE that would compensate for the cost of extra travel. Interviews with fishers (I. Naya, pers. comm.) indicated that seasonal proliferation of algae, which makes sea urchin harvesting difficult, occurs earlier (around March, late in the season) in FOs closer to port (Lira) than in those between Capes Fisterra and Nave.

Serial depletion and CPUE at the scale of a single FO

The pattern of distribution of fishing effort within an FO was well illustrated by analysis of the successive recorded visits to FO 7, the largest identified FO. The majority of these visits (except for visits 7, 9, and 10) were by Boat 2. Intensity functions were fitted to individual visit data as well as to the cumulative effort data prior to each visit, and contours were determined using an intensity cut-off of 0.04 m^{-1}, as before. The plot of cumulative and daily contours shows that each new visit (with the exception of visit 6) covered regions located in the periphery of the cumulative area harvested during previous visits (Figure 11). The result was a gradual area expansion of the FO over time; the trajectory of cumulative area was only slightly concave (Figure 11, bottom left). CPUE did not indicate depletion in the six visits for which full information

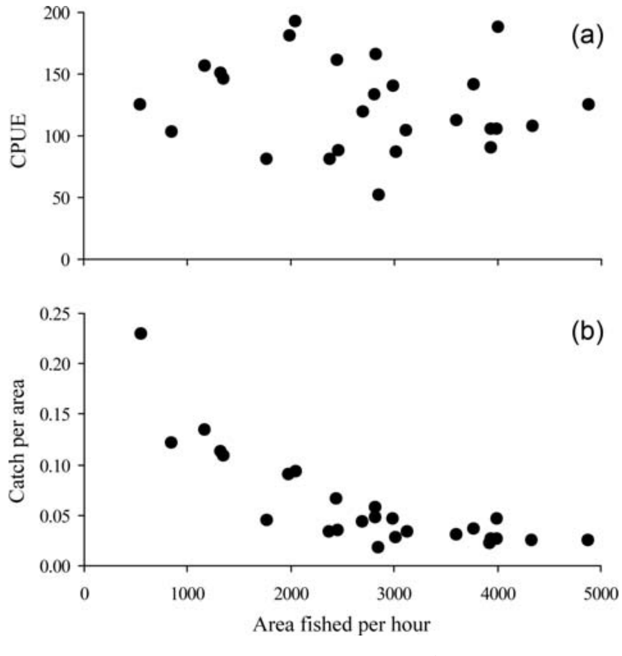

Figure 9. Relationship between CPUE (kg h^{-1}) and area fished per hour (m^2 h^{-1}) (top), and between catch per unit of area (kg m^{-2}) and area fished per hour (bottom). The latter was estimated as the number of 25 m^2 cells that had at least one GPS diving record. Each point corresponds to a daily visit to a FO.

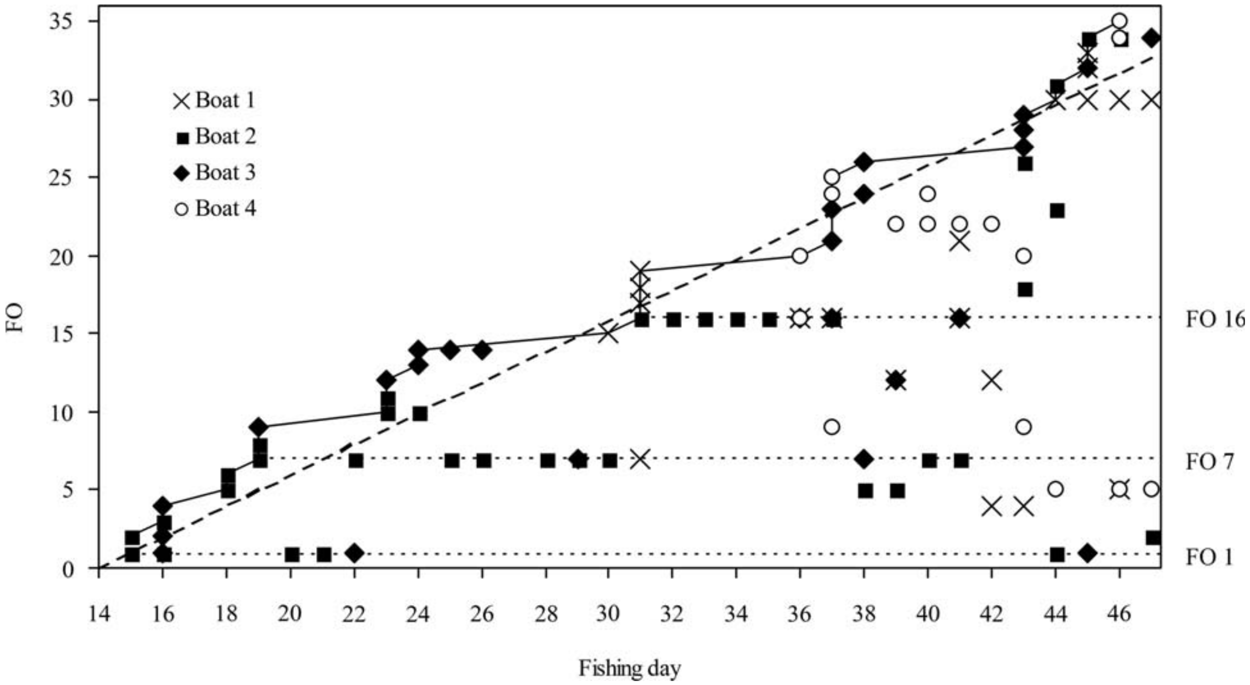

Figure 10. Fishing opportunities visited by the fleet over the recorded period. The solid line connects first visits to FOs; the dashed line corresponds to a first-visit rate of one FO per day. Dotted lines highlight the three FOs that concentrated most of the effort.

was available (Figure 11, bottom right), a result that is consistent with a pattern of serial harvesting.

Discussion

Fishing intensity

Tracking boat trajectories with GPS-based data loggers, an inexpensive technology, allowed characterization of patterns of fishing intensity at a hierarchy of spatial scales. Profiles of boat speed were used to partition trajectories and fishing time into their travel and effective fishing components, as has been also done in previous studies employing GPS (Marrs *et al.*, 2002) or VMS (e.g. Gerritsen and Lordan, 2011). GPS and data loggers have been used before to investigate patterns of spatial fleet behaviour in the artisanal sea urchin fisheries of southern Chile (Barahona *et al.*, 2005, their fig. 11; Molinet *et al.*, 2008, their figs 9.13–9.18).

In the case of commercial diving, fishing locations recorded by GPS at regular intervals can be considered “pseudo-events” (points in a continuous bi-dimensional spatial process), and their spatial distribution pattern can be used to map fishing intensity. To that end, discrete and continuous approaches allowed the identification and clustering of FOs. The discrete approach is the most frequently used (e.g. Harrington *et al.*, 2007; Mills *et al.*, 2007; Gerritsen and Lordan, 2011). Continuous kernel estimators have been used to map fishing intensity in scallop dredge or trawl fisheries, and abalone diving fisheries (Harrington *et al.*, 2007; Bogazzi, 2008; Buxton *et al.*, 2011). The continuous approach analogue to cell size is the bandwidth, a parameter that can be fine-tuned, e.g. considering the width of the strip visually scanned by divers. In addition to the bandwidth, the size of the estimated positive area depends on the choice of cut-off point used to bound FOs; we set it at an intensity of $0.04\ \mathrm{m}^{-1}$, equivalent to one GPS record per $25\ \mathrm{m}^2$, the cell size used in the discrete approach. That cell size, in turn, is commensurate with the area visualized by a diver at a fixed location. The discrete approach has the advantage of being easier to implement and more understandable by non-academic users, particularly with regards to decisions made in the analysis (e.g. cell size vs. bandwidth or cut-off points). Besides, the continuous approach tends to smooth the internal pattern of effort allocation within FOs and to inflate the positive area. The approach was, however, useful for the detection of intra-FO shifts in effort allocation, discussed later.

Caution is needed in the interpretation of identified FOs. While they reflect resource abundance (fishers do not fish where there is nothing to be fished), their location and extension also depend on a fisher’s knowledge, location-specific factors (depth, exposure to weather, distance from port), and resource quality (e.g. size or gonad condition). In a sense, FOs map abundance as perceived by fishers, weighted by factors determining suitability (Walters *et al.*, 1993). FOs are not static: as shown for FO 7, they change in the short term as cumulative effort accrues, and may shift from year to year depending on the local dynamics of the resource. Long-term changes in FO location and extension are a potentially valuable indicator of resource status (Mundy, 2005). One drawback is that, unlike other indicators (e.g. CPUE), mapping of fishing intensity requires complete information.

Concentration curves, mostly used in fishery science to describe aggregated patterns of abundance (Myers and Cadigan, 1995; Orensanz *et al.*, 1998, 2004; Petitgas, 1998; Tamdrari *et al.*, 2010), were explored in this study to characterize patterns of effort allocation. An analogous approach was employed previously to investigate changes in effort concentration over time in the sea urchin fishery from southern Chile (Barahona *et al.*, 2003, their figs 4.26–4.28, as “rarefaction curves”; Moreno *et al.*, 2006, their fig. 3.7). In that case, expansions and contractions of effort concentration were interpreted as indicative of changes in resource abundance.

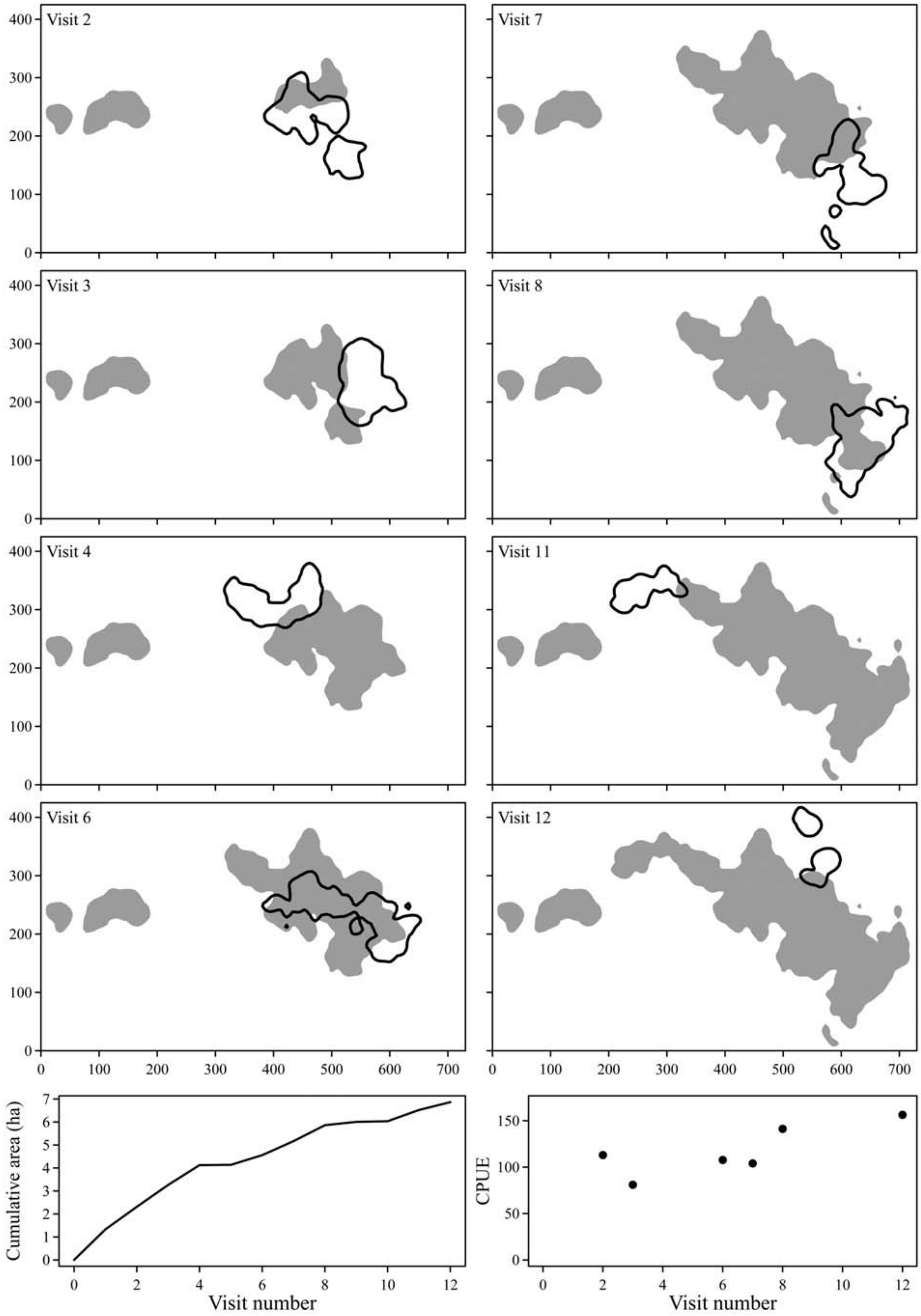

Figure 11. Area fished during successive visits to FO 7 (kernel estimator). Black contours in the eight top panels bound the area fished during selected visits (visits 5, 9, and 10 were of little significance and are omitted for clarity); shaded polygons correspond to the cumulative area fished prior to each of those visits. Bottom left: cumulative area of FO 7 over successive fishing visits. Bottom right: CPUE (calculated only for trips with complete information).

While GPS technology proved a cost-effective tool in the analysis of fishing intensity, there are some due warnings regarding its use. Travelled distance estimated from GPS records can be overestimated because of linear interpolation error (e.g. Deng *et al.*, 2005, their fig. 4), and in the case of high polling frequency (<40 s) and low speeds (<1 m s^{-1}) because of GPS error (Palmer, 2008). In our study, target polling frequency was 5 s and the corresponding average speed during fishing operations was 0.4 m s^{-1}. Differences observed in the speed and distance travelled while fishing, calculated with two polling frequencies, may be due to both sources of bias. The cells used to map effort allocation were small (25 m^2) relative to the accuracy of the GPS (<15 m RMS), meaning that the real location of a record may often correspond to neighbouring cells. For that reason we expect maps of fishing intensity to be slightly "jigged". Using a larger cell size would ameliorate this problem, but would create others which we find less desirable. Increasing the cell size from 25 to 225 m^2, for example, led to a doubling of the estimated positive area. While GPS error is a serious concern when CPUE refers to catch per area swept by discrete trawl or dredge hauls, it does not affect the estimation of diving time, the effort unit used in diving fisheries.

Catch per unit of effort

While CPUE is the most widespread fishery-dependent index of abundance, its shortcomings for the assessment of benthic fisheries have been repeatedly acknowledged (Hilborn and Walters, 1992; Orensanz and Jamieson, 1998; Buxton *et al.*, 2005; Mundy, 2005). The main reason is hyperstability (abundance dropping faster than CPUE) due to serial spatial depletion. The lack of a significant intraseason decline in CPUE observed in our study, as well as in other sea urchin fisheries (Miller and Nolan, 2008), is a manifestation of this problem. CPUE was stable at the scale of individual FOs, while positive area increased through successive visits. Divers stop operating in an area if they perceive (based on experience) that they will not meet their catch expectations. Being visual predators, they perceive depletion before its effects become apparent in the data, leading to a relatively high CPUE threshold for deciding when to move to another location (Gorfine and Dixon, 2001). Saturation related to handling time (discussed later) may also contribute to CPUE stability. Contrary to intuitive expectations (Prince and Hilborn, 1998; Mundy, 2005), the short-term (e.g. intraseason) performance of CPUE as an indicator of resource depletion may not improve by "zooming in", i.e. by refining the spatial scale of collection and analysis of information on catch and effort.

While within-season trends in CPUE were generally uninformative about depletion, even at the smallest possible spatial scale, CPUE may be informative about long-term trends in abundance, and contrasts in stock status across regions. Interviewed fishers unanimously indicate a significant drop in CPUE over the last decade (I. Naya, pers. comm.). Monitoring CPUE and effort allocation across seasons using the approach explored in this study should allow assessment of depletion trends. Tracking catch and effort across years and at small spatial scales has proven informative in other diving fisheries (Keesing and Baker, 1998; González *et al.*, 2006) even when a strictly linear relationship between local abundance and CPUE is unlikely.

Alternative indicators of stock abundance have been proposed in order to overcome the limitations of CPUE. The ratio between search and fishing time, for example, has been suggested as an index to describe stages in the development of a fishery (Caddy, 1979). Handling time is expected to be relatively more important at early stages, whereas searching time is expected to increase as the resource is depleted. In our case, divers had a good knowledge of the location of FOs, investing little time in exploration even though the stock is acknowledged to be depleted.

The identification and mapping of FOs via the analysis of fishing tracks, and the quantification of their surface (i.e. positive area), allowed for the calculation of an alternative, intuitively suitable index of local abundance: cumulative catch per unit of area. Catch per area has been proposed as an index of abundance for other diving fisheries, such as the California sea urchin fishery (Schroeter *et al.*, 2009) and the Tasmanian abalone fishery (Mundy, 2005; Buxton *et al.*, 2011). In those cases, catch per area was based on single diving events, analogous to catch per tow in a trawl and dredge fishery. In the latter, standard CPUE indices, measured in catch per hour or catch per tow, are reflective of catch per area swept; no such direct link between catch per time and catch per area can be established in diving fisheries. Catch per diving time ($=$ CPUE) and catch per unit of area may be very different indices depending on the correlation between diving time and effective area fished. An inverse relationship between CPUE and diving area per hour was shown for Tasmanian abalone (Buxton *et al.*, 2011) and interpreted as an increase in search time at lower densities. Such a relationship was not observed in the Galician sea urchin fishery; instead we found an inverse relationship between catch per area (in a visit) and positive area covered per hour of diving. This pattern may indicate that fishers stay longer in high-density patches (cells), which produce higher catches, even if their CPUE is not affected. Hyperstability would be, to some extent, a result of catch rate "saturation" due to handling time, which may effectively constrain divers' CPUE. This factor may be less important at current resource levels; fishers report much higher CPUEs obtained in the past (I. Naya, pers. comm.). Another compensatory factor is that divers may swim faster when density is lower while maintaining a reasonably constant catch rate. In these cases, cumulative catch per unit of positive patch area would be a better index of local density than either CPUE or catch per area in a single diving event. While still at a research stage, this is a direction in which we expect that increased availability of fine-scale effort data will open up new possibilities for the monitoring of diving or hand-gathering fisheries. The main promise of the approach resides in its possible use to support the implementation of strategies that are less dependent on estimates of fishing mortality and biomass (e.g. rotation or reserves).

Fleet behaviour

Cumulative catch and effort by FOs were linearly related, indicating little contrast in average CPUE among FOs. This was to be expected should fishers behave according to the Marginal Value Theorem (MVT; Charnov, 1976; Hilborn and Kennedy, 1992). For fishers to maximize profits, they should concentrate first on the most suitable FOs, subsequently reallocating effort as FOs are depleted. Consequently, at any given point in time, CPUE would be equal among all the FOs being harvested. The pattern of serial harvesting observed, exemplified by zooming into one FO, together with an absence of decline in CPUE over successive visits, indicate that the process of depletion does not necessarily result in a gradual decrease in suitability as local abundance decreases. Rather, CPUE may fluctuate without trend until the patch is depleted and the FO is abandoned. The lack of contrast in CPUE among FOs may still reflect some degree of fishery-induced equalization of densities, but operating at interannual time-scales.

While CPUE must be a significant driver of fleet behaviour, anomalies in trends allowed the identification of factors, other than perceived abundance, that affect FO suitability, and may in turn contribute to conceal depletion. First, a shift to distant areas at the end of the season was driven by the timing of algal proliferation. Second, the two highest CPUE values were registered at only 2 km from port, towards the end of the season; corresponding tracks covered a small area and overlapped with each other. The likely reason is that fishers "stored" underwater catches exceeding the daily quota. This is a frequent practice in many S fisheries, a way to reduce costs while adjusting to landing regulations.

Implementation

One limitation of the use of indices incorporating positive fished area and cumulative catch per area is that they require complete records of both effort and catch at a fine scale. GPS records provided detailed information on the spatial distribution of fishing intensity. Complementation of GPS tracking with voluntary logbooks (e.g. Marrs *et al.*, 2002) is not a realistic proposition in our case because the small size of the boats makes on-board recording difficult. A combination of information on effort retrieved from GPS recorders and on catch from port interviews may be the best option to implement a monitoring programme in this and other small-scale benthic fisheries. Monitoring has been based solely on port interviews in other sea urchin fisheries, e.g. from British Columbia (Campbell *et al.*, 2001; Perry *et al.*, 2002) and Nova Scotia (Miller *et al.*, 2008). We found that port interviews, by themselves, are not appropriate to identify the location and extension of fishing grounds with the precision required to construct spatially explicit indicators of abundance such as those discussed earlier.

Implementation of a monitoring programme incorporating GPS recording and port interviews would require the assistance of trained practitioners at the level of the confrarías. Such practitioners would fit the profile defined for "barefoot ecologists" (Prince, 2003, 2010; Ernst *et al.*, 2010). In Galicia, there is a formal figure that matches that role: "technical assistants", usually biologists whose services are retained by the confrarías and subsidized by the regional fishery authority. The design of a monitoring system should include the training of technical assistants on the specifics of data gathering and basic tools of analysis, a specific version of the toolbox envisaged by Prince (2003).

Supplementary material

Supplementary material available at the *ICESJMS* online version of the paper provides additional information on the sea urchin fishery of Galicia and details about field work.

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