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Spatial distribution and demography of the green sea urchin, *Strongylocentrotus droebachiensis*, around Île Blanche and the eastern tip of Île aux Lièvres (Quebec) in 2011

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

A benthic imagery survey was conducted in August 2011 between 2 and 18 m depth around Île Blanche and the eastern tip of Île aux Lièvres in the Upper St. Lawrence Estuary. The objective was to characterize the bottom and measure the abundance and size structure of the green sea urchin, *Strongylocentrotus droebachiensis*, in order to estimate the legal biomass in the area on the south side of these islands where commercial fishing occurs (Area 8). The conversion of the numbers and sizes of urchins measured by imagery into biomass was based on a weight-length relationship derived from green sea urchin samples collected using scuba diving on both sides of the islands. Bottoms less than 4–5 m deep including the passage between the two islands, supported seagrass beds with abundant kelp. The density and mean size of legal-size green sea urchins (≥ 50 mm) were higher on the north side than on the south side of the islands. Between 2008 and 2011, fishing on the south side was concentrated in a territory of 0.794 km^2, in which the survey showed a fairly high mean abundance of legal-size sea urchins (about 15 individuals per m^2). The maintenance of high densities of sea urchins in this territory could be explained by a more favourable environment for growth due to a fairly regular influx of macroalgae from the passage between the two islands. It is also possible that this territory is supplied by a sporadic influx of large sea urchins from the north side via the passage between the two islands as a result of storm surges combined with strong tidal currents. Sea urchins of non-legal size, quite abundant near this fishing territory, represented a potential recruitment. The biomass of legal-size green sea urchins in the fishing territory on the south side was estimated at 1,233 ± 311 t.

INTRODUCTION

BIOLOGICAL SYNOPSIS

The green sea urchin, *Strongylocentrotus droebachiensis*, is an echinoderm that abounds in all boreal and arctic marine regions. On the east coast of North America, its distribution extends from Cape Cod in the United States to the Canadian Arctic Archipelago (Scheibling and Hatcher 2001). The green sea urchin prefers to live on hard substrates (bedrock, stones, rocks and gravel) in the subtidal zone, generally between 0 and 50 m depth, but is sometimes found on soft bottoms (Scheibling and Hatcher 2001) up to 300 m depth (Jensen 1974). In Quebec, the green sea urchin is found in great abundance in the maritime parts of the territory, including the areas of the St. Lawrence Estuary where salinity is greater than 15‰ (Himmelman et al. 1979, 1984; Lavergne and Himmelman 1984; Pelletier and Gauthier 2002). This value of 15‰ corresponds roughly to the green sea urchin's lower tolerance level to hyposalinity, which averaged 16.3‰ in seven different studies (range 14–21.5‰; Russell 2013), and will therefore be used as the critical salinity threshold for green sea urchin survival.

The green sea urchin is currently exploited only for its gonads, considered a great delicacy. Exploitation of this species is therefore dependent on its breeding cycle. The green sea urchin has separate sexes, but it is impossible to differentiate males from females by their external appearance or by the appearance of their gonads. Therefore, both sexes are fished. There are five gonads, with size and weight varying greatly during the breeding cycle. In the St. Lawrence Estuary, the gonads increase in size and weight during the fall, reaching their maximum at the end of winter (up to 25% of the individual's weight). Spawning takes place in May or June depending on the location, and generally the gonad weight remains below 10% of the individual's weight throughout the summer (Himmelman et al. 1979, 1997; Starr et al. 1993). Therefore, the period between September–October and between April–May is most interesting for green sea urchin exploitation in the Estuary (Himmelman et al. 1997).

At the time of egg-laying, the gametes of the green sea urchin are released into the water column and fertilization takes place in free water. The first life stages of the green sea urchin are pelagic larvae, a life phase that lasts between one and four months. Subsequently, the larvae settle on the bottom and metamorphose into juveniles with an initial test diameter (i.e. the diameter of its calcareous shell excluding the spines, a measurement hereinafter simply called diameter) of about 0.5–1.0 mm (Scheibling and Robinson 2008). The rate of growth after benthic deposition is highly variable and depends on the physical environment and the availability of quality food (e.g. Blicher et al. 2007). In the St. Lawrence Estuary, sexual maturity is reached at about 3–4 years of age when the diameter is about 25–30 mm (DFO 2008a). The legal size of 50 mm in diameter is reached around the age of 5–7 years (DFO 2008a). However, these age estimates should be considered with caution as recent work indicates that the current sclerochronology age determination technique is marred by uncertainties (Narvaéz et al. 2016).

The green sea urchin is considered trophically as an opportunistic generalist that feeds on whatever is available in its environment, but with a strong preference for certain macroalgae (Himmelman 1969; Lawrence 1975; Scheibling and Hatcher 2001). Among the macroalgae present in the Estuary and Gulf of St. Lawrence, the green sea urchin is particularly fond of certain brown algae including *Alaria, Chordaria, Saccharina*, *Laminaria* and *Petalonia*, as well as the green alga *Ulvaria* (Vadas 1977; Larson et al. 1980; Himmelman and Nédélec 1990; Lemire and Himmelman 1996). Kelp is particularly valued because it can be abundant and is easy to detect chemically, while being highly digestible and nutritious (Scheibling and Hatcher 2001). The brown alga *Agarum* and red algae (with the exception of a few species such as *Chondrus crispus* and *Coralina officinalis*) are rarely consumed and are even avoided by the green sea urchin if other food sources are available (Vadas 1977; Himmelman et al. 1979; Larson et al. 1980; Himmelman and Nédélec 1990; Lemire and Himmelman 1996). The brown alga of the genus *Desmarestia* and most of the fucales are, for their part, generally little or moderately appreciated (Himmelman and Nédélec 1990; Scheibling and Hatcher 2001). In the absence of its preferred food, the green sea urchin can survive by feeding on the algae it usually ignores, or on a wide range of foods from microbial film to live or dead animal prey (e.g. sponges, mussels, barnacles, bristle worms, gastropods, etc.), including its own species (Lawrence 1975; Scheibling and Hatcher 2001; Fournier and Cartier 2006; Dupont and Himmelman 2008).

However, body growth and gonad development in sea urchins are closely related to the quantity and quality of available food (Himmelman 1978; Jong-Westman et al. 1995; Minor and Scheibling 1997; Meidel and Scheibling 1999; Brady and Scheibling 2006). Experiments performed by Vadas (1977), Larson et al. (1980), Lemire and Himmelman (1996) and Fournier and Cartier (2006), among others, demonstrated that kelp in particular favoured very good somatic and gonadal growth in the green sea urchin. Himmelman et al. (1997) also reported that the highest gonadal indices in nature were measured on individuals living near a *Laminaria* bed, while the smallest gonads were measured on individuals living on a bottom of fine sediment or having access only to poor quality algal food (e.g. *Agarum cribrosum*).

FISHERY

Because winter fishing is limited or prevented by severe weather and ice, harvesting of green sea urchin occurs primarily early in the spring before egg laying and in the fall. In Quebec, two harvesting methods are allowed: scuba diving or whelk traps. The use of towed fishing gear is prohibited except within aquaculture sites where the Ministère de l'Agriculture, des Pêcheries et de l'Aquaculture du Québec (MAPAQ) authorizes the use of a small dredge. Some management measures are in effect for the green sea urchin. First, a minimum legal size of 50 mm in diameter is imposed. Second, there is a limited number of fishing licenses per area and a limited number of divers or traps per license. Divers are limited to five per boat. Traps are limited to 100 per boat and must have a maximum volume of 0.5 m^3, a minimum mesh size of 102 mm and four escape vents with a diameter of 44.45 mm. Use of traps is prohibited from April to October or November, depending on the fishing area (DFO 2000, 2008a). Additional effort or catch control measures may be applied in some fishing areas.

The first landings of green sea urchins in Quebec took place in 1991 (7 t). Landings increased until 1997, reaching 159 t. Annual landings were subsequently below 25 t until 2000. An increase in annual landings was recorded from 2001 to 2005 (187 t), followed by a strong increase to 762 t in 2007. Subsequently, landings declined to 341 t in 2009, mainly because of greater control of the fishing effort, and then fluctuated between 516 and 687 t from 2010 to 2015 (DFO 2016). Since 2003, more than 90% of green sea urchin landings in Quebec have come from the St. Lawrence Estuary (DFO 2012, 2016).

The St. Lawrence Estuary is divided longitudinally along its centre into two green sea urchin fishing areas: Area 9 on the north side and Area 8 on the south side (Figure 1). A substantial portion of the green sea urchin landings in Quebec come from Area 9 (e.g. 689 t, or 91% of total landings in 2007) and more specifically from the Saguenay River mouth sector. Other parts of Area 9 have been exploited sporadically, including the Saint-Siméon region and the north side of Île aux Lièvres and Île Blanche, from which landings of about 10 t were obtained in 2003 and 2005 and about 20 t in 2004 and 2009 (DFO 2008a; Sainte-Marie et al. 2012). In Area 8, landings come from three main fishing sites located: (i) around the eastern part of Île Verte, (ii) around Île aux Pommes (northeast of Île Verte, not shown in Figure 1), and (iii) on the south side of Île Blanche and the eastern tip of Île aux Lièvres (DFO 2008a, 2012). Due to the limited number of fishers, landings from these three sites cannot be disclosed (DFO 2012).

BACKGROUND AND OBJECTIVES OF THE STUDY

Île aux Lièvres and Île Blanche, as well as Île aux Fraises and the Îles du Pot à l'Eau-de-Vie (Figure 1), are part of a 25 km-long shoal covering 1,400 ha, including 440 ha of tidal flats, which is integrated into the Saguenay–St. Lawrence Marine Park. This habitat is considered one of the most typical of the Lower St. Lawrence. Île Blanche is a protected area that is part of the Îles de l'Estuaire National Wildlife Area, which is also recognized as an Important Bird Area (IBA). It is a major gathering place for shorebirds during fall migration and the nesting site of a large colony of common eider, *Somateria mollissima dresseri* (IBA Canada 2012). Île aux Lièvres is owned by La Société Duvetnor, a private non-profit corporation dedicated to protecting the natural wealth of the St. Lawrence islands. According to the report submitted by Biorex Inc. (1999), the marine sector encompassing the eastern tip of Île aux Lièvres and Île Blanche is intensively frequented by beluga whales (threatened species), harbour seals and grey seals, and sometimes by harp seals, and is a foraging territory for several seabirds (black-legged kittiwake, northern gannet, razorbill, gulls, American black duck, golden-eye, long-tailed duck). Some of these birds are predators of the green sea urchin (e.g. eider ducks: Guillemette et al. 1996). The southern side of Île aux Lièvres and Île Blanche can also be an aggregation area for herring larvae between June and December (Fortier and Gagné 1990). This area is therefore part of an extreme protection zone because of its unique characteristics and its ecological importance.

The recent development of the sea urchin fishery south of Île Blanche and Île aux Lièvres, as well as the possibility of regular exploitation north of these islands, raise questions about the appropriate fishing effort for sustainable exploitation and full maintenance of ecosystem functions in this sensitive area. The primary objective of this study is therefore to provide answers by characterizing the habitat, spatial distribution, abundance, size structure (diameter) and biomass of the green sea urchin in this sector. We were also interested in a possible dynamic of passive movements of green sea urchins from north to south of Île aux Lièvres and Île Blanche due to strong storms, as suggested by some stakeholders in the fishery.

MATERIAL AND METHODS

SALINITY IN THE STUDY AREA

Salinity is a determining factor in green sea urchin distribution in the Upper St. Lawrence Estuary (Himmelman et al. 1984). Since salinity data specific to our study area were sparse and not continuous over time, we used the retro-predictions of the hourly salinity around Île Blanche over a full year from a coupled ocean-atmosphere model (Saucier and Chassé 2000; Saucier et al. 2009). The year 2005 was chosen as an example because of its good hydraulicity, and the mean salinity was calculated for three depth strata: 0–5 m, 5–10 m and 10–15 m (D. Lefaivre and A. D'Astous, MLI, pers. comm.).

SAMPLING AND ANALYSIS OF PHOTOGRAPHS

Between August 18 and 23, 2011, a survey of green sea urchin populations was conducted around Île Blanche and the eastern tip of Île aux Lièvres (Figure 2). Sampling was planned according to 13 transects (T5 to T17) perpendicularly intersecting the long axis of the islands, with the transects being separated from one another by a distance of about 500 m (Figure 2). T11 was flanked on both sides by a parallel transect 100 m away (T11 E and T11 W, Figure 2) in order to assess small-scale population variability in another study. Although the Estuary and the islands are oriented in a direction going roughly from southwest to northeast, by convention we considered the disjointed segments of a transect on one side or the other of the islands as belonging to the north side (Area 9) or to the south side (Area 8).

Weather and current conditions did not permit complete sampling of all transects (Figure 2). On the south side of Île Blanche and Île aux Lièvres, segments of all transects except T17 were sampled. On the north side, only the odd-numbered transect segments were sampled, except for T7. On each sampled transect segment, we filmed a bottom surface of approximately 0.34 m^2 (hereinafter referred to as a quadrat) at preset depths of 2, 4, 6, 8, 10, 12, 14 and 16 m (the depth always being in reference to the tide datum) and only once (on T5 south) at a depth of 18 m. The maximum sampling depth was limited by the length of the camera's cable, and the depth of 18 m could not be repeated on the other transects given the risk of losing the camera. The transects were sampled from offshore toward the shore, at the first occurrence of the targeted depth. Due to the strong currents at certain tidal periods, the sampling platform was sometimes swept off the target sampling position. On the south side, four additional quadrats were sampled at high tide in the T9 intertidal zone to assess the upper limit of sea urchin distribution and the extent of the kelp bed. Also on the south side, 30 additional quadrats were randomly added at depths between 3 and 10 m where fishing for green sea urchin took place from 2008 until the spring of 2011. Eight more random quadrats placed along the shallow passage between Île aux Lièvres and Île Blanche were surveyed at high tide (Figure 2).

Depths greater than 8 m were sampled from the parent ship CCGS *Calanus II*, while those at 8 m or less were surveyed from the *Macareux*, a semi-rigid inflatable boat that is also equipped with a GPS and a sounder. Additionally, variable bottom surfaces ($\leq$ 1 m^2) were sampled by divers at 4 and 8 m depth on the north side and 2 and 4 m on the south side of T11 (Figure 2). All green sea urchins found on and in the substrate were placed in dive bags with 2 mm mesh, brought to the surface and measured in diameter (without spines) to the nearest 0.1 mm using a caliper.

Footage was recorded using a Sony HD video camera (model HDRHC9) placed in a waterproof case and mounted vertically in a metal frame equipped with two lamps, the base of which was equipped with tensioned ropes forming a quadrat of about 45 by 75 cm, or 0.34 m^2 (Figure 3). The camera was connected by a cable to a surface monitor displaying the bottom in real time in order to ensure that the camera was stationary long enough for the sediments raised by deposition of the frame to dissipate and a sequence of sharp images to be obtained. The effective area recorded by the camera varied between 0.25 and 0.41 m^2 (overall mean 0.35 m^2) depending on the zoom used. While loading the camera in the waterproof case, the zoom button was accidentally pressed a few times, thus modifying the surface filmed on some video cassettes (see Appendix 1 for the calibration and calculation of the filmed surface). A sharp image was extracted from each filmed quadrat sequence, for a total of 222 images (quadrats), with 68 on the north side and 154 on the south side of the islands.

The nature of the bottom was characterized for each quadrat photographed or sampled using scuba diving. The types of physical substrate selected for the description of the bottom were determined by observation and measurement of the different sediment particles (rock, gravel, sand, etc.) represented on the images (Table 1). When present, macroalgae were identified by genus or species and the area covered by this biological substrate was estimated. Subsequently, the types of physical and biological substrates were grouped into different categories: the single type of substrate or the grouping of two or three types of substrate, accounting together for more than 70% of the bottom coverage, was retained to characterize the quadrat. Assessment of the surface (area) of the quadrats filmed and measurement of sediment particles were carried out using Image-Pro Plus 6.1 (Media Cybernetics Inc.) image analysis software after calibration (see Appendix 1).

In order to determine the density and size structure of the green sea urchins, the individuals visible in each of the quadrats filmed were counted and measured in diameter to the nearest 0.1 mm using the software Image-Pro Plus. All sea urchins appearing entirely in the images were considered; sea urchins on the margins of the image were considered only if their centre was visible (i.e. more than half of the individual inside the quadrat). It was possible to determine the edges of the test quite clearly, excluding spines, and to measure the diameter by adjusting the contrast and considering the limits of the ambulacral regions. The diameter was estimated in different ways according to three scenarios:

1) when a sea urchin was completely visible and positioned horizontally or vertically, the recorded diameter was based on the mean of three measurements, according to three different ambulacral regions when possible;
2) when a sea urchin was partially visible (on the edge of the image), the diameter was calculated by averaging the double of one to three measurements of the radius of a circle made from the centre to the approximate perimeter of the test;
3) when a sea urchin was at an angle other than vertical or horizontal, a combination of the two previous methods was applied and the mean of the estimated diameters was calculated.

The variation between "independent" diameter measurements obtained for the same sea urchin was less than 3.5 mm in 97.4% of cases.

Some quadrats had significant macroalgal coverage, which could hide sea urchins on the underlying physical substrate. In these specific cases, the density of green sea urchins in the quadrat was established as follows:

1) three quadrats (1.4% of the quadrats analyzed) were 30–60% covered, mainly by kelp and the green macroalga *Ulvaria*. In these three cases, the visible physical substrate was sand and no sea urchins were seen in the images. As sand is not a substrate favourable to sea urchins, density was established at zero for the total surface of each of these quadrats;
2) ten quadrats (4.5%) were 30–75% covered, mainly by tufts of red macroalgae with a foliaceous (*Phycodrys*) or filamentous thallus. The visible physical substrates consisted mostly of gravel, sometimes with sand, and no sea urchins were visible in the images. We considered that these types of macroalgae were not a preferred environment for sea urchins and the density was thus established at zero for the total area of each of these quadrats;
3) three quadrats (1.4%) were 25–50% covered, mainly by kelp, with small clumps of red macroalgae. The visible physical substrate was rocks, gravel and sand, and sea urchins were seen. For these quadrats, we subtracted the area covered by macroalgae from the total area of the quadrat and calculated the density relative to the remaining area;
4) eleven quadrats (5%) were 95–100% covered, mainly by kelp. The density of sea urchins was recorded as unknown, although one or more sea urchins were visible on the surface of the macroalgae. These quadrats were not considered in the mean sea urchin density calculations, but were indicated on the maps with distinct symbols.

In order to establish a diameter-weight relationship allowing the numbers and sizes of green sea urchins identified to be converted into biomass, an extensive range of green sea urchin sizes was collected by scuba diving at depths of 4 and 8 m in the north and south segments of T11 (independently of quadrats sampled by diving). These sea urchins were measured in diameter to the nearest 0.1 mm using a caliper, blotted and weighed to the nearest 0.1 mg fresh using a Mettler PE6000 scale.

DATA ANALYSIS

We mapped the spatial distribution of bottom types in the study area, as well as the fishing positions from the ZIFF files for 2008 to 2011. The main fishing ground was roughly delimited by establishing the outline of the territory where the fishing effort was concentrated and determining its area. For each quadrat, the density expressed as number of individuals per square metre (m^2) was calculated for green sea urchins of non-legal size (diameter < 50 mm), of legal size (diameter ≥ 50 mm) and of all sizes combined.

Size frequencies (structure) of green sea urchin were established for the north and south side of the islands by size classes of 5 mm in diameter, considering possible diameter measurement errors and uncertainty due to calibration of the image analyzer (see Appendix 1 for more details). Since size structures showed that green sea urchins were significantly larger on the north side than on the south side (see results), we explored the hypothesis of a displacement of sea urchins from north to south, by looking for a distinctive size "signature" at the eastern mouth of the passage between Île aux Lièvres and Île Blanche. For the purpose of this analysis, we defined a sub-area encompassing the quadrats located in front of the eastern mouth of the passage between the two islands (Figure 2). In addition, the abundance of green sea urchins ≥ 70 mm in diameter was mapped north and south of the islands.

A weight-length relationship for the green sea urchin was established for each side of Île Blanche using samples collected by scuba diving. The two relationships were compared in slope and y-intercept by analysis of covariance (ANCOVA), after logarithmic transformation (base 10) of the data. The weight-length relationship allowed the total biomass to be calculated for each quadrat by converting green sea urchin diameters into weights and summing them. Total biomass per quadrat was reported per square metre (m^2) and mapped for green sea urchins of all sizes combined.

Size frequency and weight-length relationship graphs for green sea urchins were made using Microsoft Excel 2002 (Microsoft Office, Washington, USA). Distributions of sea urchin density and biomass and of fishing effort were mapped using MapWindow Open Source 4.8.4 (Geospatial Software Lab, Idaho State University, USA), and the area in which fishing was concentrated was calculated using ArcGIS 10 (Esri, California, USA). All statistical analyses were performed using SYSTAT 12 (SYSTAT Software Inc., Washington, USA). The central trend statistics used in the document are the mean with its standard error and the median. Density and biomass expressed per m^2, as well as diameter, were compared between the two sides of the islands or between regions on one side of the islands using the non-parametric Mann-Whitney U test (median test).

RESULTS

DESCRIPTION OF THE STUDY AREA

The study area is characterized by a much more pronounced slope on the north side of the islands than on the south side (Figure 2). The area of the bottoms easily accessible by diving is therefore more restricted on the north side than on the south side of Île Blanche and the eastern tip of Île aux Lièvres. To the north of these islands, the bottoms were almost exclusively gravel or rock, while in the south they were predominantly gravel with a large patch of sand extending to the northeast, possibly continuously from the 5 m isobath at the eastern mouth of the passage between the two islands (Figure 4). Large rocks (> 20 cm) were uncommon and when present, they rarely covered the entire surface of a quadrat and were often contiguous to gravel.

The hourly salinity variation in the 0–5 m deep strata around Île Blanche and the eastern tip of Île aux Lièvres for 2005 is shown in Figure 5. In 2005, the study area experienced four episodes of mean salinity below the critical threshold of 15‰ for the green sea urchin, the most severe being from April 15 to 20, and the others being from May 2 to 4, from May 15 to 19, and from June 1 to 3 (Figure 5). Salinity dropped below 16‰ for 3 hrs on October 29 (15.3–15.8‰) and for 2 hrs on October 30 (15.7–15.8‰), but did not reach the critical threshold (Figure 5). From April 16 to 19, 2005, the mean salinity in the 0–5 m depth stratum was below the critical threshold of 15‰ for 58 hours out of a total of 96 hours (60.4% of the time), including five periods of 8–11 consecutive hours each. Salinity did not exceed 15.3‰ during the four interludes of 1–4 hrs between these periods of very low salinity. During 2005, mean salinity in the 5–10 m and 10–15 m strata remained above 15.7‰ and 16.4‰ respectively. The decreasing gradient of salinity from the deepest to the shallowest stratum indicates that salinity was definitely lower than the mean in the first 2.5 m of the 0–5 m stratum, with the opposite being true for the last 2.5 m of this same stratum (D. Lefaivre, MLI, pers. comm.).

Fixed macroalgae were only found at depths less than 4–5 m, both in the north and south, forming a narrow belt around the islands. The very shallow bottom of the passage (in the intertidal and infralittoral zone) between the two islands was characterized by a very dense algal cover consisting mainly of large kelp (*Saccharina* sp., *Agarum cribrosum*), the red algae *Palmaria palmata* and *Phycodrys rubens* and the filamentous brown alga *Desmarestia*. The area of the seagrass bed in the passage between the two islands up to the 5 m isobath on the north side and 0 m on the south side was about 0.75 km^2.

The mapping of fishing positions recorded from 2008 to 2011 made it possible to delimit an area of 0.794 km^2 where the fishing effort was concentrated. This area is located on the south side and is centred on the opening of the passage between Île Blanche and Île aux Lièvres (Figure 6).

DENSITY

Figures 7 to 9 show that the density of green sea urchins per m^2 varied widely over the study area. The minimum density values per m^2 were 0 for all sea urchin size categories, on both the north and south sides of the study area, while the maximum density values observed were 25.1 non-legal sea urchins per m^2 on the north side, 50.1 legal sea urchins per m^2 on the north side and 66.5 sea urchins of all sizes per m^2 on the south side (Figure 10).

On the north side of the study area, the infralittoral zone of Île Blanche and the segment of T15 at the western mouth of the passage between the two islands were characterized, at least up to 12 or 14 m in depth, by mainly legal-size green sea urchins at densities ≥ 15 individuals per m^2 (Figures 7–9). In contrast, the total sea urchin density was generally lower along the northern segment of T17 in the infralittoral zone of Île aux Lièvres than elsewhere on the north side of the study area, but here again legal-size sea urchins predominated (Figures 7 and 8). Non-legal-size urchin densities were generally < 10 individuals per m^2 on the north side, except at depths of 8–12 m on T13 (Figure 9).

On the south side of the study area, almost all green sea urchins were observed at less than 10 m in depth (Figure 7). The density of sea urchins was nil or very low on sandy bottoms; the few sand-bottomed quadrats where sea urchins were present were usually near stretches of gravel or rock (Figure 7). The highest densities of legal-size sea urchins (≥ 15 sea urchins per m^2) were observed near the eastern mouth of the passage between Île Blanche and Île aux Lièvres, between T14 and T16 off the eastern tip of Île aux Lièvres, and on T5 near the eastern tip of Île Blanche (Figure 8). These positions (except T5) are within or very close to the territory where most of the fishing effort took place from 2008 to 2011 (Figure 8). The highest densities of non-legal-size sea urchins (≥ 15 sea urchins per m^2) were located in front of Île Blanche and its tidal flat, near the 5 m isobath (Figure 9) where few legal-size sea urchins were observed (Figure 8).

Mean green sea urchin density was higher on the north side of the islands than on the south side (Figure 10) for sea urchins of all sizes ($P = 0.014$) and for legal-size sea urchins ($P < 0.001$). If we restrict the comparison with the north side to the part of the south side at ≤ 10 m depth, where almost all the sea urchins were found, we find that the mean densities were still always higher on the north side than on the south side (Figure 10), but the difference was no longer significant for total density of sea urchins ($P = 0.496$) and was marginally insignificant for the density of legal-size sea urchins ($P = 0.056$). The density of non-legal-size sea urchins (Figure 10) was significantly higher on the south side than on the north side, whether considering all depths on the south side ($P = 0.043$) or only those less than 10 m ($P = 0.001$). The mean density of legal-size sea urchins was clearly and significantly higher ($P < 0.001$) in the territory where fishing effort was concentrated (15.1 individuals per m^2) than in the entire study area on the south side (5.9 individuals per m^2) or only in the south part with depth ≤ 10 m (7.9 individuals per m^2). However, the mean density of legal-size sea urchins was not significantly different ($P = 0.246$) between the southern fishing territory and the north side of the islands (12.7 individuals per m^2).

SIZE STRUCTURE

Green sea urchin size frequency distributions are visually very different between the north and south sides of the study area (Figure 11). The sea urchins were significantly larger on the north side, with diameters varying between 24 and 102 mm (mean 66.8 ± 0.7 mm; median 69.2 mm) versus 15–85 mm (mean 53.5 ± 0.6 mm; median 54.7 mm) on the south side. The difference in diameter between the two sides of the study area is highly significant ($P < 0.001$). The percentage of legal-size sea urchins relative to all sea urchins observed was 87% on the north side and 74% on the south side. The average of the mean sea urchin diameter per quadrat at a given depth (transects only) was significantly higher on the north side (> 65 mm) than on the south side (< 56 mm) for depths of 4 to 10 m (Figure 12). However, the average of the mean diameters showed a clear downward trend at greater depths on the north side, while remaining relatively stable on the south side, so that there was a convergence of size between the two sides of the islands at mean values around 55–60 mm toward 14 and 16 m depth (Figure 12).

Non-legal-size green sea urchins were under-represented in our photographic inventory because of the difficulty of detecting them in images, either because they were too small or hidden in crevices. The smallest sea urchin measured on our images was just under 15 mm in diameter, while several sea urchins under 10 mm were sampled by the divers. Visual comparison of size frequency distributions between sea urchins measured on images and those collected by scuba diving on T11 strongly suggests that the photographic method greatly underestimated the number of sea urchins < 35 mm in diameter (Figure 13). Nevertheless, the diving sampling confirms that sea urchins are larger on the north side (mean 49.4 ± 2.8 mm; median 55.9 mm) than on the south side (mean 39.5 ± 2.1 mm; median 42.9 mm) of the study area (Figure 13), with the difference being evident visually (Figure 13) and statistically ($P = 0.002$). The maximum size of green sea urchins sampled by diving on T11 was also notably larger on the north side (85.8 mm) than on the south side of the islands (68.9 mm).

The sub-area at the eastern mouth of the passage between Île Blanche and Île aux Lièvres (Figure 2) was characterized through imagery by larger green sea urchins than in the rest of the study area on the south side (Figure 11). The diameter of sea urchins in the sub-area of the eastern mouth (mean 63.6 ± 2.1 mm; median 64.2 mm) was not different ($P = 0.150$) from that on the north side of the islands (respectively 66.8 and 69.2 mm, see above). On the north side of the study area, sea urchins with a diameter ≥ 70 mm accounted for 46.7% of the observed population and were widely distributed (Figure 14). In the south, these large sea urchins accounted for only 9.7% of the observed population and were mainly concentrated near the passage separating the two islands (Figure 14).

LENGTH-WEIGHT RELATIONSHIP

The relationships between the diameter and weight of green sea urchins on the north and south sides of Île Blanche and of the eastern tip of Île aux Lièvres are presented in Figure 15 for the non-transformed and transformed data in their common logarithm. The point clouds representing north and south urchins are superimposed (Figure 15) and diameter and weight are tightly correlated (in the case of north and south, $r^2 > 0.99$ after logarithmic transformation). The comparison by ANCOVA of the linear regressions obtained after logarithmic transformation of the data shows that there is no difference in slope ($F_{(1, 138)} = 0.408$; $P = 0.524$) or y-intercept ($F(_{1, 138}) = 0.260$; $P = 0.611$) between the weight-length relationships of the north and south. The data on the north and south sides of the islands were therefore combined to establish a common regression for non-transformed and transformed data, the plots and equations of which are shown in Figure 15.

BIOMASS

Figure 16 shows that the highest total green sea urchin biomass values (> 3 kg per m^2) were mainly located on the north side of the islands and in the territory on the south side where fishing was concentrated in 2008–2011, or in its immediate periphery. Fairly high biomasses, between 2.0 and 2.9 kg per m^2, were also observed near the eastern tip of Île Blanche. These high biomasses consisted mainly of legal-size sea urchins. Elsewhere, total biomasses were lower (between 0 and 1.9 kg per m^2) and consisted mainly of non-legal-size sea urchins.

Mean biomass (Figure 17) was significantly higher on the north side than on the south side of Île Blanche and the eastern tip of Île aux Lièvres for green sea urchins of all sizes ($P = 0.014$) and of legal size ($P < 0.001$), with the opposite being observed for green sea urchins of non-legal size. If comparison with the north side is restricted to the part of the south side at ≤ 10 m, where almost all sea urchins were found, the total and legal biomass per m^2 was still significantly higher on the north side than on the south side ($P = 0.045$ and $P = 0.010$ respectively). The biomass of legal-size sea urchins per m^2 was clearly and significantly higher ($P < 0.001$) in the territory where fishing effort was concentrated (1.5 kg per m^2) than in the entire study area on the south side (0.6 kg per m^2) or only in the part of the south side less than 10 m deep (0.8 kg per m^2). The biomass of legal-size sea urchins in the territory where fishing was concentrated from 2008 to 2011 was estimated at 1,233 ± 311 t. This estimate is the product of the mean legal biomass per m^2 in the territory where fishing was concentrated (excluding quadrats T11 E and T11 W, being 1.55 kg per m^2, see Figure 17) and of the area of this territory (0.794 km^2). The biomass estimate is somewhat uncertain due to a positive bias related to the calibration of the underwater images (Appendix 1) and a negative bias arising from the difficulty of evaluating the number of urchins in images with heavy algal coverage.

DISCUSSION

This work allowed the green sea urchin’s spatial distribution, abundance and size structure to be specified, while providing information on the nature of the bottoms, around Île Blanche and the eastern tip of Île aux Lièvres. Our study area straddles two fishing areas. The south side (Area 8) of our study area has been regularly fished since 2008, but fishing on the north side (Area 9) has been sporadic and of low intensity (Sainte-Marie et al. 2012) despite the existence (demonstrated in this document) of a relatively large green sea urchin bed. The low fishing effort on the north side may be due to its difficult accessibility from North Shore ports (too far), the pronounced bathymetric cline, and strong tidal currents that limit dive time (Sainte-Marie et al. 2012). The southern side of the islands (Area 8) is generally shallower with less powerful tidal currents.

The photographic survey method used for this green sea urchin inventory also makes it possible to characterize the nature of the bottoms surveyed, which offers a perspective on the species’ habitat. This method is non-destructive and particularly well suited to heterogeneous and hard bottoms on which towed sampling gear (e.g. dredge, trawl) or grab samplers are inefficient or unusable. However, given the potential for visual obstruction by macroalgae, the often cryptic (hidden) nature of juvenile sea urchins, and the limited resolution of the camera, the photographic method does not allow for identification of all sea urchins present in all quadrats. This limitation is evident in the comparison between the size structures obtained by photography and by divers in this study, which suggests that sea urchins < 35 mm were greatly underrepresented in imagery relative to their actual abundance. However, besides the infrequent cases where seaweed coverage may have concealed sea urchins, we believe that legal-size sea urchins (≥ 50 mm) were well quantified in our study.

Before us, Pelletier and Gauthier (2002) assessed the green sea urchin populations in the Lower St. Lawrence region between Cacouna and Rimouski using the same general technique used in this study. However, these two photographic inventories differed in the area of the quadrat used (filmed)—it was smaller in the previous study (0.25 m^2) than in the present one (0.34 m^2), which may have made it possible for Pelletier and Gauthier (2002) to detect smaller size sea urchins thanks to being closer up. Indeed, the sea urchins measured by Pelletier and Gauthier (2002) were between 8 and 85 mm in diameter, with a mean size of 34 mm.

The density, size structure and biomass of the green sea urchin in our study area were highly variable at small and medium spatial scales (tens of metres to kilometres), as also demonstrated by other inventories in the Upper and Lower St. Lawrence Estuary (Himmelman et al. 1979; Pelletier and Gauthier 2002; Sainte-Marie et al. 2012). In our study area, the mean legal sea urchin biomass per m^2 for the north and south sides (approximately 1.9 and 0.6 kg per m^2 respectively), as well as for the territory where commercial fishing was concentrated on the south side (approximately 1.5 kg per m^2), was equal to or greater than values reported from elsewhere in the Upper Estuary (Himmelman et al. 1979; Pelletier and Gauthier 2002). The only exception is the mouth of the Saguenay Fjord (at the junction of the Upper and Lower St. Lawrence Estuary), where the mean legal sea urchin biomass on the fishing grounds was two to three times higher (Sainte-Marie et al. 2012) than around Île Blanche and the eastern tip of Île aux Lièvres.

Although the demography of the green sea urchin was highly variable at small spatial scales within our study area, the mean size and mean density (and thus the biomass) of the total population and its legal component on the south side were significantly lower than those on the north side. It is likely that these differences largely reflect the effect of the fairly intense fishing on the south side since 2008, while the north side is fished only sporadically and at very low intensity (DFO 2012). Since fishing pressure is applied to sea urchins ≥ 50 mm, it is plausible that the mean and maximum sizes and density of sea urchins have decreased. This explanation is all the more likely given that the density of sub-legal sea urchins was higher on the south side than on the north side.

On the south side of Île Blanche and the eastern tip of Île aux Lièvres, we noted that legal- and non-legal-size green sea urchins were found on different bottoms. Legal-size sea urchins mainly occupied the bottom near the passage between the two islands, where few non-legal sea urchins were observed. At this location, where fishing effort was highest, density and biomass of legal urchins are closer to those in the north. However, non-legal-size sea urchins tended to occupy the bottom more to the east, where there are few legal-size sea urchins and much lower biomasses. These sub-legal size sea urchins represented potential recruitment. However, it must be assumed that the establishment and survival of young green sea urchins around Île Blanche and Île aux Lièvres are strongly conditioned by variations in salinity, as small sea urchins are less tolerant of hyposalinity than larger ones (Himmelman et al. 1983; Drouin et al. 1985).

Two non-exclusive hypotheses could explain the concentration of legal-size green sea urchins at the eastern mouth of the passage between Île Blanche and Île aux Lièvres. The first would be a passive transfer of large sea urchins from north to south by currents associated with tides and storm surges. The sub-area at the eastern mouth of the passage shows a distribution of size frequencies approximating that observed on the north side. In addition, the mapping indicates that sea urchins ≥ 70 mm were not numerous on the south side compared to the north side, but were nevertheless concentrated near the eastern mouth of the passage between the two islands. Siddon and Witman (2003) have shown that larger sea urchins are more easily dislodged by currents than small sea urchins. Their results also show that to dislodge 25%, 50% or 95% of sea urchins 50–60 mm, currents of about 4, 5 and 7.5–9.9 m/s are required respectively. According to the Atlas of Tidal Currents (DFO 2008b), tidal currents around Île Blanche and Île aux Lièvres can generally reach up to 3.6 knots (1.9 m/s), depending on tide range, and up to 4.7 knots (2.4 m/s) at the eastern tip of Île Blanche's tidal flats at the strongest point of the ebb tide during spring tides. In the passage between the two islands, the current can reach up to 3.3 knots (1.7 m/s) from north to south at ebb tide. Although these currents alone seem insufficient to dislodge large sea urchins, during storm surges Siddon and Witman (2003) recorded currents of 5 m/s on a protected site and 8.8 m/s on an exposed site (as Île Blanche and Île aux Lièvres are). In addition, the green sea urchin's attachment strength to the substrate decreases as salinity decreases (Russell 2013). It is therefore possible that a transfer of sea urchins between the north and the south may occur under special and sporadic circumstances (e.g. a westerly storm at ebb tide during high tide ranges). The same phenomenon could also occur at the eastern tip of Île Blanche, explaining the presence of a few quadrats with high densities of legal-size urchins on the south side of this location. However, we believe that this hypothesis—even if proven—cannot by itself explain the concentration of large sea urchins near the eastern mouth of the passage between Île Blanche and Île aux Lièvres. Sea urchins may have stronger substrate attachment behaviours or may disperse deeper when the sea is agitated to reduce or avoid dislodgement (Siddon and Witman 2003; Lauzon-Guay and Scheibling 2007). In addition, the dense mat of macroalgae observed in the passage between the two islands could slow the current and possibly partially hinder the transport of sea urchins.

The other hypothesis to explain the concentration of legal-size sea urchins on the south side near the eastern mouth of the passage between the two islands would be an increased presence of food at this location. Although they may fail to transport large quantities of sea urchins, the currents will certainly convey macroalgae detached from the bottom of the passage during storms. Since tidal or storm currents are more often oriented from west (north) to east (south) in the passage between Île Blanche and Île aux Lièvres because of bathymetry and circulation (D. Lefaivre, MLI, pers. comm.), the southern side is the most enriched by drifting macroalgae. It is known that the density of large sea urchins is generally higher near kelp beds than on bottoms lacking in food (Lavergne and Himmelman 1984; Gagnon 2003; Brady and Scheibling 2006; Lauzon-Guay and Scheibling 2007). However, in some habitats with little or no potential for establishment and growth of macroalgae, high densities of large sea urchins may be locally supported where there are recurrent inputs and accumulation of drifting macroalgae (Himmelman et al. 1983; Filbee-Dexter and Scheibling 2016). In addition, Dupont and Himmelman (2008) report that the arrival of drifting macroalgae causes a rapid aggregation of sea urchins, especially large ones, which are able to move more quickly. Sea urchins with access to this more-or-less regular supply of quality food would grow faster, reaching legal size more quickly.

In any case, the large seagrass bed in the passage between Île Blanche and Île aux Lièvres and the narrow belt of macroalgae around these two islands certainly play a key role in the productivity and quality of green sea urchins in this sector. The extent and persistence of these seagrass beds, despite the devastating browsing potential of the green sea urchin (e.g. Ling et al. 2015), are probably ensured by periodic decreases in surface salinity below the critical threshold (15‰) for this species and by severe storms that prevent establishment and limit the advance of green sea urchin browsing fronts at shallow depth. It should also be noted that the physiological stress induced by a decrease in salinity has a negative impact on the green sea urchin's feeding rate, thus reducing grazing pressure even at non-lethal salinity thresholds (Narvaez et al. 2016). Refuge areas for macroalgae are rarer in the saltier waters of the Lower Estuary and the Gulf of St. Lawrence, where bottoms favourable to macroalgae are generally completely stripped by grazing green sea urchins (e.g. Himmelman et al. 1983).

CONCLUSION

This study allowed characterization of the bottoms and mapping of green sea urchin distribution in the vicinity of Île Blanche and the eastern tip of Île aux Lièvres in the summer of 2011. The bottom under 4-5 m in depth surrounding these islands, as well as the passage separating them, supported a seagrass beds with abundant kelp. The density and size of legal green sea urchins (≥ 50 mm) determined by benthic imagery were higher in the north (little or no fishing) than in the south (regularly fished) of these islands. Fishing on the south side was concentrated from 2008 to 2011 in a territory of 0.794 km^2, in which the imaging survey demonstrated a fairly high density of legal-size sea urchins (around 15 individuals per m^2). The maintenance of high densities of sea urchins in this territory could be explained by a more favourable environment for growth due to a fairly regular influx of macroalgae from the passage between the two islands. It is also possible that this territory is supplied by a sporadic influx of large sea urchins from the north side via the passage between the two islands as a result of storm surges combined with strong tidal currents. Sea urchins of non-legal size, abundant near this fishing territory, represented a potential recruitment. The biomass of legal-size green sea urchin in the fishing territory was estimated at 1,233 ± 311 t.

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TABLES

Table 1. Substrate types used to describe quadrats during benthic imaging analysis.

Substrate	Description
Fine sand	Diameter not measurable
Coarse sand	Diameter < 0.5 cm
Small gravel	Diameter between 0.5 and 5 cm
Large gravel	Diameter between 5 and 7 cm
Small rocks	Diameter between 7 and 20 cm
Large rocks	Diameter > 20 cm
Macroalgae	Brown, red or green algae

FIGURES

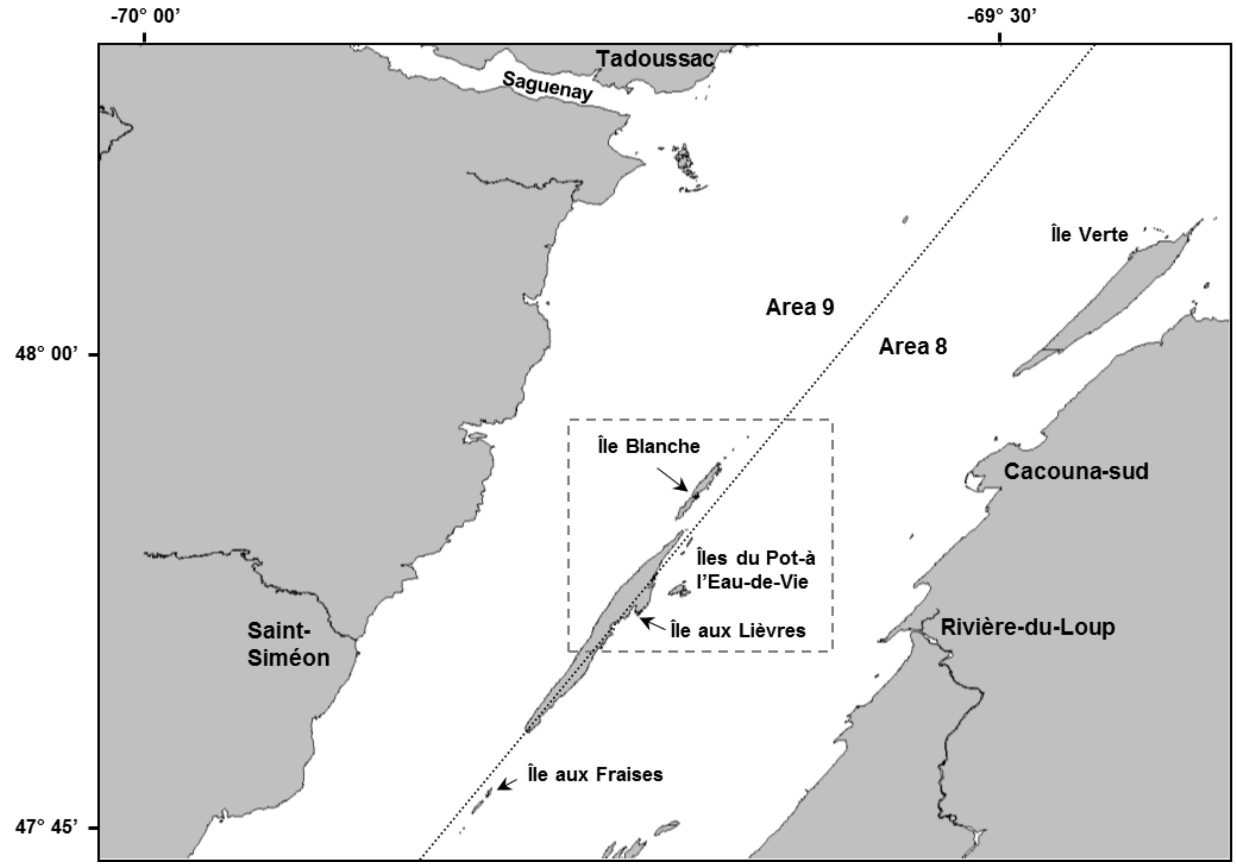


Figure 1. Delineation of green sea urchin fishing areas 8 and 9 in the St. Lawrence Estuary, separated by a fine dotted line, and location of the study area (square delimited by a dashed line) encompassing Île Blanche and its tidal flats and the northeastern part of Île aux Lièvres.

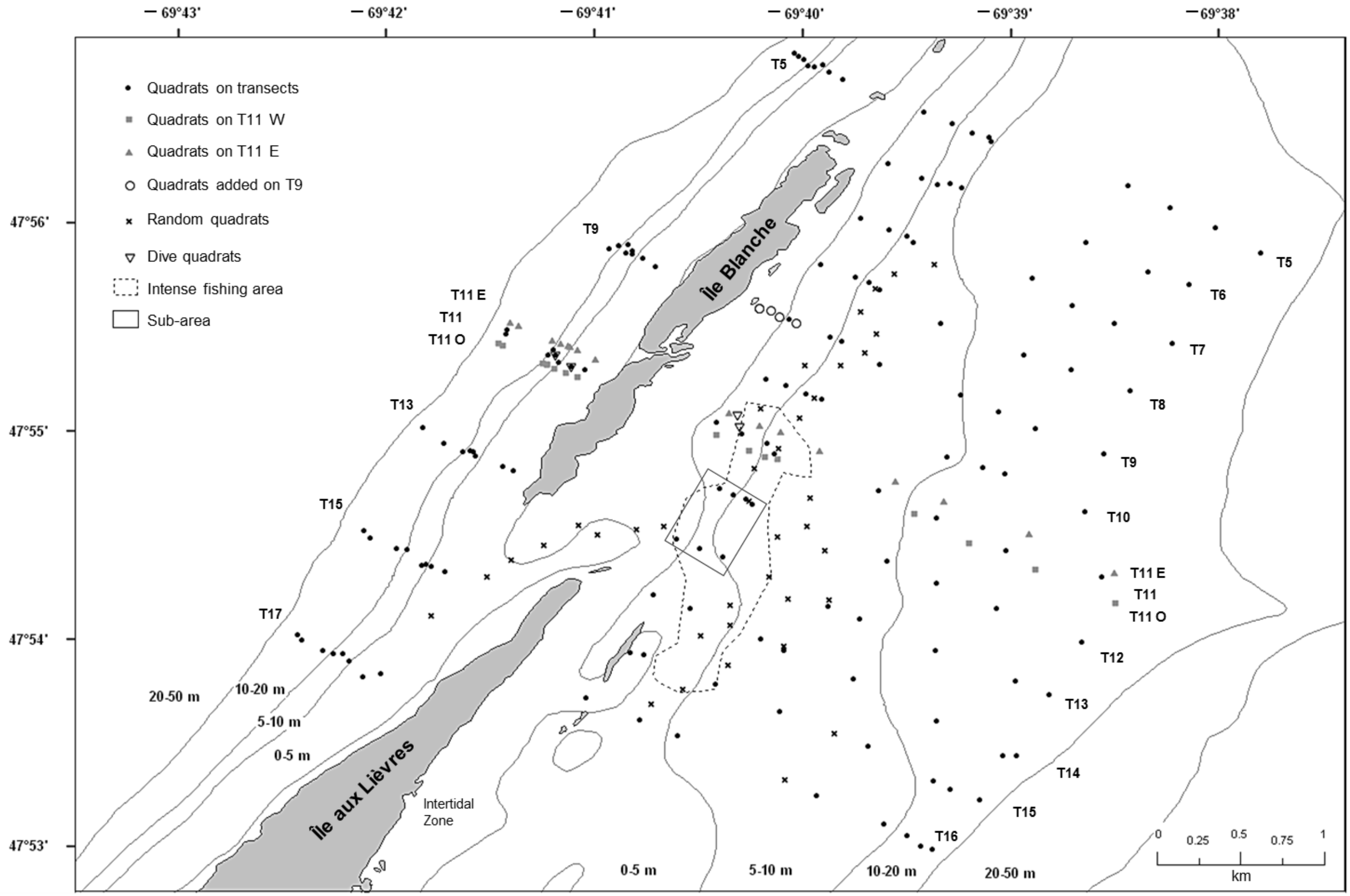


Figure 2. Map of transects (T) and quadrats sampled on both sides of Île Blanche and the eastern tip of Île aux Lièvres between August 18 and 23, 2011. The territory where the fishing effort for green sea urchin was concentrated from 2008 to 2011 is delimited by an irregular outline in dashed lines. A sub-area defined at the eastern mouth of the passage between the two islands is shown delimited by a square.

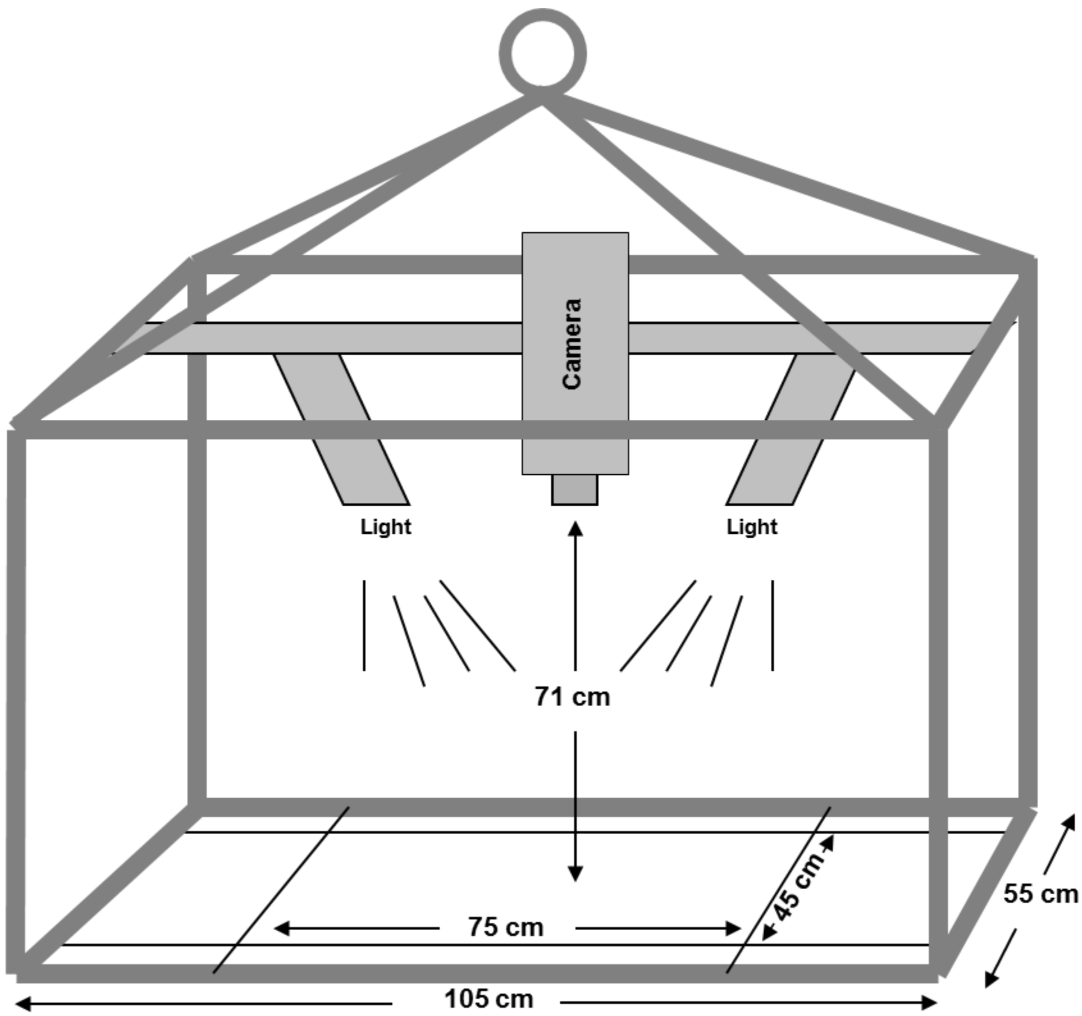


Figure 3. Schematic representation of installation of the underwater camera for video shooting.

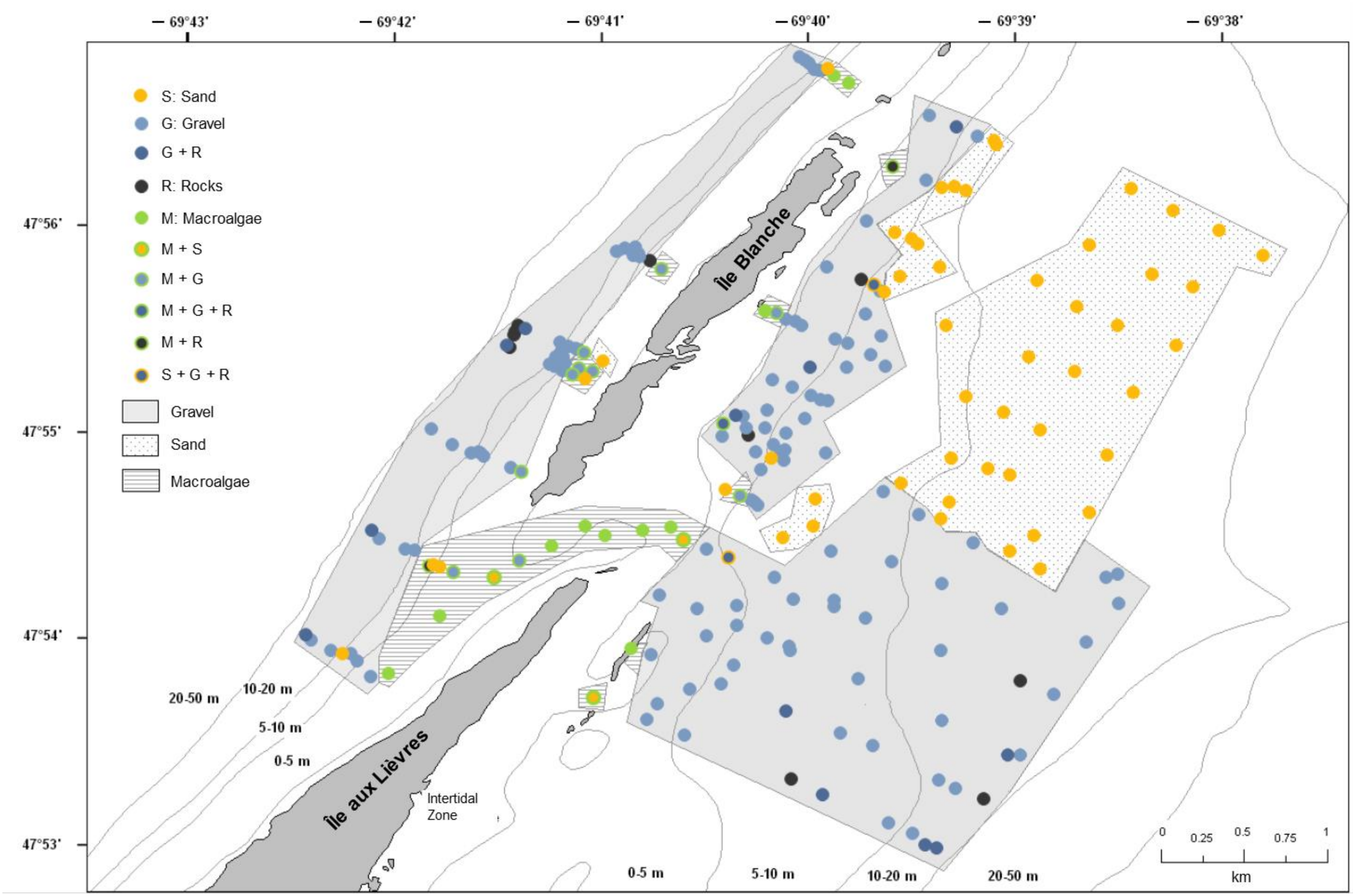


Figure 4. Map of substrate categories covering more than 70% of the surface of quadrats photographed or physically sampled and delimitation of bottoms mainly composed of sand, gravel or macroalgae around Île Blanche and the eastern tip of Île aux Lièvres in August 2011.

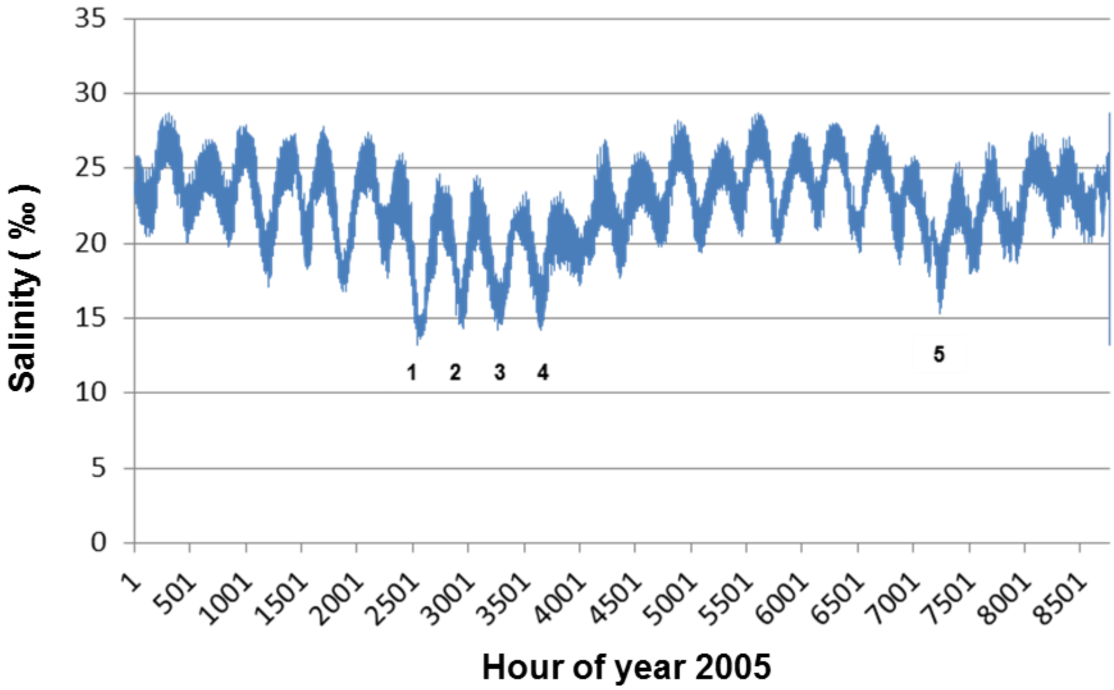


Figure 5. Hourly variation in mean salinity of the 0–5 m depth stratum around Île Blanche and the eastern tip of Île aux Lièvres in 2005. Figures in the graph refer to periods of time when salinity was below 15‰ (1: April 15–20; 2: May 2–4; 3: May 15–19; 4: June 1–3) or between 15 and 16‰ (5: October 29–30). The vertical line on the far right represents the full range of salinity during 2005.

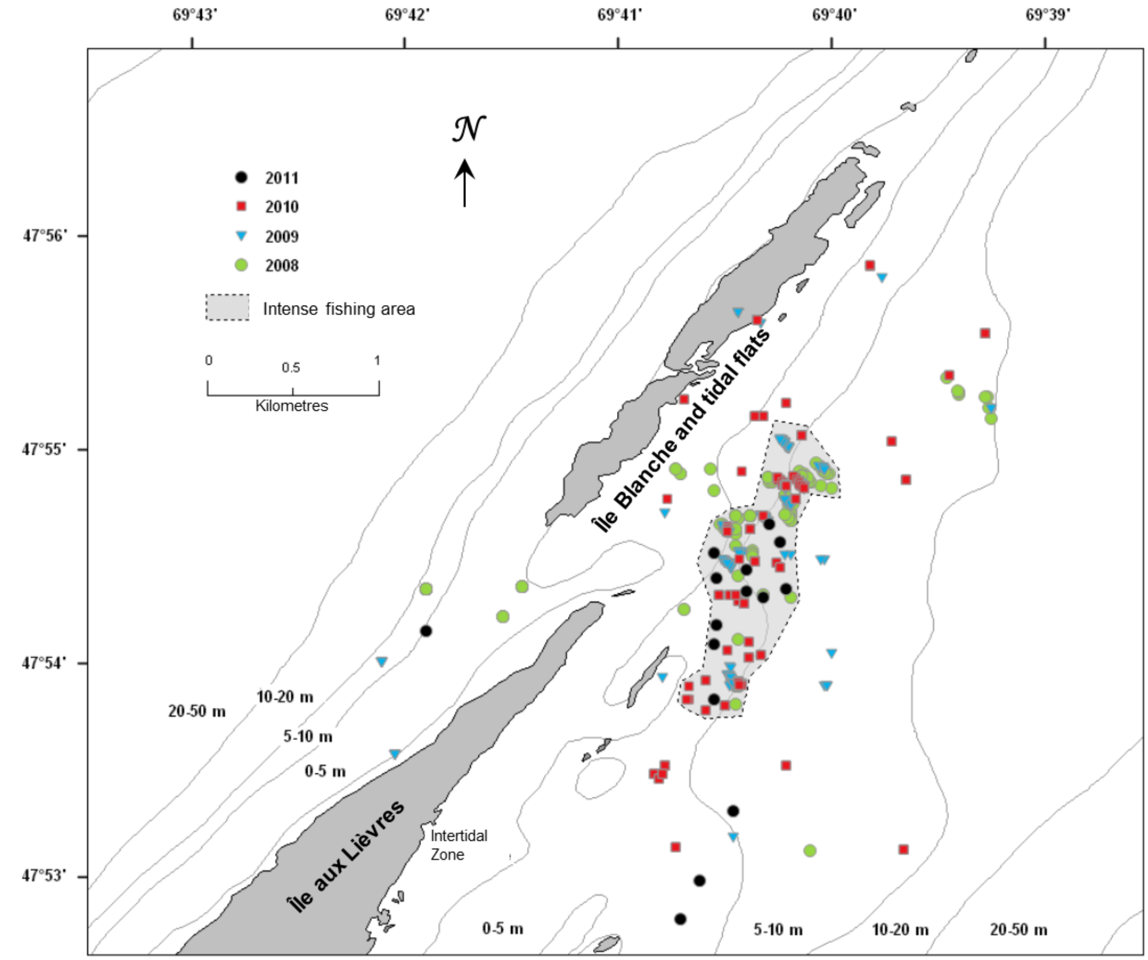


Figure 6. Map of fishing positions and delimitation of territory where green sea urchin fishing effort was concentrated from 2008 to 2011 around Île Blanche and the eastern tip of Île aux Lièvres.

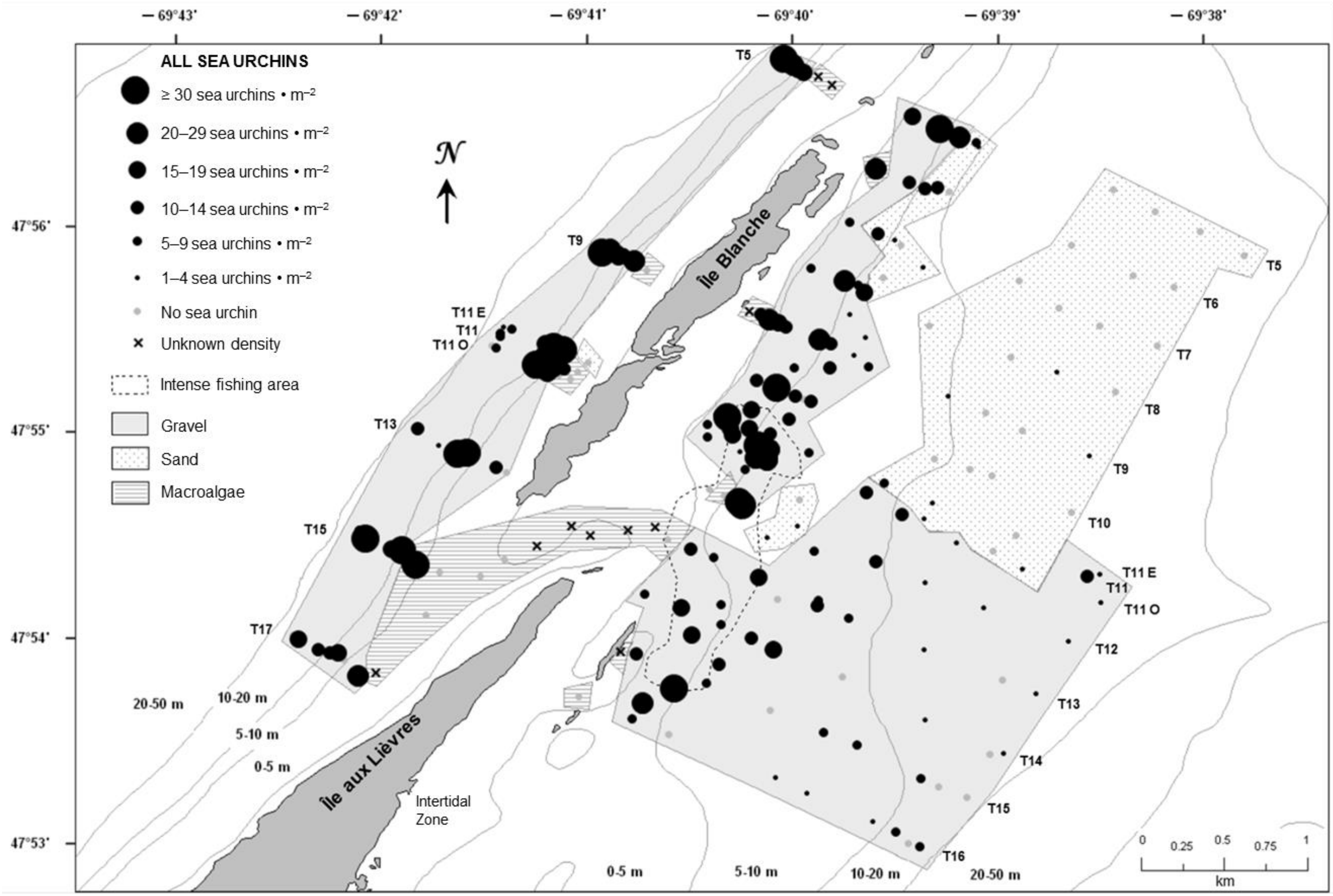


Figure 7. Map of total green sea urchin density in number per square metre observed on each of the quadrats sampled around Île Blanche and the eastern tip of Île aux Lièvres in August 2011. Dominant substrate type and territory where fishing was concentrated from 2008 to 2011 are indicated.

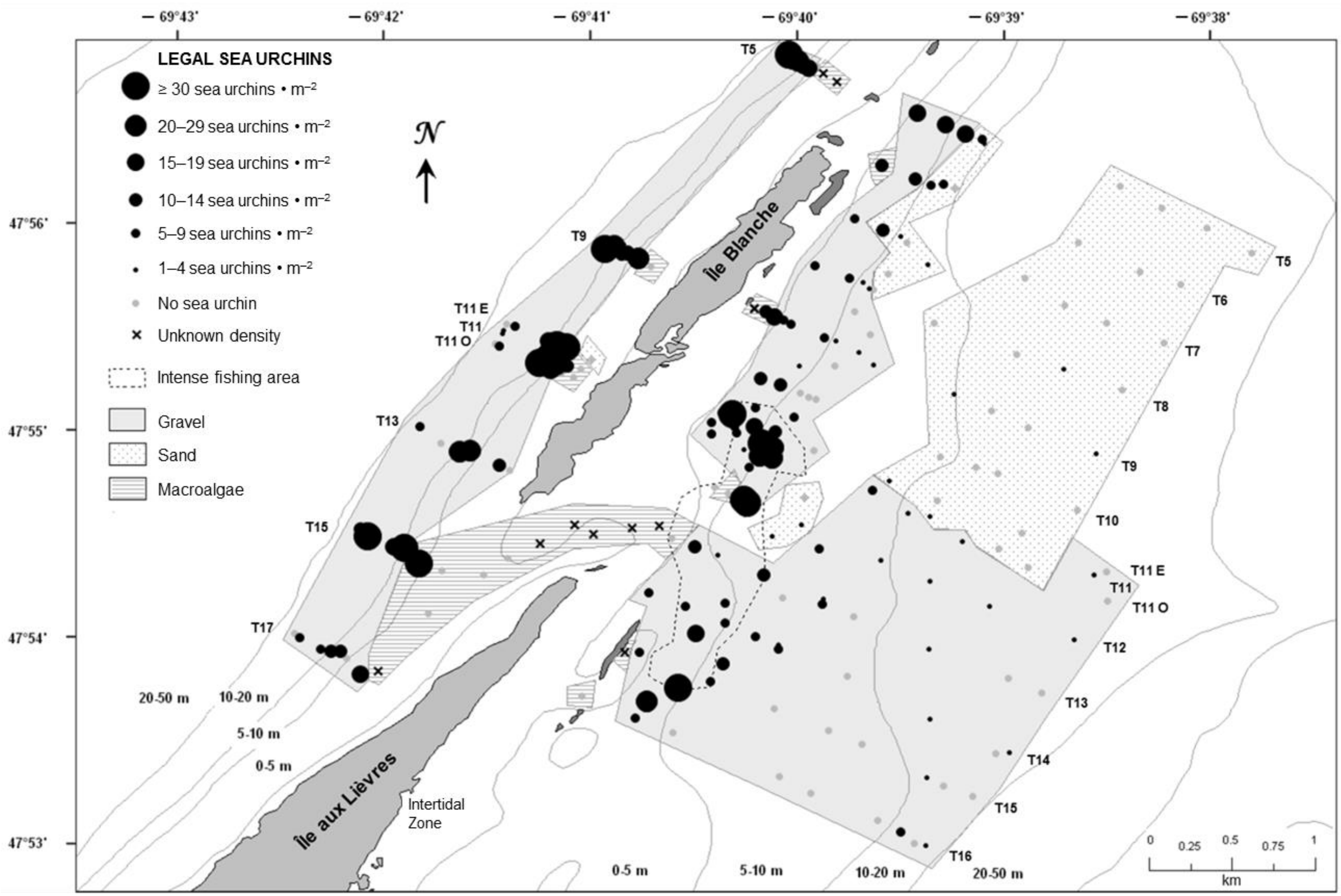


Figure 8. Map of legal green sea urchin density (test diameter ≥ 50 mm) in number per square metre observed on each of the quadrats sampled around Île Blanche and the eastern tip of Île aux Lièvres in August 2011. Dominant substrate type and territory where fishing was concentrated from 2008 to 2011 are indicated.

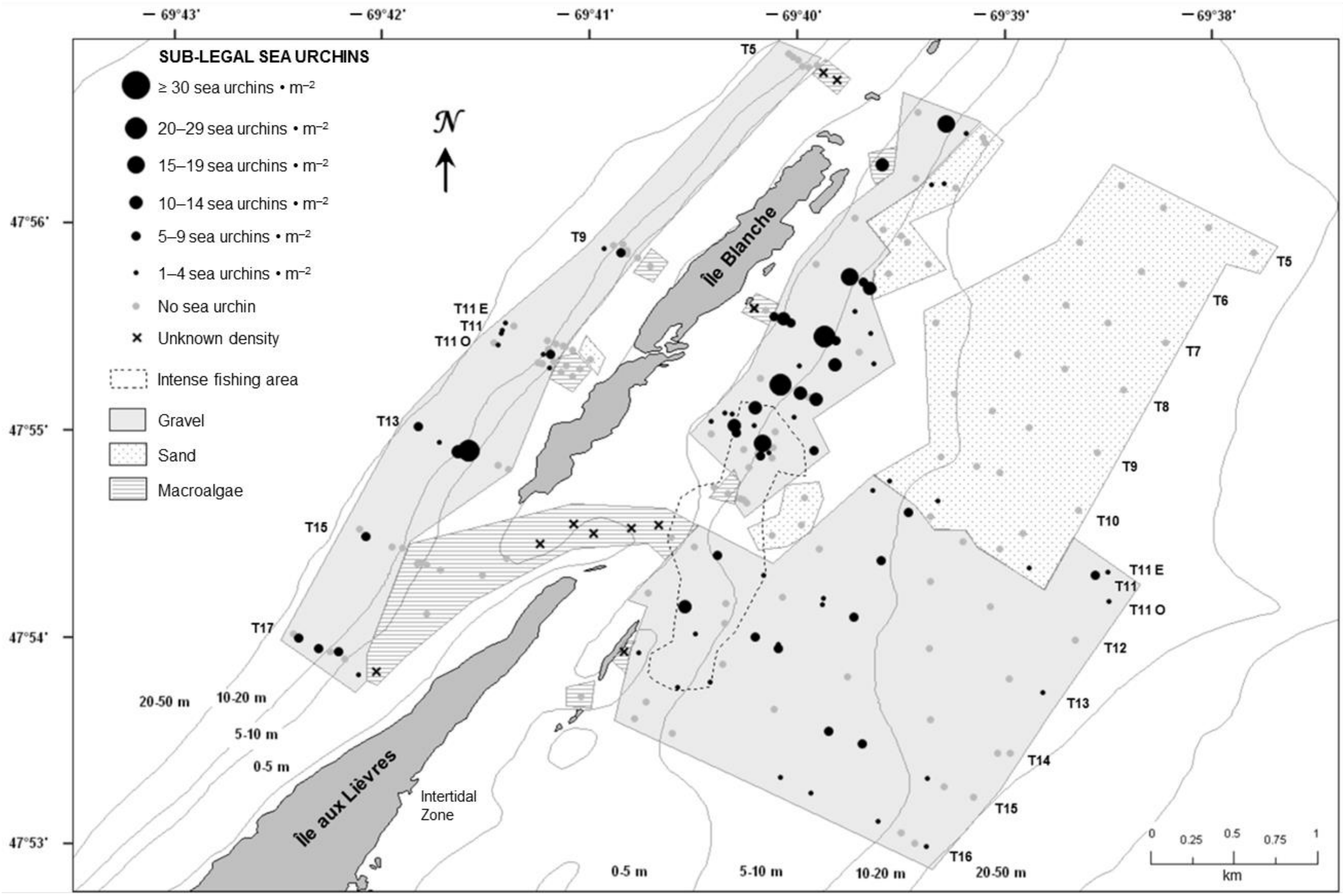
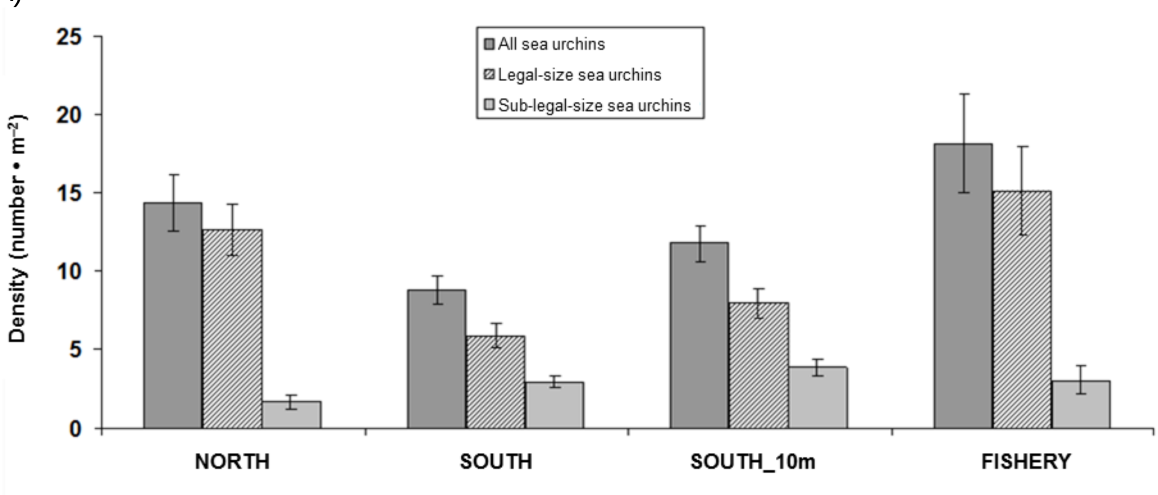


Figure 9. Map of sub-legal green sea urchin density (test diameter < 50 mm) in number per square metre observed on each of the quadrats sampled around Île Blanche and the eastern tip of Île aux Lièvres in August 2011. Dominant substrate type and territory where fishing was concentrated from 2008 to 2011 are indicated.

A)



B)

		Density: number per m^2		
Side of Islands		**All sea urchins**	**Legal sea urchins**	**Sub-legal sea urchins**
NORTH	Min / max	0 / 50.1	0 / 50.1	0 / 25.1
	Mean	14.3 ± 1.8	12.7 ± 1.7	1.7 ± 0.5
SOUTH	Min / max	0 / 66.5	0 / 49.9	0 / 22.2
	Mean	8.8 ± 0.9	5.9 ± 0.7	2.9 ± 0.4
SOUTH: ≤ 10 m	Min / max	0 / 66.5	0 / 49.9	0 / 22.2
	Mean	11.8 ± 1.1	7.9 ± 1.0	3.9 ± 0.5
SOUTH: fishing territory	Min / max	0 / 66.5	0 / 49.9	0 / 16.6
	Mean	18.1 ± 3.1	15.1 ± 2.8	3.0 ± 0.9
SOUTH: fishing territory, excluding transects 11 E and 11 W	Min / max	0 / 66.5	0 / 49.9	0 / 16.6
	Mean	18.7 ± 3.8	15.4 ± 3.4	3.4 ± 1.1
SOUTH: fishing territory, transects only	Min / max	0 / 66.5	0 / 49.9	0 / 16.6
	Mean	16.5 ± 4.3	13.3 ± 3.6	3.2 ± 1.2
SOUTH: fishing territory, transects only excluding 11 E and 11 W	Min / max	0 / 66.5	0 / 49.9	0 / 16.6
	Mean	16.9 ± 6.0	13.0 ± 5.0	3.9 ± 1.6
SOUTH: fishing territory, random quadrats only	Min / max	8.0 / 43.7	0 / 11.9	8.0 / 39.8
	Mean	21.2 ± 4.8	18.6 ± 4.8	2.7 ± 1.4

Figure 10. Results of green sea urchin survey around Île Blanche and the eastern tip of Île aux Lièvres in August 2011. A) Mean density (± standard error) for the NORTH side, the SOUTH side, the south side area ≤ 10 m depth (SOUTH_10 m) and the fishing territory (FISHERY). B) Minimum, maximum and mean density values (± standard error) for the different sectors covered by the survey. Densities are in number of sea urchins per m^2.

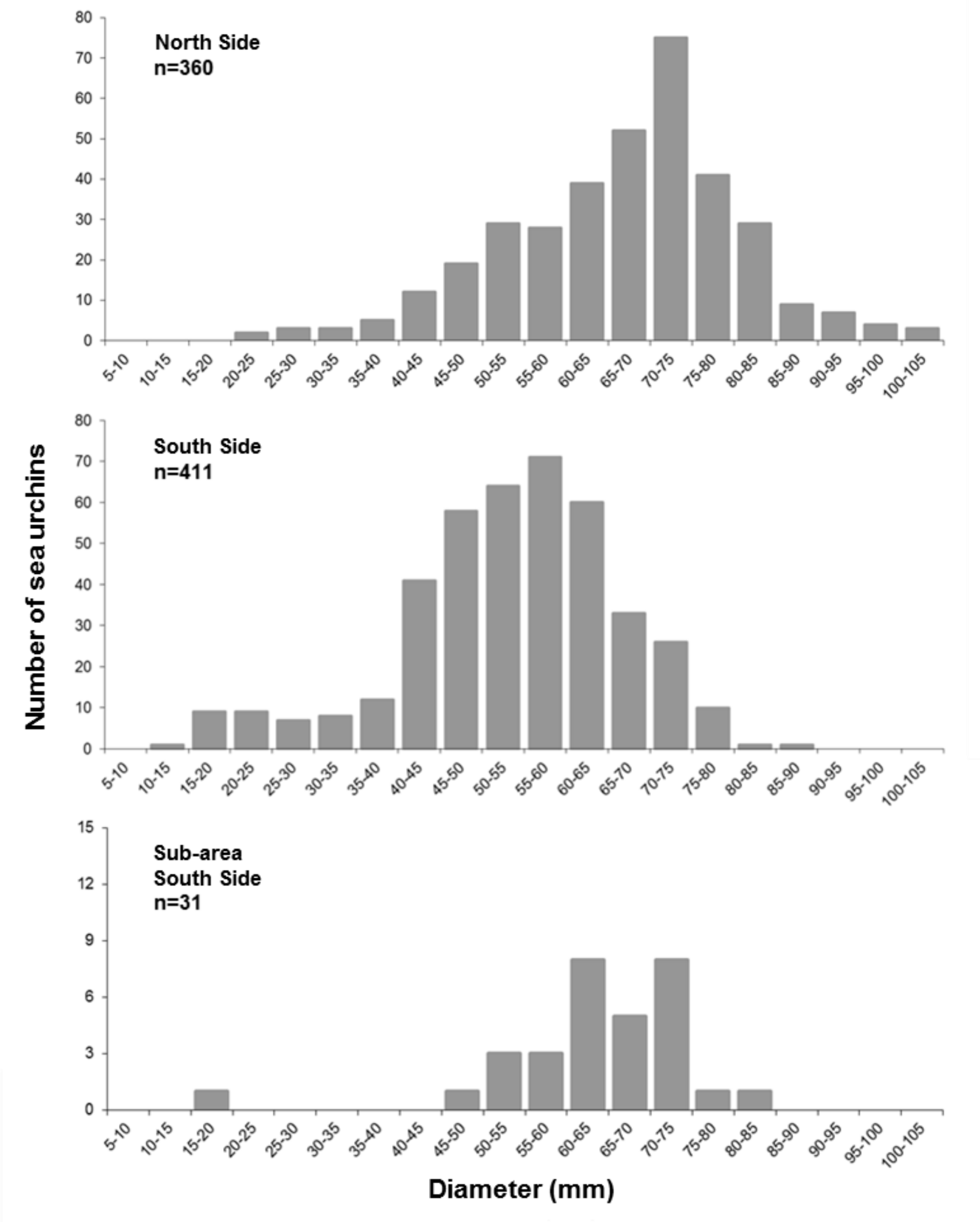


Figure 11. Histogram of size frequencies (test diameter) in 5-mm classes observed in August 2011 on the north and south sides of Île Blanche and the eastern tip of Île aux Lièvres, as well as in the sub-area at the eastern mouth of the passage between these two islands. The total number of sea urchins measured per sector is indicated (n).

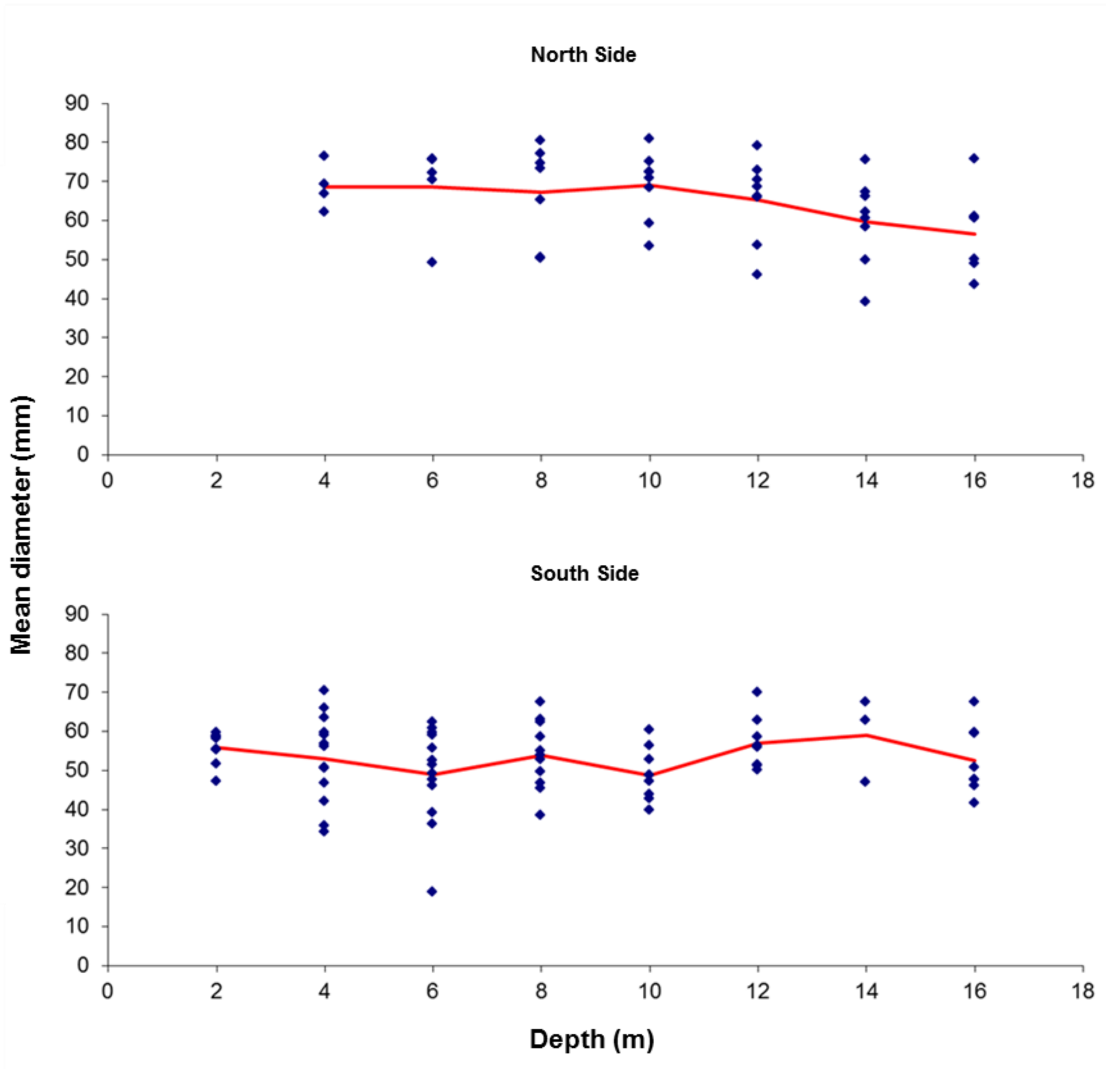


Figure 12. Mean test diameter of green sea urchins per quadrat on transects as a function of depth on the north and south sides of Île Blanche and the eastern tip of Île aux Lièvres in August 2011. The solid line connects the average of the mean diameters at each depth.

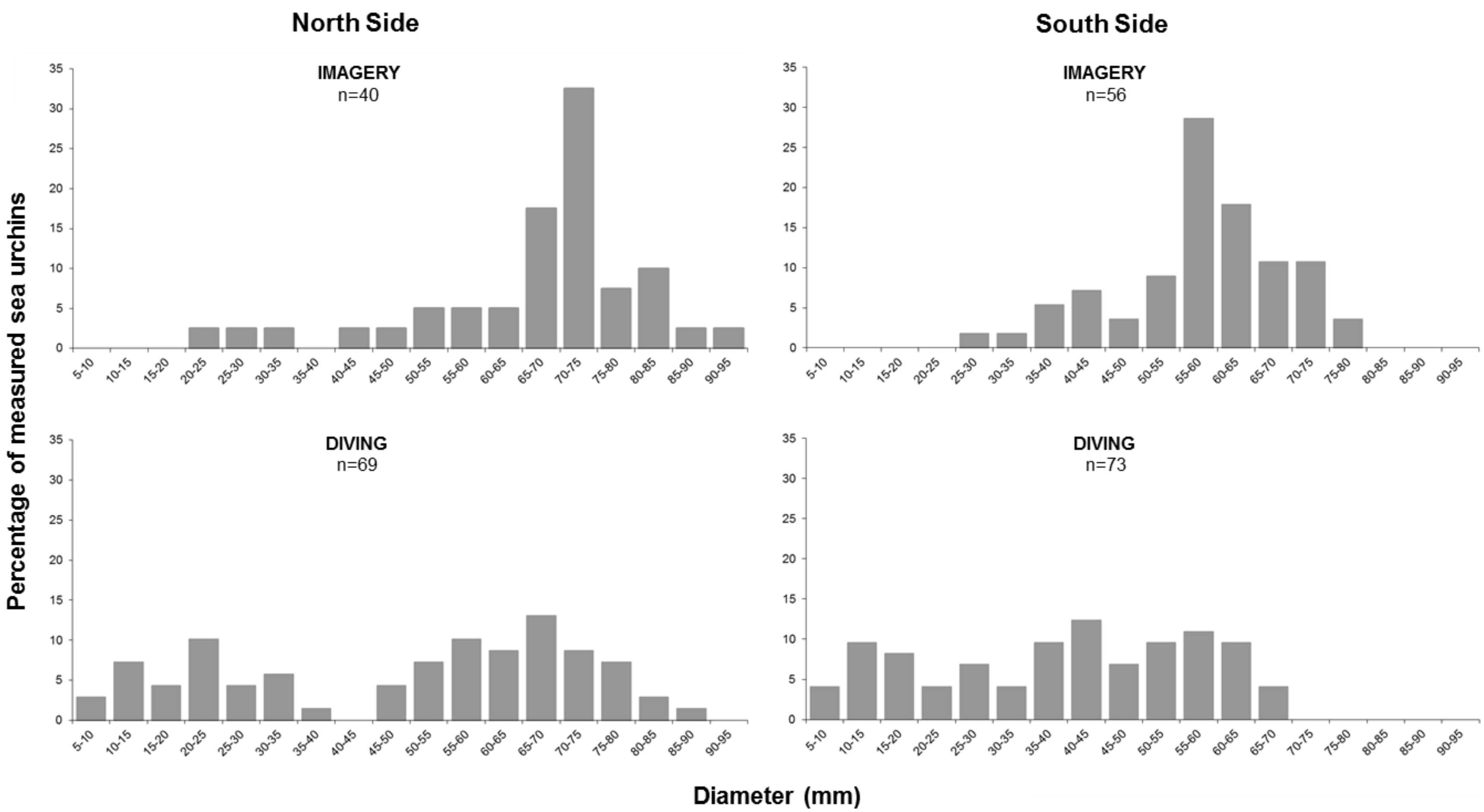


Figure 13. Size frequency distribution (in percentage) of green sea urchins measured on quadrats sampled by camera (imagery) and scuba diving (diving, on T11, T11W and T11E) at 4 and 8 m depth on the north side and at 2 and 4 m depth on the south side of Île Blanche in August 2011. The total number of sea urchins measured in test diameter per sector is indicated (n).

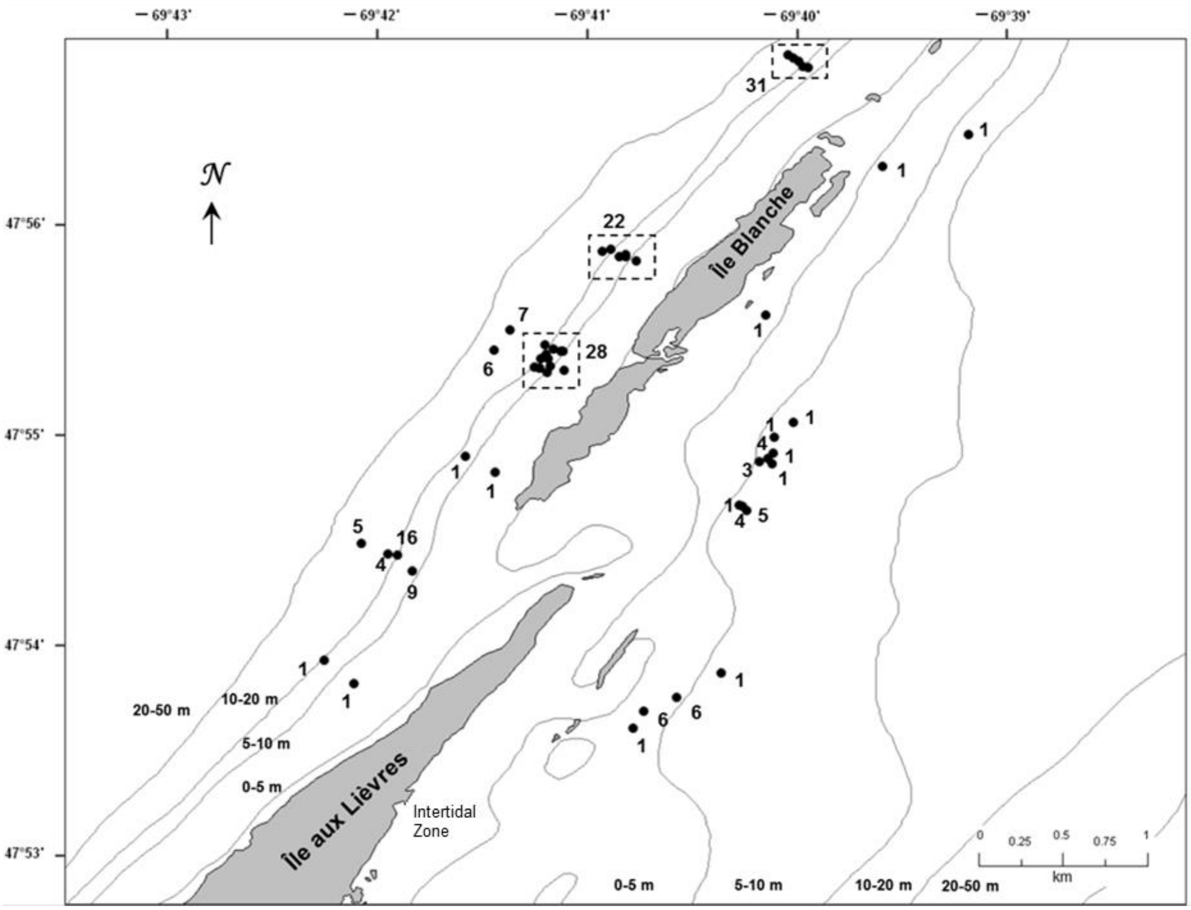


Figure 14. Spatial distribution and gross number of green sea urchins with test diameter ≥ 70 mm on camera-sampled quadrats around Île Blanche and the eastern tip of Île aux Lièvres in August 2011. The number of sea urchins per quadrat or group of quadrats (surrounded by a dashed box) is indicated.

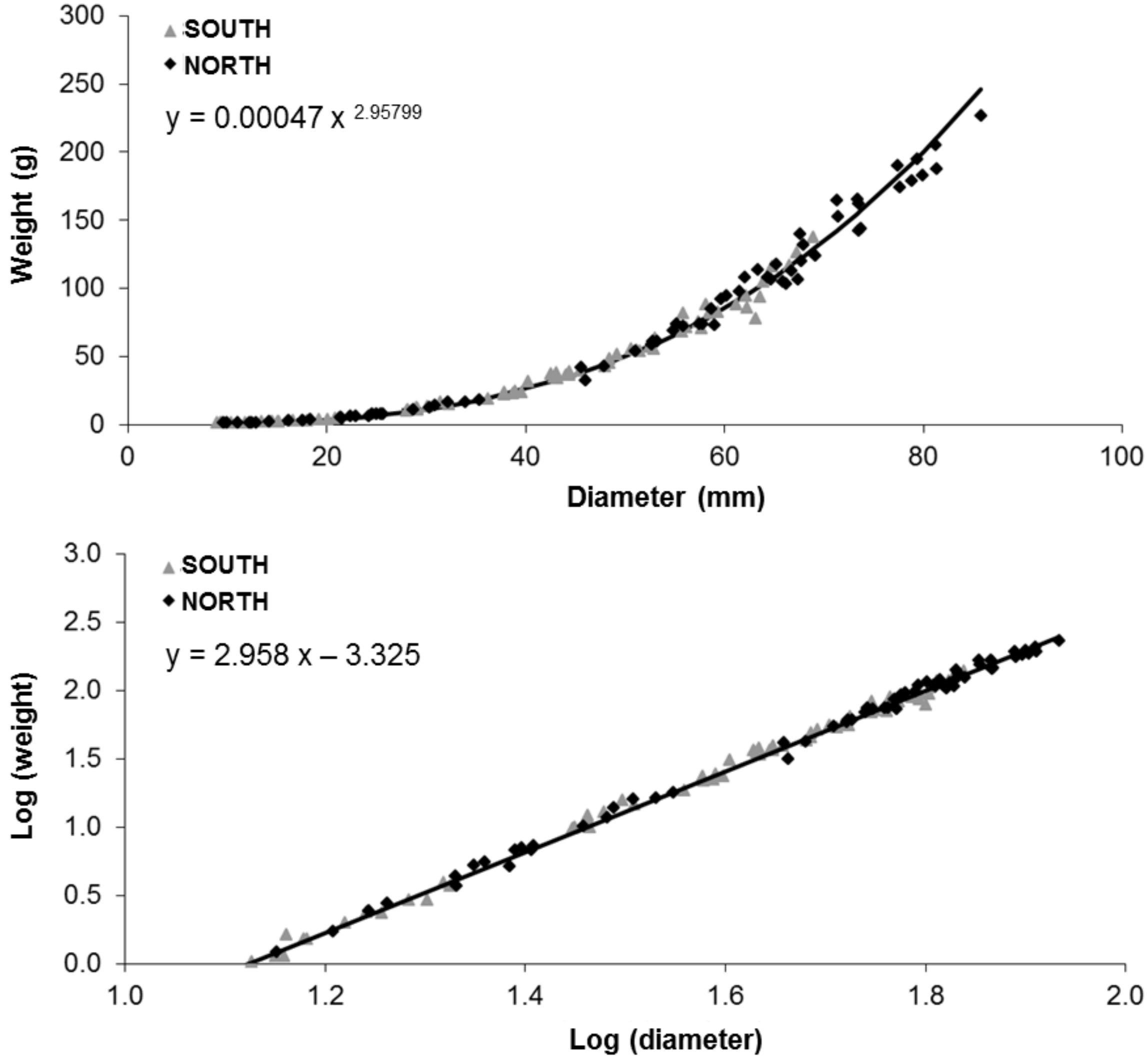


Figure 15. Relationship between test diameter and weight of green sea urchins collected by scuba diving on the north and south sides of Île Blanche and the eastern tip of Île aux Lièvres in August 2011. The data are non-transformed in the top graph and transformed to their logarithm to the base 10 in the lower graph (only log_{10} weights greater than 0 are shown); the descriptive regressions using all data are provided (in both cases: $r^2 = 0.99$ and $P < 0.001$).

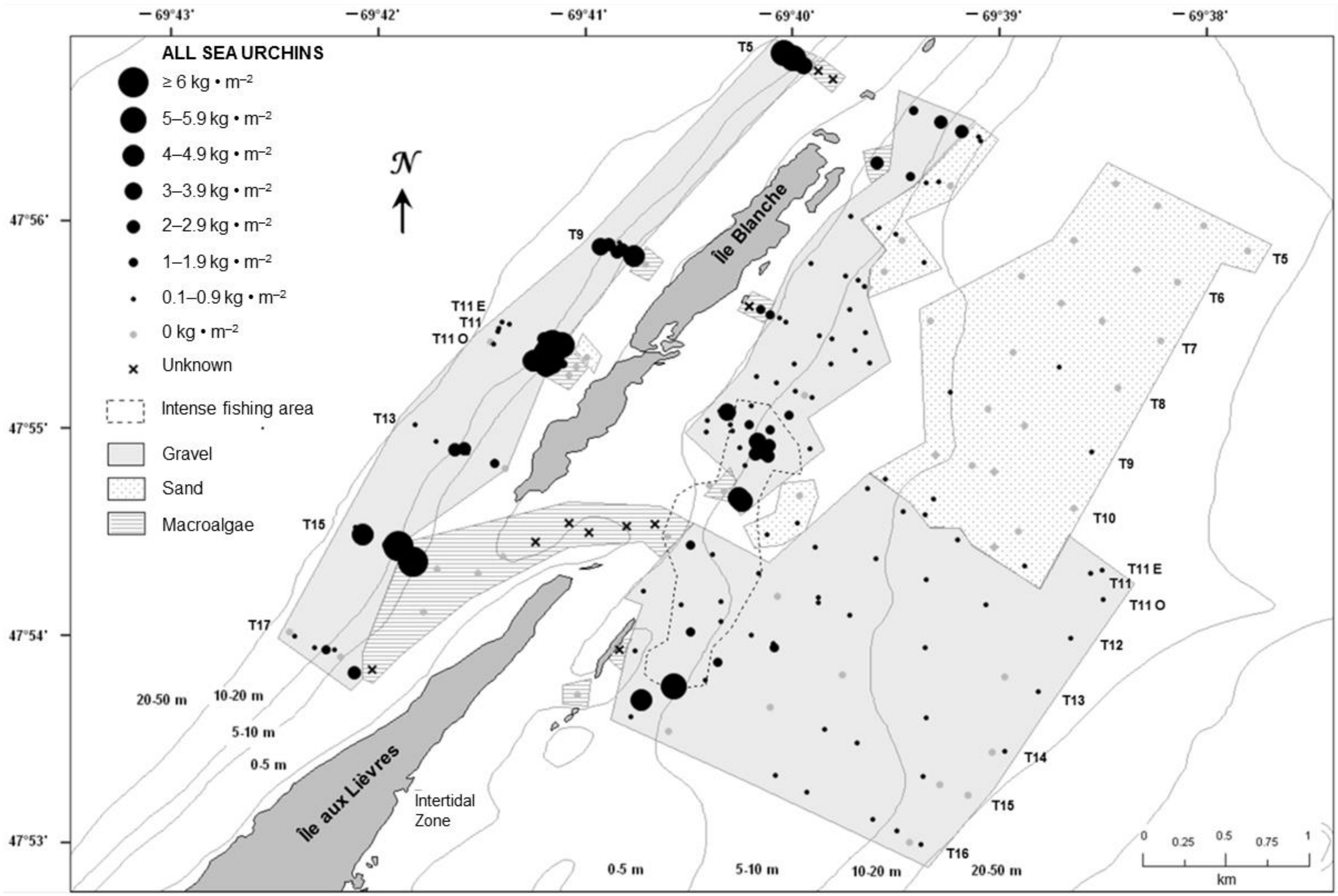
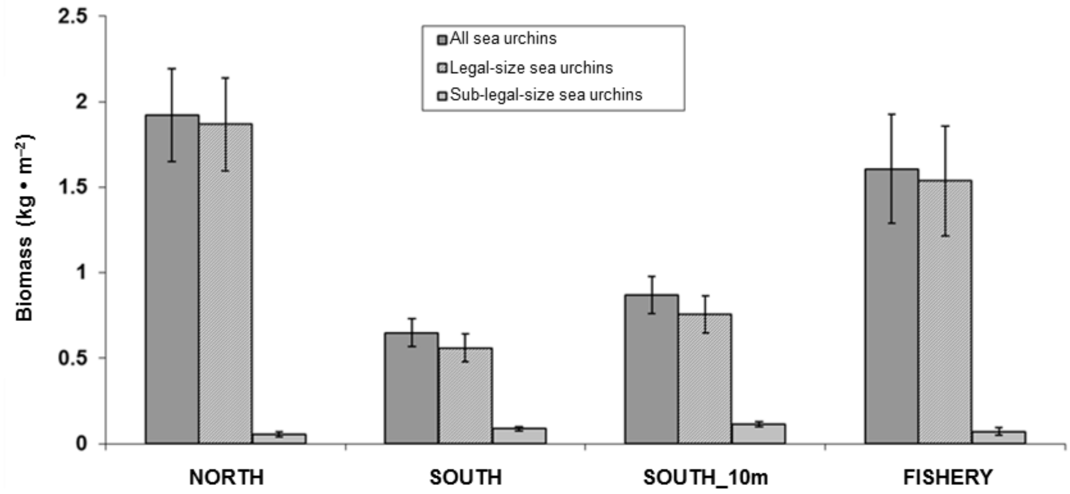


Figure 16. Map of total green sea urchin biomass in kilograms per square metre observed on each of the quadrats sampled around Île Blanche and the eastern tip of Île aux Lièvres in August 2011. Dominant substrate type and territory where fishing was concentrated from 2008 to 2011 are shown.

A)



B)

Side of Islands		Biomass: kilograms per m^2 All sea urchins	Legal sea urchins	Sub-legal sea urchins
NORTH	Min / max	0 / 8.70	0 / 8.70	0 / 0.76
	Mean	1.92 ± 0.3	1.86 ± 0.3	0.05 ± 0.02
SOUTH	Min / max	0 / 5.42	0 / 5.35	0 / 0.71
	Mean	0.65 ± 0.1	0.56 ± 0.1	0.09 ± 0.01
SOUTH: ≤ 10 m	Min / max	0 / 5.42	0 / 5.35	0 / 0.71
	Mean	0.87 ± 0.1	0.76 ± 0.1	0.11 ± 0.02
SOUTH: fishing territory	Min / max	0 / 5.42	0 / 5.35	0 / 0.37
	Mean	1.61 ± 0.3	1.54 ± 0.3	0.07 ± 0.02
SOUTH: fishing territory, excluding transects 11 E and 11 W	Min / max	0 / 5.42	0 / 5.35	0 / 0.37
	Mean	1.64 ± 0.4	1.55 ± 0.4	0.08 ± 0.03
SOUTH: fishing territory, transects only	Min / max	0 / 4.75	0 / 4.75	0 / 0.37
	Mean	1.40 ± 0.4	1.34 ± 0.4	0.07 ± 0.03
SOUTH: fishing territory, transects only excluding 11 E and 11 W	Min / max	0 / 4.75	0 / 4.75	0 / 0.37
	Mean	1.37 ± 0.5	1.29 ± 0.5	0.09 ± 0.04
SOUTH: fishing territory, random quadrats only	Min / max	0.64 / 5.42	0.56 / 5.35	0 / 0.30
	Mean	1.99 ± 0.7	1.91 ± 0.7	0.08 ± 0.04

Figure 17. Results of green sea urchin survey around Île Blanche and the eastern tip of Île aux Lièvres in August 2011. A) Mean biomass (± standard error) for the NORTH side, the SOUTH side, the south side area ≤ 10 m depth (SOUTH_10 m) and the fishing territory (FISHERY). B) Minimum, maximum and mean biomass values (± standard error) for the different sectors covered by the survey. Biomass is in kilograms of sea urchins per m^2.

APPENDIX

Appendix 1: Calibration of the image analysis software and measurement of the surface filmed by the camera

While loading the camera into the waterproof case (with each cassette change), the zoom button was accidentally pressed, and to a greater degree on cassettes 2, 3, 7 and 8, thus changing the filmed area. Because of the zoom and the magnifying factor of the water, the boundaries of the quadrat (75 x 45 cm) (Figure 3) disappeared from the filmed field, making it impossible to calibrate the image analysis software (Image-Pro Plus 6.1, Media Cybernetics Inc.).

To remedy this problem, we first performed a tank experiment with the same camera to establish the water magnification factor. This factor was established as 1.305 (see “Correction factor details” section below).

Out of the water, the limits of the 75 x 45 cm quadrat were always visible in the picture. As the camera filmed continuously, it was possible, when the camera was raised between two quadrats, to extract an image taken out of the water for each of the cassettes. For each image taken out of the water, the calibration of the analyzer was established using the measurement of the long side (75 cm) of the quadrat. Subsequently, we established the width and height of the field filmed by the camera out of the water. By dividing these values by the water’s magnification factor, we obtained the width and the height of the field filmed under water by the camera (see table below). From these values, we were able to establish a calibration for the underwater images and thus measure the diameter of the sea urchins and the different sediment particles (rock, gravel, etc.) for the habitat characterization.

Example:

Total width of the field filmed by the camera out of the water = 1.109942 m
Correction factor for water = 1.305
Width of the field filmed under water = 1.109942/1.305 = 0.85053 m

Table of the width, height and surface of the image filmed out of and under water (after correction) for each cassette:

Cassette	Field out of water		Correction factor	Field under water		
	Width (m)	Height (m)		Width (m)	Height (m)	Surface (m^2)
1	1.1099	0.6238	1.305	0.85	0.48	0.41
2	1.0217	0.5742	1.305	0.78	0.44	0.34
3	1.0454	0.5876	1.305	0.80	0.45	0.36
4	1.0931	0.6144	1.305	0.84	0.47	0.39
5	1.0783	0.6061	1.305	0.83	0.46	0.38
6	1.0998	0.6181	1.305	0.84	0.47	0.40
7	0.8729	0.4906	1.305	0.67	0.38	0.25
8	1.0187	0.5725	1.305	0.78	0.44	0.34

On cassettes 1, 4, 5 and 6, the field filmed under water made it possible to see the ropes delimiting the 75 x 45 cm quadrat. These were curved by the action of the current but still allowed the analyzer to be calibrated based on the underwater images. This allowed us to validate the results obtained with the method described above. The results show that the first calibration method can produce measurements about 6% greater than the second method. In terms of sea urchin diameter, this represents a difference of 1 mm for the smallest sea urchin measured (15 mm in diameter) and 6 mm for the largest (102 mm in diameter). For the sake of uniformity of results, we applied, for all video cassettes, the first calibration method described in this appendix (developed using images taken out of the water). The variation observed between the two calibrations is a reason why the size frequencies were made using size classes of 5 mm.

CORRECTION FACTOR DETAILS

- Field covered by the camera underwater in wide mode (W) on the plane formed by the frame at the bottom: 84.14 x 46.87 cm;
- Under the same conditions, on the captured images, 1 pixel = 0.0436 cm or 1 cm = 23 pixels;
- The magnification factor measured from air to water in conditions of 28.5‰ and 6.0 °C is 1.305;
- Out of the water, the image suffers from a non-negligible spherical distortion (factor of +22 in Adobe Lightroom);
- Calibration in the air at the edge of the image will introduce inaccuracy in measurements in the water;
- Underwater spherical distortion is negligible, so a measurement in the centre is equivalent to a measurement in a corner and the straight lines are not deformed;
- There is a significant loss of resolution toward the edges of the image.