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Mapping and biomass estimation for a harvested population of *Gelidium sesquipedale* (Rhodophyta, Gelidiales) along the Atlantic coast of Morocco

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The alga *Gelidium sesquipedale* is harvested by divers along the Atlantic coast of Morocco and used for agar production. Management of this natural resource has become necessary due to increasing industrial demand. Detailed maps were prepared to determine the distribution and biomass of the species, including a bathymetric map of potential sites that was constructed using a global positioning system coupled to an echo sounder. Samples were then harvested at these sites by scuba diving, and geostatistical tools were used to determine the biomass. This method was applied for four years along 20 km of the largest *Gelidium* beds (El Jadida). In 1999, biomass was estimated at 13,700 to 16,800 tonnes wet weight, and mean biomass density was about 800 g m^{-2}, with the maximum not exceeding 3200 g m^{-2}. These values are lower than those found for Spanish or French populations. In 2003, the estimated biomass was 33% less. A comparative study indicated that overharvested *G. sesquipedale* had been replaced by *Halopithys incurvus.*

INTRODUCTION

The exploitation of the alga *Gelidium sesquipedale* (Turner) Thuret (Rhodophyta, Gelidiales) began in the early 1950s in Morocco. Harvesting was limited at first to wrack seaweed and was progressively extended to handpicking by scuba divers. Harvesting, drying and processing now provide regular or seasonal work for more than 8000 people along the Atlantic coast from Larache to Cap Barbas (Fig. 1a). The raw material collected supplies two factories that extract and purify more than 1000 tonnes of agar, and about 4000 tonnes of dry seaweed are exported directly.

Although *G. sesquipedale* is present all along the coast (Gayral 1958; Kabbaj 1994), it forms dense and easily exploitable populations at only a few sites subjected to intensive disorganized exploitation. Even though harvesting is only allowed from 1 July to 30 September, poachers work throughout the year. This has led to an appreciable reduction in the size and density of *G. sesquipedale.* On the most overexploited sites, another red alga, *Halopithys incurvus* (Hudson) Batters, has tended to replace *G. sesquipedale.*

Studies performed in Spain by Borja (1986, 1987, 1988, 1991, 1994) indicated that this resource could be best managed by limiting diver harvesting and relying on the gathering of wrack seaweed. However, this policy cannot be applied in Morocco where wrack tonnage is quite low. According to Kaas & Barbaroux (1998) and Gorostiaga (1990, 1994), 60–80% of the *G. sesquipedale* biomass in Morocco is uprooted by winter storms and currents which probably carry the alga out to sea rather than towards the shore, as in France and Spain.

In this context, a study of Moroccan *G. sesquipedale* beds was carried out to determine their real extent, estimate their biomass and regenerative ability, and establish a program for optimal exploitation of this renewable resource. The detailed mapping of the natural beds reported here was a first step to estimating the biomass. To develop the necessary tools, the study focused on the El Jadida beds where scuba diving was first used for harvesting. These beds are still the leading source of *G. sesquipedale* in Morocco and also the area where signs of overexploitation are most obvious.

MATERIAL AND METHODS

Gelidium sesquipedale, which is found along the East Atlantic coast of Europe and Africa from Belle-Ile (France) to southern Morocco, colonizes exposed rocky shore areas from low spring tide level to 25 m depth. The thallus, which can reach 40 cm in length, is formed of erect fronds that survive for one or two years and are supported by a system of creeping axes. These perennial axes ensure thallus fixation to the substratum and vegetative reproduction by layering. Sexual reproduction is not very active in this species. The percentage of fertile thalli is very low, and Mouradi-Givernaud *et al.* (1999) observed that only plants collected in the shallowest waters showed reproductive structures.

The El Jadida site (Fig. 1) is a 15 km long rocky plateau that slopes gently downward, reaching a depth of 10 m at a little more than 1 nautical mile from the shore. Under a heavy swell, the entire area is subjected to breaking waves. Coastal

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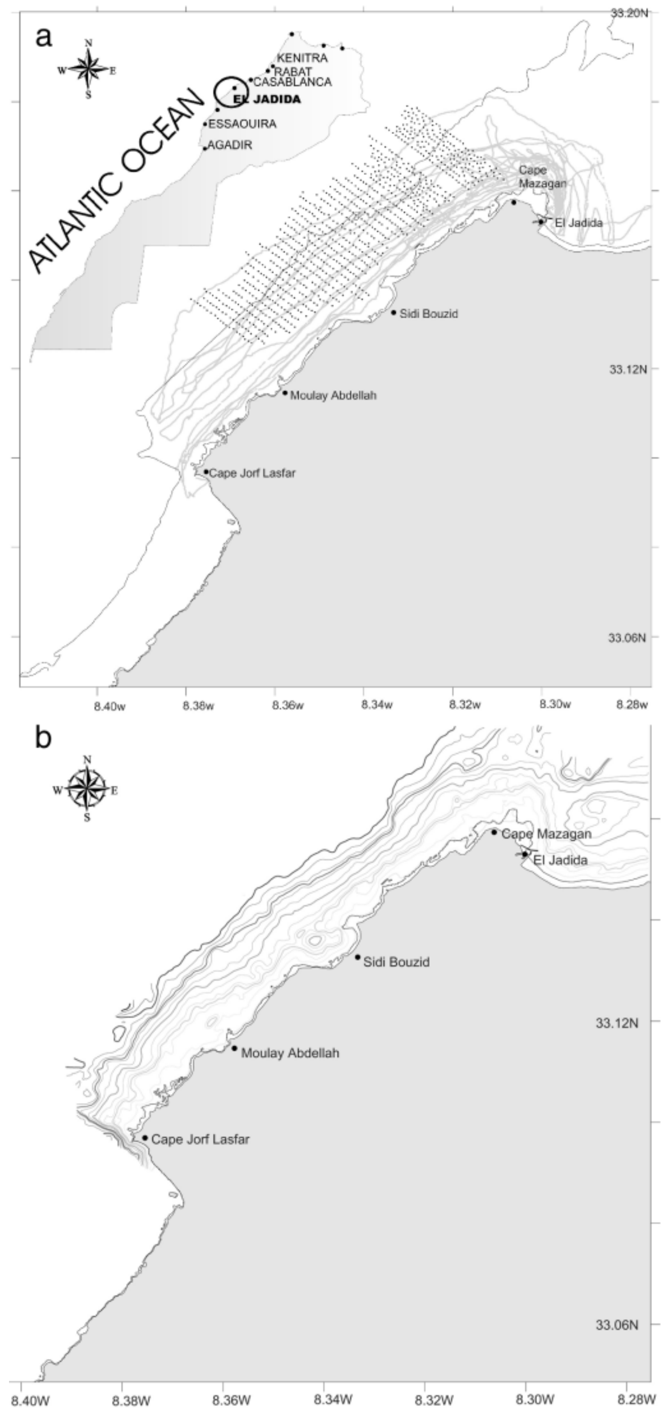

Fig. 1a. Data used to construct bathymetric charts. Lines indicate the route of the boat. Dots represent the sampling points for bathymetric modelling.
Fig. 1b. Calculated bathymetric map of the covered area.

upwelling during summer ensures low annual temperature variations.

The preference of this species for areas of high hydrodynamic activity makes access to populations rather difficult. Many are located in breaking wave areas where strong underwater currents and turbulence complicate the work of divers. When swells are higher than 1 m, many areas become inaccessible. Owing to heavy weather conditions, field study must be carried out mainly between May and September. Because biomass estimation must be ready before the official start of the harvesting period, only two months remain for that work (in fact, only 20 days because of weather and marine conditions).

The method used to obtain the most accurate representation of the population with a minimal number of samples involved the construction of a detailed bathymetric chart defining the potential areas for *G. sesquipedale* growth and then determining the distribution of sampling points on the basis of these data.

Construction of a bathymetric map

Because depths on marine charts outside of harbour areas are not sufficiently detailed in the 0–10 m range, a differential global positioning system coupled to an echo sounder and a computer was set up on a small open boat to obtain bathymetric records. Position and depth were recorded every two seconds with a precision of 5 m for the position and 20 cm for the depth. Bathymetric data were collected during a three week cruise as well as during each sampling trip. More than 70,000 data (Fig. 1) were collected, corrected for tide level and plotted on a bathymetric chart using a kriging method under Surfer 7 software (Golden Software, Golden, CO, USA). The geostatistical tools provided with Surfer allowed rapid, accurate interpolation from a set of randomly spaced or unspaced data in order to obtain a regular matrix of interpolated values. The software plotted isobathymetric lines from these values.

Sampling plan

On the basis of the bathymetric chart, sandy bottom areas and sites deeper than 20 m were excluded from the sampling plan design.

Two sampling methods were assessed in 1999; the first one was based on regularly spaced transects (1 km apart) perpendicular to the shore and sampled every 200 m. The second one used a grid system with a 0.5×0.5 nautical miles mesh size, each square being sampled three times. Statistically the latter method is known to be more accurate but it is also more costly in time and labour. If no significant differences in the results are observed, the first method, being less onerous, will be used for further investigations.

Sampling

All algae were collected within a 0.25 m^2 iron frame randomly placed by a diver at each point of the sampling plan on three different occasions.

Sample analysis

Each sample was manually spin-dried, and the total fresh weight noted. The different species were then sorted and weighed individually.

Mapping and biomass estimation

All values were processed with the Surfer 7 geostatistical program. The most suitable variogram model was then selected

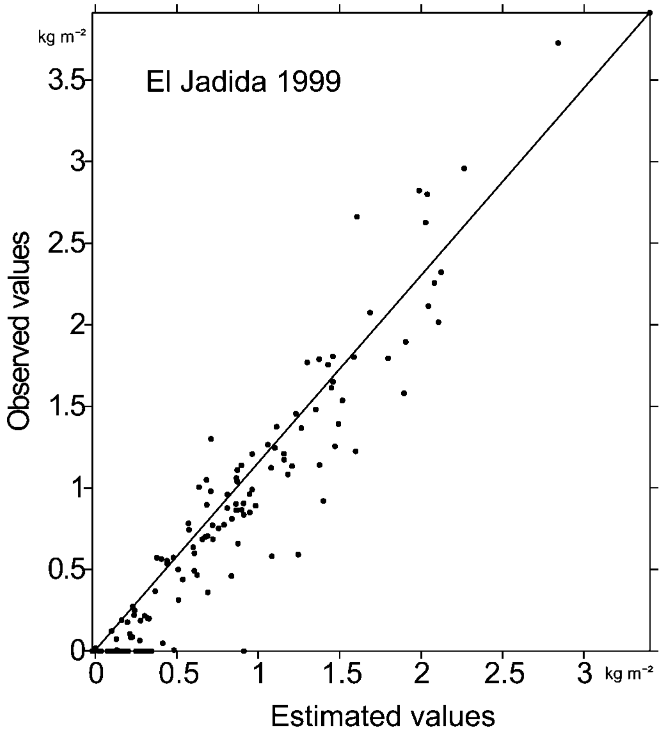

Fig. 2. Observed vs estimated values of *G. sesquipedale* density when applying the kriging method.

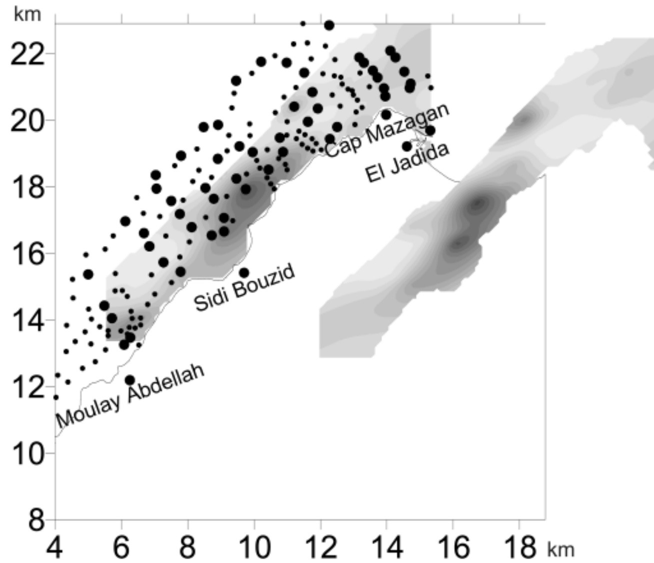

Fig. 3. Representation of the biomass estimation using the grid (figure on the left) and the transect (figure on the right) method. Sampling was as follows: small dots, grid; large dots, transect.

before gridding with the kriging algorithm (Cressie 1991). The goal is to build an estimation of the function F($\underline{x}$) where $\underline{x}$ = (x,y) at a given point $\underline{x}_p$ of the plane out of known values of F at a number of points, m, surrounding x_i; F($\underline{x}_p$) = $\Sigma W_i.F(\underline{x}_i)$. The critical point is to determine W_i for each considered position. Kriging makes an estimation of W_i out of the covariance between the points as a function of the distance which separates them. This is done through the semivariagram function for the *n*(h) points x_i and y_i separated by a distance h = $|x_i - y_i|$:

$$\gamma(h) = [1/2n(h)]\Sigma(x_i - y_i)^2 \text{ with } (i \in [1:n(h)])$$

The three-dimensional function of the variogram allowed for an estimate of variance as a function of the relative distance and angle of map points. This geostatistical method provided three-dimensional modelling of the biomass from the data set.

For bathymetry (Fig. 1a, b), Surfer calculated a regular rectangular matrix of points from the biomass data set. The process of blanking which marks areas of a grid or map as ‘no data’ areas was used to eliminate contour lines over particular regions of the contour map. In this case, the coastline and the 20 m isobathymetric line were used as the blanking file.

After kriging, biomass isodensity lines were superimposed over the bathymetric chart. From this matrix, the software also calculated the area between two consecutive isolines, allowing estimation of biomass according to three procedures: a minimum estimation based on a biomass density value equal to the lower isoline, a maximum estimation based on the upper isoline value and a midrange estimation based on the average value of the two isolines.

RESULTS

Estimation in 1999 and selection of the sampling technique

Initial observations at El Jadida indicated that *G. sesquipedale* is found from the low spring tide level, with maximum density occurring between 2 and 10 m (few plants grow at depths of more than 15 m). Above this depth range, some flat rocks are completely exposed at low tide and therefore unsuitable for *G. sesquipedale.*

The chart constructed in 1999 from data collected between May and the end of June indicated that *G. sesquipedale* distribution was not homogeneous. The major part of the area showed quite low densities (less than 1 kg m^{-2}). The seaweed formed dense populations only north of Sidi Bouzid (where densities of 3.4 kg m^{-2} were measured) and in two small areas north of Cape Jorf Lasfar. Mean biomass density was between 0.7 and 1.05 kg m^{-2}. To calculate the variogram we had recourse to a spherical model (Pannatier 1996), whereas sampling errors and short-scale variability were assessed through the nugget effect.

The agreement between the calculated grid and the original values is shown in Fig. 2 which shows a slight tendency for the model to overestimate small values and underestimate large ones.

Figure 3 shows the result of this technique applied to the data from the two sampling methods used in 1999 and covering the same area. A comparison between the two estimated populations by means of a two-way analysis of variance (Table 1) revealed no significant difference at a 5% risk level. Thus the transect method, less costly in time and manpower is sufficient to estimate the algae density.

In 1999 the total biomass for the whole of the El Jadida beds was estimated at 20,000–30,000 tonnes wet weight, and the evaluation for the subarea where the two techniques were used gives a production of 13,700–16,800 tonnes fresh weight.

Table 1. ANOVA. Comparison between the grid and the transect sampling methods.

Source of variation	Sum of squares	Degrees of freedom	F	Critical value for F
Density	50332308.06	8	96.23	3.44
Method	44214.05	1	0.68	5.32
Error	523044.47	8		
Total	50899566.59	17		

Table 2. Biomass evolution within the area studied between 1999 and 2003 (tonnes fresh weight).

	Minimum	Maximum
1999	13,675	16,810
2000	8787	10,832
2001	8002	11,808
2003	7013	11,193

Halopithys incurvus was found everywhere in the El Jadida beds. High densities were recorded in confined areas, and it was sometimes found together with *G. sesquipedale*. An accumulation of high-density patches was found near Cape Mazagan. However, the biomass density of *H. incurvus* never exceeded 1.2 kg m^{-2}.

Comparison of years 1999–2003

A comparison of the common areas studied during these years showed variations in the distribution of *G. sesquipedale* and *H. incurvus*.

A highly dense *G. sesquipedale* area (Fig. 4) observed north and north west of Sidi Bouzid in 1999 was reduced in size in 2000, and the area of maximum density had shifted to a deeper area more to the south. This phenomenon continued in the following years and only a small spot of relatively high density remained in 2003 in front of this site. Near Cape Mazagan, the areas of relatively high algal densities vanished within this period of time.

Within four years the area studied showed an appreciable decline in biomass of about 49–33% depending on the minimum or maximum estimation (Table 2).

The plot of biomass distribution vs biomass density (Fig. 5) showed that biomass in 1999 was concentrated in areas covered by densities of 0.8–2.7 kg m^{-2}, whereas in 2000 the largest part of the biomass was found in areas with densities lower than 1.5 kg m^{-2}. Within four years, areas that had had a high biomass density showed a considerable decline. In 2003 the major part of the biomass occurred in areas with a density of around 500 g m^{-2} of *G. sesquipedale*.

The distribution of *H. incurvus* also changed, showing greater homogeneity in 2000 than in 1999. This species was widely distributed in 2000, and the highest densities were observed in areas where it was nonexistent or poorly represented in 1999. However, reduced biomass was noted off Cape Mazagan. Total biomass was estimated to have increased from 3000–5500 to 5700–7400 tonnes.

DISCUSSION

Although samples were collected in May and June, corresponding to the maximum period of *G. sesquipedale* development (Mouradi-Givernaud *et al.* 1999), biomass densities were quite low. Maximum values, which did not exceed 3.4 kg m^{-2} in 1999, 2.6 kg m^{-2} in 2000 and 1.4 kg m^{-2} in 2003 were found in less than 1% of the colonized area. In untapped populations, biomass density can reach 8 kg m^{-2} (Kaas & Barbaroux 1998), with mean values of 2–3.5 kg m^{-2} (Borja 1987, 1988; Gorostiaga 1994; Kaas & Barbaroux 1998). In Morocco, a biomass greater than 4 kg m^{-2} was found only in

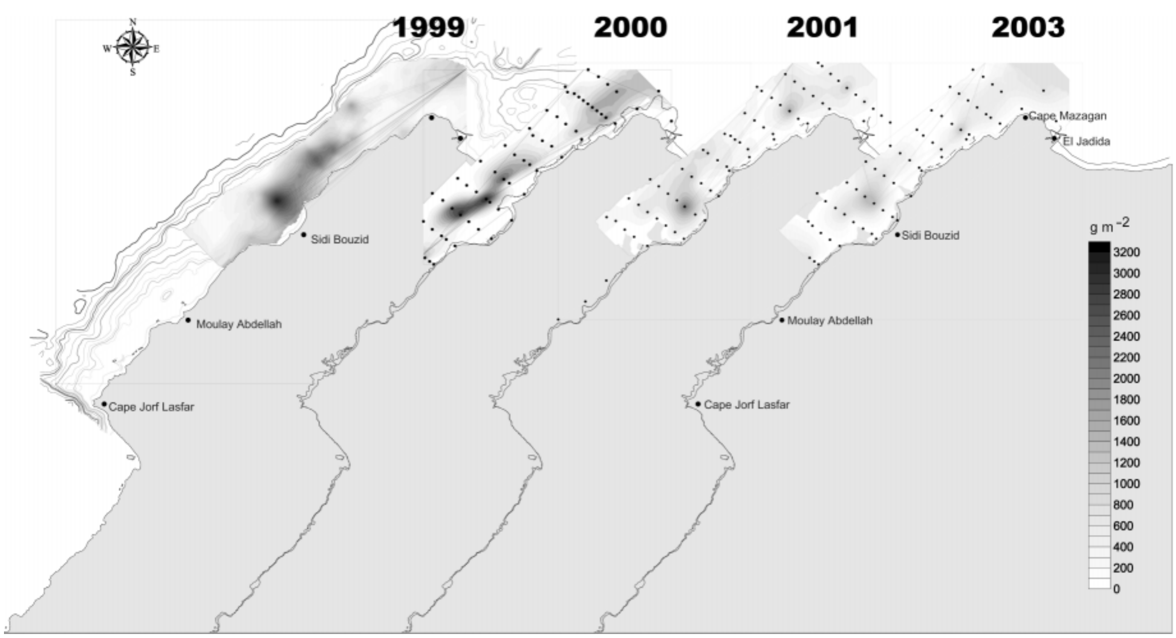

Fig. 4. Distribution of *G. sesquipedale* from 1999 to 2003. ● Sampling points.

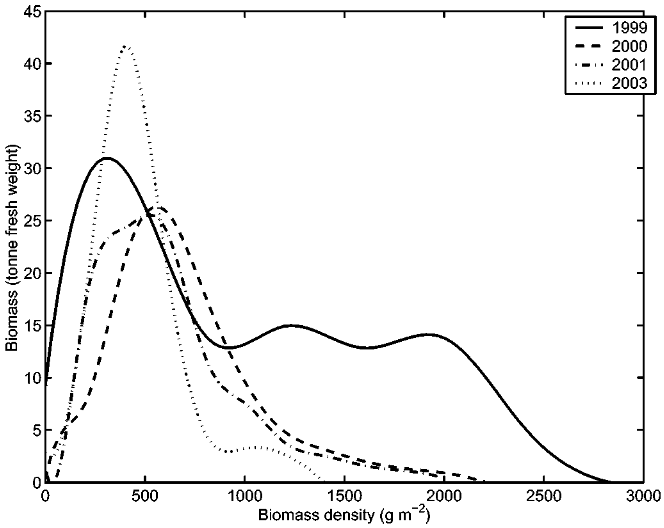

Fig. 5. The relationship between biomass density and biomass. The impact of harvest appears clearly. From 1999 to 2003 areas of high density disappeared and mean *G. sesquipedale* bed density do not exceed 500 g m^{-2}.

small isolated and unexploited *G. sesquipedale* beds. Overharvesting is the likely explanation for the low densities observed in the El Jadida beds. The influence of the previous official harvesting campaign and poaching during winter and summer apparently account for the present state of these beds in May and June. The relative effect of official harvesting and poaching suggests two slightly different interpretations of the results:

If poaching is minimal, it may be concluded that summer harvesting is too great, leading to degradation of the natural beds.

If considerable poaching occurs, it may be concluded that the situation has resulted from bad management of the resource and that poachers are 'eating the seed corn'. In this case, it is not possible to have a clear indication about the future of the resource.

Seoane-Camba (1966) showed that areas picked totally clean in summer recovered only 10% of their density a year later, whereas less thorough picking and cutting allowed total recovery in one or two years (Seoane-Camba 1966; Gorostiaga 1990). According to Borja (1991) and Kaas & Barbaroux (1998), faster recovery can be expected when part of the basal part of the alga remains.

The changes occurring from 1999 to 2003 indicate a degradation of *G. sesquipedale* beds, resulting in reduced density and biomass, and an invasion by *H. incurvus.* These results are in agreement with the observations of *G. sesquipedale* harvesters. After five years of survey, it is now certain that degradation is continuous and not the result of nonsignificant interannual variations.

In places where *G. sesquipedale* is disappearing, *H. incurvus* progressively settles down and remains in place.

Although the highest density recorded for *H. incurvus* was less than half that of the highest values for *G. sesquipedale,* the larger morphology of *H. incurvus* allows a greater coverage than *G. sesquipedale* for an equal biomass.

In Portugal, a technique based on available statistics to do with harvest effort (Santos *et al.* 2001) gave encouraging results in the management of the standing stock. Unfortunately, this method is not applicable in Morocco because it needs data about the catch per unit effort and total seaweed biomass landed, which are rather unreliable in Morocco.

CONCLUSIONS

An efficient method for mapping *G. sesquipedale* beds was designed. A five year survey applying this method showed that biomass densities at exploited sites were much lower than those of untapped beds. However, further studies are required to confirm that harvesting is degrading this natural resource. Longer recording periods are necessary to take account of natural long-term variations.

Measures should be taken to stop poaching during winter and spring in order to assess the real influence of official summer harvesting on the resource. More reliable data are required concerning the tonnage harvested, plucking frequency and intensity, collection sites and times. It remains difficult to establish experimental sites because of the chronic poaching problem.

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