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Conservation and resource management in small tropical islands: Trade-offs between planning unit size, data redundancy and data loss

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ABSTRACT

Resource management and conservation require the definition of planning units (PUs), i.e., the spatial domain where management decisions are applied. PUs are either pre-established in size and shape following management constraints or are data driven (DDPUs) by overlay of multidisciplinary data layers. The trade-offs between these two approaches have not been investigated previously for small tropical islands and their characteristics. Here, we use resource density, fishing pressure and susceptibility to mortality for a giant clam fishery in a small French Polynesia atoll to discuss the suitability and impact of the two approaches in conservation management. Aggregation to pre-established PU grids highly affected data even for PU as small as 2500 m^2, with higher loss of spatial information for density and fishing effort. By contrast, DDPU rendered well small scale patterns of interest but reduced redundancy. Our results stress the importance of considering the initial patterns of data in the definition of planning units, and we suggest a 3 steps process to identify adequate trade-offs between PU size, PU redundancy and data loss to properly draw practical recommendations for small islands.

1. Introduction

Spatially explicit conservation plans are useful decision support tools for managers (Pelletier and Mahévas, 2005). In particular, these plans require the definition of a network of spatial planning units (PUs). Once the network is established, relevant properties are considered homogenous inside each PU, and they may be, individually or as clusters, the object of specific management actions (Moilanen et al., 2009). Their shape can be regular (square or polygonal) or irregular if they follow administrative and environmental boundaries and units of ownership or tenure (e.g., Pressey and Nicholls, 1989; Hermoso and Kennard, 2012; Ma et al., 2012a).

The use of PUs extended during the past decade with the development of spatially explicit models. These models benefit, for example, systematic conservation planning (Ball et al., 2009; Moilanen et al., 2009; Deas et al., 2014), population, and fishery studies (Pelletier and Mahévas, 2005), and usually combine biological and sociocultural data (Léopold et al., 2014). Often, the shape and size of PUs are defined according to planning objectives and management capacities (e.g., surveillance logistical capacities, (Moilanen et al., 2009)). However, the consequences of such *ad hoc* choices remain unclear in terms of data and model quality as discussed for freshwater systems by Hermoso and Kennard (2012). Indeed, relevant spatial patterns visible in initial data but smaller than PU size may be missed when data is degraded to fit the pre-established size and shape of PUs. Conversely, when PUs are small relative to the initial data variation, some configurations may be over-represented in a network. A predefined, arbitrary, PU network may thus notably influence models output and management decisions (Pressey and Logan, 1998; Ferrier and Wintle, 2009; Nhancale and Smith, 2011). When the grain size of important data (e.g., resource stocks, fishing locations) is small like for Pacific island fisheries (Hamel and Andréfouët, 2010; Hamel et al., 2013; Léopold et al., 2014), it seems that defining a PU network according to data

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accuracy and spatial pattern would be a more sensible approach than defining PUs on the basis of management possibilities only.

To understand how arbitrary PUs may alter management decision in the context of tropical island small fisheries, we compare the influence of geometry and design of PUs on data loss and redundancy. Data redundancy is defined here as the proportion of PUs sharing the same combination of data values. For this, we used data layers that are currently judged critical for the sustainability of a small giant clam fishery in a remote atoll of French Polynesia to 1) assess how aggregation for different PU sizes affect data values and spatial patterns; 2) compare redundancy for two PU designs: a systematic grid and a data driven network (DDPU). Trade-offs between PU grid size, PU redundancy and data loss is examined to draw recommendations for conservation and management of small islands.

2. Methods

2.1. Study sites

French Polynesia is located in the Central Pacific Ocean and includes 118 islands distributed in five archipelagos. This study focuses on Tatakoto, an isolated and semi-closed atoll located in the eastern Tuamotu Archipelago (Fig. 1). Very high stock and densities were reported for the small giant clam *Tridacna maxima* in this lagoon in 2004 (up to 544 ind m^{-2}; Gilbert et al., 2005) although the stock is not even, with patchy densities found throughout the lagoon depending on habitat types, depth and location (Gilbert et al., 2006). Highest densities and stocks were found on the patch reefs of the eastern lagoon (Fig. 2). Patch reef size is typically on the order of few tens of meters (see Fig. 6 in Gilbert et al., 2006).

Only 287 inhabitants live on Tatakoto, all aggregated in the western end of the atoll (Tumukuru village). However, *T. maxima* stock is subjected to a significant exploitation with up to 20 tons of flesh sent annually toward the French Polynesia main island, Tahiti (in 2007, DRMM data). Less significant, but growing, exploitation also includes the temporary collection of live specimen for the aquarium trade. Fishing grounds are known to be different depending on the type of fisher activity, with professional-like fishers traveling greater distances than others (Gilbert et al., 2007).

The significant extraction of giant clam and the fairly small lagoon size (17.7 km^2), promoted the decision in 2004 by the Service de la Pêche (Fishery Services of French Polynesia) and in agreement with the local population, to create a 0.5 km^2 No Take Area (NTA) in the eastern sector of the lagoon (Gilbert et al., 2005). However, this conservation and management action was offset by a massive mortality that likely occurred in 2009, probably triggered by unusual weather conditions and temperature (Andréfouët et al., 2013, Andréfouët et al., 2015). The entire lagoon was affected but Andréfouët et al. (2013) reported higher mortality rates in the NTA compared to other areas. This shallow enclosed part of the lagoon with poor water renewal could be more vulnerable to warm periods of low wind and low swell (Andréfouët et al., 2015).

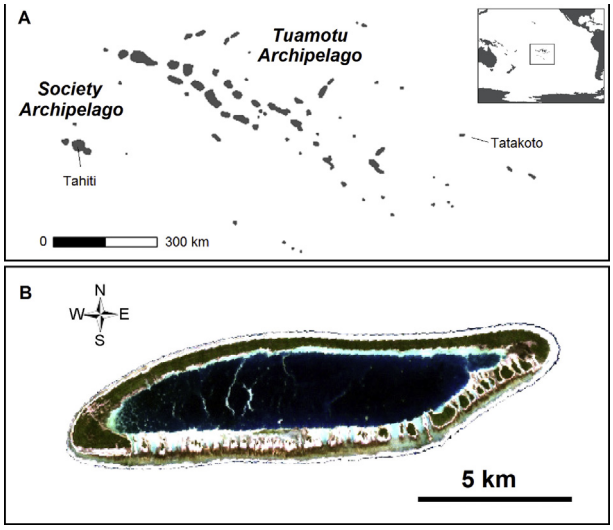

Fig. 1. A: Location map of Tatakoto atoll in French Polynesia; and B: satellite image of Tatakoto atoll (Quickbird imagery, 2.4 m spatial resolution).

The combination of spatially structured stock per habitats, differential susceptibility to mass mortality from west to east, and differential level of fishing pressure according to fisher range of behavior suggests that the lagoon is likely a tight mosaic of small areas with different exposure to fishing and mortality risk. As such, Tatakoto lagoon represents well the situation that occur in small islands where subsistence and fishing put resources at risk, and where climate-induced threats are an additional complication to design spatially explicit management plans (Bell et al., 2011).

2.2. Spatial data acquisition

Resource status was characterized by measuring *in situ* giant clam density at habitat scale (63 stations) and extrapolating to the entire lagoon using habitat maps. Densities were measured in 2004 and reported by Gilbert et al. (2006). The extensive survey implemented at Tatakoto atoll and methodological baselines are described by Gilbert et al. (2006).

Susceptibility to massive mortality was considered as the main driver of giant clam density in the past decade at Tatakoto (Andréfouët et al., 2013). Spatial data on susceptibility to mass mortality was directly issued from Andréfouët et al. (2013), who reported 91% mortality inside the enclosed shallow NTA and 59% outside, both values are an order of magnitude higher compared to other isolated islands (Apte and Dutta, 2010). Vulnerability is thus expressed as a percentage of change of density between 2004 and 2012.

We characterized the spatial distribution of fishing efforts by conducting interviews of local inhabitants in July and October 2013. Two interviews were specifically dedicated to the behavior of the most active fishers known from the local authorities. Then, seventeen interviews targeted randomly chosen households (one person interviewed by household) to map the range of fishing behavior and the associated range of fishing pressure. Interviewed people ranged from 15 to 80 years old and represented 7% of the population, but their answers were usually relevant to their entire household (spouse, children and parents), and likely represented well the population. During each interview, the questions aimed to clarify 1) the targeted size of fished giant clam; 2) depth of fishing; 3) fishing gears and tools used to collect, extract flesh from shells, and clean up giant clam flesh; 4) frequency of fishing trips; 5) catch weight; and 6) destination for catch (export to Tahiti, local consumption, etc.). For each of these 6 questions, a semi-quantitative index was defined using the key legend given in Table 1, and was attributed to each surveyed household. Euclidean distances and classification tree (group average method) were then established using Primer® 6.1.10 to provide a typology of fisher behavior.

Spatial maps of fishing effort were issued for each surveyed fisher. For fishers that swim, the fishing ground was defined arbitrary as the 100-m buffer around the mooring points, as fishers usually do not swim long distances without moving their boat (personal observation). Maps of fishing ground were compiled using the GIS Esri® ArcMap 10.1 software for each type of fishers found in the cluster. Spatial repartition of fishing effort was finally

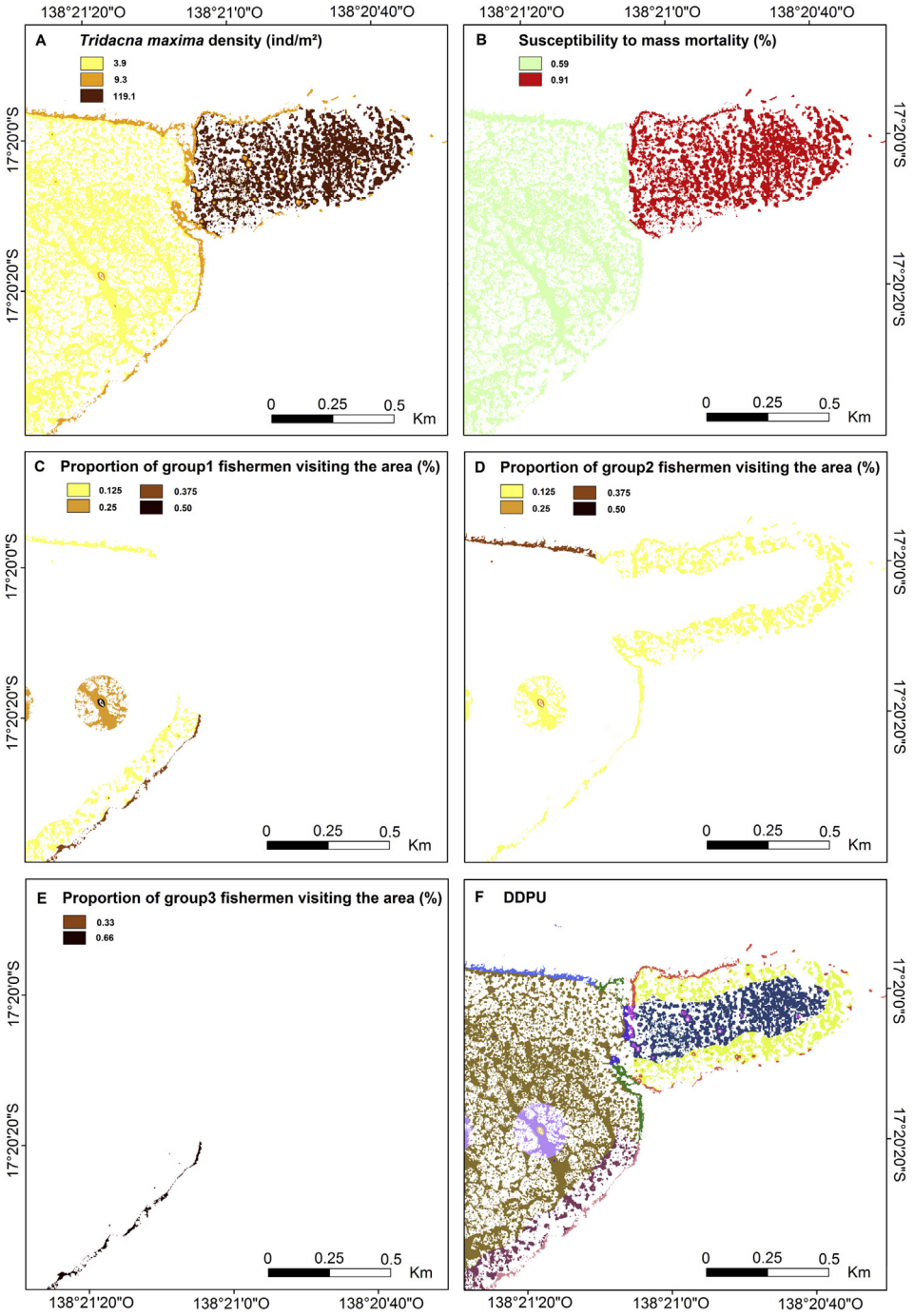

Fig. 2. Spatial data for the eastern part of Tatakoto atoll. A: density (from Gilbert et al., 2006); B: Susceptibility to mass mortality (from Andréfouët et al., 2013); C, D and E: fishing effort for the three clusters of fishers, 1, 2 and 3 respectively. A 100 m buffer around boat mooring points was used to define the fishing ground for swimming fishers; F: the DDPU map resulting from the overlay of the previous data maps. Each color represents a different planning unit. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

expressed in proportion of fishers visiting an area.

All data (i.e., giant clam density, susceptibility to mass mortality, and fishing pressure) were habitat-dependent, and all maps were therefore established using a habitat map for baseline (Andréfouët et al., 2005; Gilbert et al., 2006; Andréfouët et al., 2013). The spatial resolution (i.e., pixels' size) of the Quickbird satellite image used to map habitats was 2.4 m (Fig. 1B). However, reflectance values for one pixel can "spill over" to the adjacent ones (Bainbridge and Reichelt, 1988), we thus considered the minimum discernable unit, *sensu* Bainbridge and Reichelt (1988), to be 25 m^2.

2.3. Defining PUs

Two contrasted approaches were used to define PUs. First, maps of giant clam density, susceptibility to mass mortality, and fishing pressure established above were superimposed using the "Intersection" tool of GIS Esri® ArcMap 10.1 software, in order to obtain one single map. This "map overlay" approach provided irregular

Table 1
Semi-quantitative index value and corresponding meaning used during interviews to define a typology of fishers.

Description	Index value
Targeted size for giant clams	
Shorter than 12 cm	1
Between 12 and 15 cm	2
Longer than 15 cm	3
Depth of fishing	
Stay within foothold areas (less than a meter deep)	1
Occasionally swimming	2
Always swimming	3
Tools used for fishing	
Using knife and bag only	1
Additionally using fishing gloves	2
Additionally using a motorized boat or snorkeling gear	3
Additionally using a motorized boat and snorkeling gear	4
Additionally using rakes to sweep corals covering giant clams	5
Frequency of fishing trips	
Less than once a year	1
Less than once a month	2
More than once a month	3
More than once a week	4
Several times a week	5
Catch weight	
Less than 1 kg of cleaned flesh per month	1
Between 1 and 10 kg of cleaned flesh per month	2
Between 10 and 50 kg of cleaned flesh per month	3
Between 50 and 200 kg of cleaned flesh per month	4
More than 200 kg of cleaned flesh per month	5
Destination of catch	
Subsidence consumption of flesh only	1
Subsidence consumption of flesh and local gift	2
Subsidence consumption of flesh and gift (local and toward Tahiti)	3
Commercial activity (local or toward Tahiti)	4

PUs whose shape is directly driven by the distribution of each spatial data layer (DDPU, Fig. 2).

Second, a series of PU networks was defined following a regular square grid, with grid sizes of 25, 2500, 10,000; 40,000; and 160,000 m^2. Data where aggregated to fit the shape and scale of these pre-established PUs (Fig. 3), by computing the mean of data values falling inside each PU, weighted by the surface area covered by each value.

2.4. Assessing the relevance of PUs

The PU networks were compared using two criteria. First, the proportion of PUs sharing exactly the same combination of values for giant clam density, susceptibility to mass mortality and fishing pressure was calculated. This provided the level of redundancy of the network. Then, taking the smallest size of squared PU as reference (25 m^2), a data approximation term induced by the aggregation of data for PUs larger than 25 m^2 was calculated by eq. (1):

$$\bar{\delta} = \frac{1}{n}\sum_{n}\frac{\left|V_{ref} - V_x\right|}{V_{ref}} \quad (1)$$

where n is the number of 25 m^2 squares; and V_{ref} and V_x are the values of variable V for the 25 m^2 PUs and for the x m^2 PU respectively.

3. Results

3.1. Fishing pressure

The 19 interviews conducted with Tatakoto inhabitants identified 3 clusters of fisher behavior, respectively represented by eight (cluster 1 & 2), and three (cluster 3) interviewed fishers (Fig. 4A). All persons interviewed where potential fishers as they declared collecting giant clams, but some more occasionally than others.

Cluster 1 refers to professional fishers who collect giant clams regularly, usually searching for the largest giant clams, deep, and with enhanced fishing tools (Table 1, Fig. 4B). In particular, they use motorized boats for fishing (whether their own or borrowed to relatives), with enough power to cross the entire lagoon in less than an hour. Crop weights are high, and catches are usually for sell, whether for local islanders or for Tahiti's market.

The second cluster included less active fishers who are usually engaged in another activity (e.g., coconut farming, administrative employment) and for whom giant clam fishing therefore does not provide a significant income. They do not systematically target large clams, nor deep ones, use basic tools, and always catch small quantities. Catches are for sell and gifts, whether locally or toward Tahiti's market (Fig. 4B).

Cluster 3 included fishers who glean small giant clams in shallow areas (<1 m deep) with basic tools and only for occasional personal consumption.

The maps of fishing pressure were contrasted between the three clusters of fishers. The western area, close to the village was used by the three groups, but Cluster 1 of fishers also regularly visited by boat the patch reefs in the eastern and southern part of the lagoon. Conversely, Cluster 2 fishers preferentially visited the northern part of the atoll, where fishing grounds are accessible by road. Fishers that make the cluster 3 also occasionally visited by boat the southern areas next to small islands during week-ends, but collecting giant clams was not the main reason of their presence in these areas.

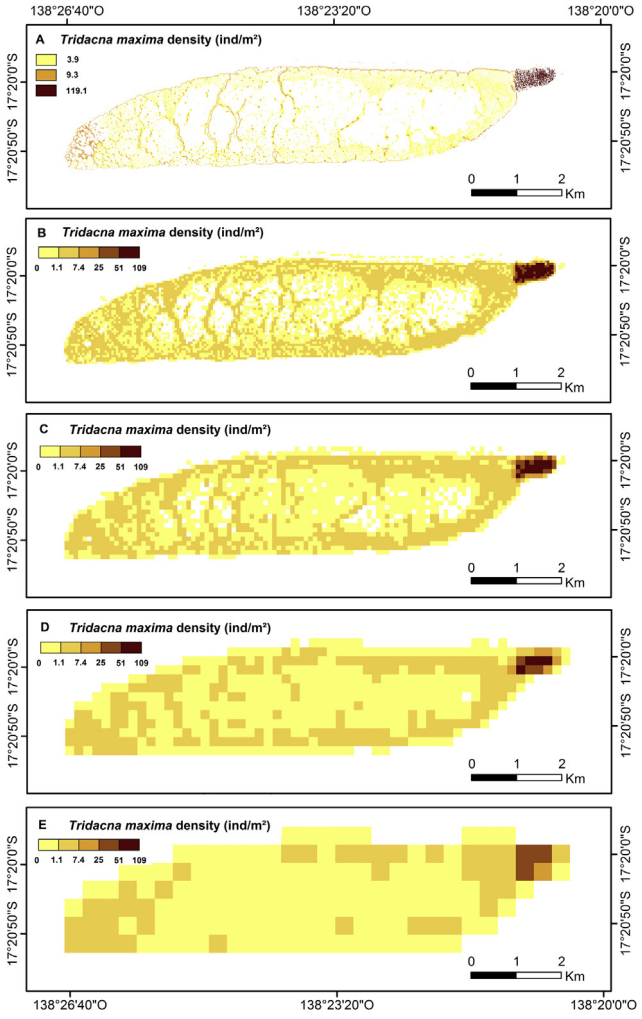

Fig. 3. Effect of data aggregation for different pre-established square grids. The figure illustrates the case for *T. maxima* density only, but similar processes are performed for susceptibility to mass mortality and fishing pressure as well. A: initial data; B: 50 m*50 m grid; C: 100 m*100 m grid; D: 200 m*200 m grid; and E: 400 m*400 grid.

3.2. Assessing the relevance of PUs

The overlay of spatial data yielded 23 DDPU (Fig. 2F) ranging in size from 956 m^2 to 2,106,591 m^2 (median: 38,819 m^2). Each DDPU is characterized by a unique combination of density, susceptibility to massive mortality, and fishing pressure. By contrast, the number of regular PUs was an increasing function of PU size (Fig. 5A), reaching 6096 and 286,134 PUs for cell sizes of 2500 m^2 and 25 m^2 respectively. Regularly gridded PUs always yielded redundant PUs, from 93% redundancy with 25 m^2 PUs down to 5% redundancy for 160,000 m^2 PUs.

Approximation induced by data aggregation from the initial data resolution (i.e., 25 m^2) to the smallest PU size (2500 m^2) was high for giant clam density ($\overline{\delta} = 215\%$) and fishing effort ($\overline{\delta} = 18.7\%$, 29.1% and 76.1% for fishing effort of cluster 1, 2 and 3 respectively). By contrast, the data approximation term $\overline{\delta}$ remained negligible for susceptibility to mass mortality events ($\overline{\delta}$ <0.03%). For all variables, data approximation quickly reached asymptotic values when PU size increased (Table 2; Fig. 5B).

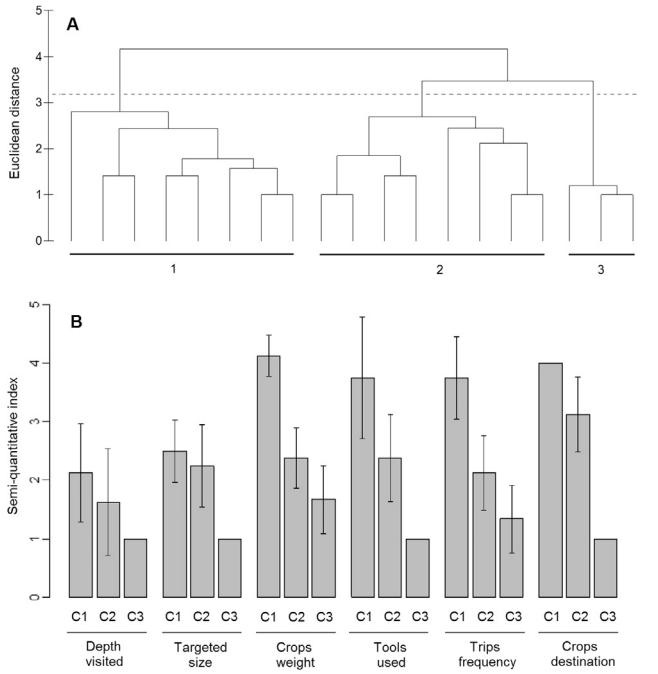

Fig. 4. A. Classification tree of fishers, based on the semi-quantitative indices in Table 1. Cluster 1 refers to professional fishers, while clusters 2 and 3 refer to non-professional and occasional fishers respectively. B: Mean ± SD of semi-quantitative index for depth and size of collected clams, catch weight, tools used for collecting, and destination of catch. C1, C2 and C3 refer to three clusters of fishers, Cluster 1, Cluster 2, and Cluster 3 respectively.

4. Discussion

4.1. PU, DDPU and data loss

The spatial aggregation of data usually leads to substantial change in data coverage and information content (Bian and Butler, 1999; Saura, 2004; Mora et al., 2008; Hermoso and Kennard, 2012; Andréfouët and Hamel, 2014). For the simple fishery of Tatakoto atoll, we also found aggregation to rapidly affect data values, even for small PU sizes (2500 m^2). As expected, the loss of spatial information was more pronounced for patchy distributed variables. This was especially true for giant clam density, since measured densities could vary by two orders of magnitude in close proximity depending on habitat distribution along the lagoon shore and patch reefs.

The degradation of spatial data to fit arbitrary PU size is likely to affect conservation plans and decision outcomes (Pressey and Logan, 1998; Nhancale and Smith, 2011; Hamel et al., 2013). For instance, the size of the planning unit was one of the most important criteria to optimize the trade-off between habitat conservation and fishing ground when designing MPA networks for small Pacific Islands (Hamel et al., 2013). Smaller units led to more satisfying trade-offs.

Data aggregation can have significant implications for modeling. Processes need to be modeled at the same resolution as the PU grid size. For instance, spawning success could be parameterized for each PU as a function of density. Here, a 215% mean underestimation of density was induced when aggregating data from 25 m^2 to 2500 m^2 PUs. This suggests that population modeling at this scale is unlikely to be fine enough to realistically predict for instance patterns of recruitment, density variations, and stock. This conclusion is certainly valid for most sessile organism fishery models in small islands.

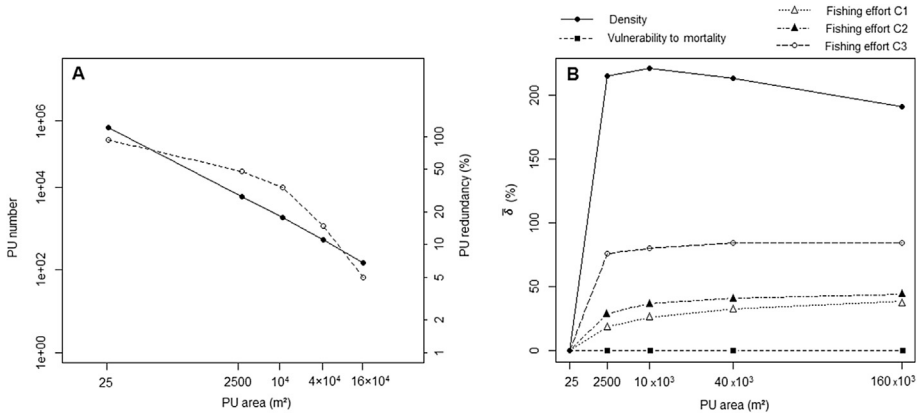

Fig. 5. A: PU number (solid line and solid circles) and PU redundancy (dashed line, open circles) obtained for the tested PU area. Redundancy is the amount of PUs which shares exactly the same combination of giant clam density, susceptibility to mass mortality and fishing effort. Note the logarithmic scales. B: Effect of PU sizes on data approximation term $\overline{\delta}$ for density, vulnerability to massive mortality, and fishing efforts. C1, C2, and C3 refer to the three clusters of fishers.

In terms of data loss, the DDPU approach is attractive to create a baseline to model small scale processes since it avoids data aggregation and preserves the initial data resolution. Map overlay techniques have been widely used in spatial studies (e.g., Hopkins, 1977; Cowling and Heijnis, 2001; Rowlands et al., 2012), and sometime criticized for their inaccuracy and underlying assumption especially for data at different resolutions (Bailey, 1988). However, in our case, map overlay is suitable because all integrated variables were by-products of the same habitat map and therefore were consistent in their initial spatial resolution (25 m^2).

4.2. PU versus DDPU: which approach for which purpose?

Both gridded and unstructured PU network have their advantages and drawbacks for tropical island management. The DDPU approach saves the accurate spatial distribution of data. It avoids both degradation of spatial data and redundant PUs. Redundant PUs have identical combination of values and unnecessarily increase the computing time required for calculation of population models. A DDPU approach is therefore of particular interest when spatial patterns of data and computing time is an issue, like for spatially integrated fishery models in small tropical islands (Van Wynsberge et al., 2013), and for complex and integrated ecological models (e.g., Ma et al., 2012b; Zhang et al., 2012). In terms of management, the network of DDPUs provides the most accurate view of the diversity of data configurations within the lagoon; an ideal monitoring protocol should look at replication across the 23 identified DDPUs, with adaptive strategy on the long run. The wide panel of DDPUs size (>10^4 m^2 or < 10^2 m^2), however, is not necessarily coherent with the scale at which decisions are typically made (PU around 10^3 m^2) in Pacific Island countries (Gilbert et al., 2005; Hamel et al., 2013). The lack of redundancy and wide range of PU sizes provided by the DDPU approach may also complicate management decisions and limit options for systematic conservation planning. A small number of non-redundant PUs (23 DDPU for Tatakoto) offers limited options when there are conflicts of interests and ambitious conservation goals (Hamel et al., 2013). A gridded PU network has the advantage of offering far more options, albeit at a cost of high number of PU and data degradation (Table 2). In that case, smaller conservation units should be favored since they allow for a more exact data representation and fewer objectives get over-achieved (see for tropical islands Mills et al., 2010; Hamel et al., 2013; see for land systems Pressey and Logan, 1995, 1998).

Choosing between one approach or the other is purpose-dependent and is a trade-off between spatial unit size, data redundancy, and spatial information loss. The PU approach allows exploring systematically conservation scenarios for decision-making, whereas the DDPU is more suitable to preserve data and for accurate fishery modeling. In practice, this is not a trivial binary choice and in many instances some intermediate solution could be required. A relevant example of a mix approach is the conservation GAP analysis achieved in the US for land systems (Jennings, 2000). Habitat maps, habitat suitability modeling, and administrative boundaries defining different management zones converge to draw practical conservation recommendations. However, to our knowledge, this approach has never been proposed to manage fisheries in tropical islands.

We hereafter suggest a three-step method to decide for DDPU, PU or an intermediate solution. We illustrate this protocol using the giant clam fishery model, but similar guidelines could be extended to any other models provided some adaptation.

Step 1: Map data relevant for key processes. For fishery, this means *a minima* mapping the giant clam density and fishing pressure. Other natural processes affecting resource dynamic can also be integrated (e.g., susceptibility to mass mortality, growth, connectivity and recruitment, reproduction efficiency, Van Wynsberge et al., unpublished data). Such effort is not trivial and it is costly (Ferrier, 2002), and although proxies and surrogates could be used (Weeks et al., 2010), this is not recommended (Deas et al., 2014; Hermoso and Kennard, 2012).

Step 2: Designing intermediate DDPU by overlay of the spatial

Table 2
Effect of PU sizes on data aggregation and PU redundancy. The data approximation term $\overline{\delta}$ for density, vulnerability to massive mortality and fishing efforts are shown. C1, C2, and C3 refer to the three clusters of fishers issued from the hierarchical classification tree.

PU area (m^2)	Number of PU	PU redundancy (%)	Density (%)	Vulnerability (%)	Fishing effort C1 (%)	Fishing effort C2 (%)	Fishing effort C3 (%)
25	286,134	92.8	0	0	0	0	0
2500	6096	47.7	215	2.97×10^{-2}	18.7	29.1	76.1
10,000	1867	33.5	221	8.94×10^{-2}	26.1	36.8	80.1
40,000	537	14.9	213	1.31×10^{-1}	32.6	40.7	84.5
160,000	151	5.3	191	1.70×10^{-1}	38.7	44.2	84.5

data identified and mapped in step 1. Step 2 creates a map of DDPU on the basis of input data only, each DDPU pointing to a unique combination of data values.

Step 3: Designing final PU according to conservation objectives and a priori management capacities. This approach is typically used in the conservation biology literature; but we suggest the process can be dependent on DDPU established in step 2, with for instance smaller PU designed for areas of high spatial complexity where aggregation processes highly affect data values.

5. Conclusion

In this study we compared the relevance of two approaches (i.e., regular planning units versus data driven planning units) for conservation planning in small tropical islands. We highlighted that planning unit configurations have a tremendous importance for fishery modeling and systematic conservation planning, even in simple biological and socioeconomic systems. This is in agreement with other recent studies that also focused on tropical islands (e.g., Hamel et al., 2013; Deas et al., 2014; Léopold et al., 2014). In particular, aggregation to pre-established planning units grids highly affected data even for planning units as small as 2500 m^2, while data driven planning units rendered well small scale patterns of interest but reduced redundancy. We stress the importance of collecting accurate data, conduct sensitivity analysis to data and management options, and carefully assess trade-offs to draw practical recommendations for tropical islands management and conservation.

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References

Andréfouët, S., Dutheil, C., Menkes, C., Bador, M., Lengaigne, M., 2015. Mass mortality events in atoll lagoons: environmental control and increased future vulnerability. Glob. Chang. Biol. 21 (1), 195–205.
Andréfouët, S., Gilbert, A., Yan, L., Remoissenet, G., Payri, C., Chancerelle, Y., 2005. The remarkable population size of the endangered clam *Tridacna maxima* assessed in Fangatau Atoll (Eastern Tuamotu, French Polynesia) using in situ and remote sensing data. ICES J. Mar. Sci. 62 (6), 1037–1048.
Andréfouët, S., Van Wynsberge, S., Gaertner-Mazouni, N., Menkes, C., Gilbert, A., Remoissenet, G., 2013. Climate variability and massive mortalities challenge giant clam conservation and management efforts in French Polynesia atolls. Biol. Conserv. 160, 190–199.
Andréfouët, S., Hamel, M.A., 2014. Tropical islands quick data gap analysis guided by coral reef geomorphological maps. Mar. Pollut. Bull. 81 (1), 191–199.
Apte, D., Dutta, S., 2010. Ecological determinants and stochastic fluctuations of *Tridacna maxima* survival rate in Lakshadweep Archipelago. Syst. Biodivers. 8 (4), 461–469.
Bailey, R.G., 1988. Problems with using overlay mapping for planning and their implications for geographic information systems. Environ. Manag. 12 (1), 11–17.
Bainbridge, S., Reichelt, R., 1988. An assessment of ground truth methods for coral reef remote sensing data. In: 6th Int. Coral Reef Symp., vol. 2, pp. 439–444.
Ball, I.R., Possingham, H.P., Watts, M.E., 2009. Marxan and relatives: software for spatial conservation prioritisation. In: Spat. Conserv. Prioritisation Quant. Methods Comput. Tools, pp. 185–195.
Bell, J.D., Johnson, J.E., Hobday, A.J., 2011. Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change. SPC FAME Digital Library, Noumea, New Caledonia.
Bian, L., Butler, R., 1999. Comparing effects of aggregation methods on statistical and spatial properties of simulated spatial data. Photogramm. Eng. Remote Sens. 65, 73–84.
Cowling, R.,M., Heijnis, C.,E., 2001. The identification of Broad Habitat Units as biodiversity entities for systematic conservation planning in the Cape Floristic Region. South Afr. J. Bot. 67 (1), 15–38.
Deas, M., Andréfouët, S., Léopold, M., Guillemot, N., 2014. Modulation of habitat-based conservation plans by fishery opportunity costs: a New Caledonia case study using Fine-Scale catch data. PLoS One 9 (5), e97409.
Ferrier, S., 2002. Mapping spatial pattern in biodiversity for regional conservation planning: where to from here? Syst. Biol. 51 (2), 331–363.
Ferrier, S., Wintle, B., 2009. Quantitative approaches to spatial conservation prioritization: matching the solution to the need. In: Spat. Conserv. Prioritisation Quant. Methods Comput. Tools, pp. 1–15.
Gilbert, A., Andréfouët, S., Gascuel, D., 2007. Dynamique des populations, modélisation Halieutique, approche de précaution et stratégie de co-gestion adaptative des pêcheries de bénitiers de trois îles de Polynésie française (Arue, French Polynesia).
Gilbert, A., Andréfouët, S., Yan, L., Remoissenet, G., 2006. The giant clam *Tridacna maxima* communities of three French Polynesia islands: comparison of their population sizes and structures at early stages of their exploitation. ICES J. Mar. Sci. 63 (9), 1573–1589.
Gilbert, A., Yan, L., Remoissenet, G., Andrefouët, S., Payri, C., Chancerelle, Y., 2005. Extraordinarily high giant clam density under protection in Tatakoto atoll (Eastern Tuamotu archipelago, French Polynesia). Coral Reefs 24 (3), 495.
Hamel, M., Andréfouët, S., 2010. Using very high resolution remote sensing for the management of coral reef fisheries: review and perspectives. Mar. Pollut. Bull. 60 (9), 1397–1405.
Hamel, M.A., Andréfouët, S., Pressey, R.L., 2013. Compromises between international habitat conservation guidelines and small-scale fisheries in Pacific island countries. Conserv. Lett. 6 (1), 46–57.
Hermoso, V., Kennard, M., 2012. Uncertainty in coarse conservation assessments hinders the efficient achievement of conservation goals. Biol. Conserv. 147 (1), 52–59.
Hopkins, L.D., 1977. Methods for generating land suitability maps: a comparative evaluation. J. Am. Plan. Assoc. 43 (4), 386–400.
Jennings, M.D., 2000. Gap analysis: concepts, methods, and recent results. Landsc. Ecol. 15 (1), 5–20.
Léopold, M., Guillemot, N., Rocklin, D., Chen, C., 2014. A framework for mapping small-scale coastal fisheries using fishers' knowledge. ICES J. Mar. Sci. 71 (7), 1781–1792.
Ma, C., Zhang, G.,Y., Zhang, X.,C., Zhao, Y.,J., Li, H.,Y., 2012a. Application of Markov model in wetland change dynamics in Tianjin Coastal Area, China. Procedia Environ. Sci. 13, 252–262.
Ma, C., Zhang, G.,Y., Zhang, X.,C., Zhou, B., Mao, T.,Y., 2012b. Simulation modeling for wetland utilization and protection based on system dynamic model in a coastal city, China. Procedia Environ. Sci. 13, 202–213.
Mills, M., Pressey, R.L., Weeks, R., Foale, S., Ban, N.C., 2010. A mismatch of scales: challenges in planning for implementation of marine protected areas in the Coral Triangle. Conserv. Lett. 3 (5), 291–303.
Moilanen, A., Wilson, K., Possingham, H., 2009. Spatial Conservation Prioritization: Quantitative Methods and Computational Tools. Oxford University Press, Oxford, UK.
Mora, C., Tittensor, D., Myers, R., 2008. The completeness of taxonomic inventories for describing the global diversity and distribution of marine fishes. Proc. R. Soc. B-Biol. Sci. 275 (1631), 149–155.
Nhancale, B., Smith, R., 2011. The influence of planning unit characteristics on the efficiency and spatial pattern of systematic conservation planning assessments. Biodivers. Conserv. 20 (8), 1821–1835.
Pelletier, D., Mahévas, S., 2005. Spatially explicit fisheries simulation models for policy evaluation. Fish Fish. 6 (4), 307–349.
Pressey, R., Logan, V., 1995. Reserve coverage and requirements in relation to partitioning and generalization of land classes: analyses for western New South Wales. Conserv. Biol. 9 (6), 1506–1517.
Pressey, R., Logan, V., 1998. Size of selection units for future reserves and its influence on actual vs targeted representation of features: a case study in western New South Wales. Biol. Conserv. 85 (3), 305–319.
Pressey, R., Nicholls, A., 1989. Application of a numerical algorithm to the selection of reserves in semi-arid New South Wales. Biol. Conserv. 50 (1), 263–278.
Rowlands, G., Purkis, S., Riegl, B., Metsamaa, L., Bruckner, A., Renaud, P., 2012. Satellite imaging coral reef resilience at regional scale. A case-study from Saudi Arabia. Mar. Pollut. Bull. 64 (6), 1222–1237.
Saura, S., 2004. Effects of remote sensor spatial resolution and data aggregation on selected fragmentation indices. Landsc. Ecol. 19 (2), 197–209.
Weeks, R., Russ, G.R., Bucol, A.A., Alcala, A.C., 2010. Shortcuts for marine conservation planning: the effectiveness of socioeconomic data surrogates. Biol. Conserv. 143 (5), 1236–1244.
Van Wynsberge, S., Andréfouët, S., Gilbert, A., Stein, A., Remoissenet, G., 2013. Best management strategies for sustainable giant clam fishery in French Polynesia islands: answers from a spatial modeling approach. PLoS One 8 (5), e64641.
Zhang, X.,C., Ma, C., Zhan, S.,F., Chen, W.,P., 2012. Evaluation and simulation for ecological risk based on emergy analysis and Pressure-State-Response Model in a coastal city, China. Procedia Environ. Sci. 13, 221–231.