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Are different levels of habitat description good surrogates of each other? An example using coral reef geomorphology.

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Are different levels of habitat description good surrogates of each other? An example using coral reef geomorphology.

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Abstract

Marine protected areas (MPAs) have been highlighted as an efficient tool for biodiversity conservation but adequate conservation plans may require substantial data. Acquisition of biodiversity (species) data is time and money consuming and under the hypothesis that biodiversity is related to habitats, use of habitat as surrogates of biodiversity is appealing. However, this has remained difficutlt to justify due to bias in biodiversity data itself. Nevertheless; asssuming that the potential exists, the next question is "which level of habitat description is the most adequate to substitute species list; are there any differences between habitat descriptions and can they be used one for another?" In other words, can habitat descriptions be surrogates of each other? We focus here on the later question. For coral reef habitats, assessment of surrogacy between different levels of description is possible using a worldwide geomorphological data set and habitat typology from the Millennium Coral Reef Mapping Project. Here, using this typology, we studied surrogacy between three levels of geomorphological description for the coral reefs of 19 Pacific countries. We used two different approaches: a pattern-based and a selection based approach. For each pairs of level description, the level of coarsest description was tested as surrogate for the level of finest description (reference level). Surrogacy for all three combinations of surrogate/reference levels of habitats description was satisfying for both pattern based and selection based approaches. Surrogacy is best between the two most precise levels of description. Using the 19 countries, three levels of habitat description and two surrogate approaches (pattern-based with correlation of richness, and selection-based with 3 representation objectives), we discuss the influence of geomorphological complexity on the results. The final conclusions suggest that the use of coarse habitat descriptions is justified in many cases, since it can substitute effectively finer levels of descriptions.

Keywords: conservation planning, surrogacy, habitat, coral reefs, geomorphology, Millenium Coral Reef Mapping Project.

Contents

Introduction

Marine Protected Areas (MPAs) are efficient tools for biodiversity conservation whereas they protect species, communities and ecosystems (Cvitanovic et. al, 2012). As conservation planning attempts to represent and maintain the biodiversity of the targeted region in a reserve network, MPAs implementation targets the inclusion of the highest amount of biodiversity in a limited space. The first step in conservation planning is often to measure and map biodiversity in the focal area (Margules & Pressley, 2000). True estimators of biodiversity (species diversity, genes) can be used to estimate real biodiversity (Sarkar and Margules, 2002), but their surveys are time and money consuming. This leads to use "second hand" indicators intending to represent these true estimators. These indicators are estimator surrogates (Sarkar et al, 2005, Reyers et al. 2000). These estimator surrogates are units ultimately used to represent biodiversity when no other data exist. This can include environmental data (Ferrier & Watson, 1997), indicator species (Beger et. al, 2007, Ward et. al, 1999), flagship species, or habitats (Dalleau et al, 2012) .

The use of habitat for coral reef biodiversity studies is interesting because it is the only level of biological description that can be mapped from remote sensing images at large spatial scale, thus providing full data coverage without spatial gaps for a given area (Hamel & Andréfouët, 2010, Andréfouët, 2008). For coral reefs, their efficiency as estimators surrogate of species as been tested several times, with contrasted results, partly likely due to different description levels of habitat structures (Arias-Gonzales et al. 2012, Van Wynsberge et al. 2012, Dalleau et al 2010). Thus, despite their theoretical potential for conservation scenario, the value of habitats for conservation planning and as surrogates remains poorly understood. In particular, there are no clear emergent guidelines to help selecting an adequate level of habitat description to use as surrogate of a given species assemblages (or community). One difficulty in testing the effectiveness of habitats level as surrogate to biological true estimators of biodiversity has been recently reemphasized (Van Wynsberge et al. 2012) : the biological true estimator itself and its own bias, given a sampling strategy and effort.

Indeed, in previous studies, all the tests on the value of habitats as surrogates necessarily used some sort of biological dataset as a reference. However, this reference data set is itself specific in terms of sampling efforts, strategies and quality, and this may strongly bias the assessment of the value of the surrogate (Van Wynsberge et al. 2012). This will likely remain a challenge difficult to overcome, and it is not safe to predict that the problem will be resolved one day. Thus, does that mean that using habitats as surrogates of biodiversity is necessarily a dead-end? Not necessarily. Indeed, according to the "habitat heterogeneity hypothesis", habitat richness and specie richness are positively linked (Simpson, 1949, MacArthur & Wilson, 1967), and thus habitats should be theoretically used as true estimator of biodiversity instead of biological data. Under this reasonable hypothesis, many still propose conservation plans using habitats as a cost-effective way to establish conservation plans, and, more importantly, habitats can be explicit conservation targets themselves. Several coarsely defined habitats are listed as priority conservation targets (seagras beds, mangroves, coral reefs, estuaries), and thus habitat in itself can be included in planning exercises as targets or as surrogates of biodiversity (Torres-Pulliza et al. 2013). Under this logic, it is interesting to test how different habitat descriptions are commutable, without bias. When used as true estimator of biodiversity, habitat description should be, in principles, as precise as possible. However, similar to biological census, precise habitat data have a cost, in term of money and time for acquisition and mapping. Use of coarser habitat description would allow reducing this cost. That is why, in this paper, we explore the potential for different levels of habitat description as surrogate of each other.

A habitat, in a mapping context is often described as a hierarchical entity, using a variety of geomorphological, structural, benthic and taxonomic descriptors. The amount of informed descriptors is dependent on time, money and expertise. Often, compromises on the amount of detail need to be done depending on the surface area to map and resources available. Generally, habitat maps based on geomorphological attributes are faster and cheaper to produce than habitat maps detailing architecture, benthic cover and dominant structural species. Because geomorphological maps are easier and cheaper to produce, it is interesting to ask if geomorphological maps could be effective surrogates of other habitat maps. Using habitat maps of different level (biological and geomorphological), it is possible to asses surrogacy relation between those levels. For instance, in the Seychelles Islands, Hamylton et. al. (2012) compared with statistical measurements of good-fit (thus using a pattern-based approach) if coarse geomorphological maps and computed geomorphological richness (number of mapped classes) could be good predictor of habitat richness when habitats are mapped at a much finer level of thematic precision. The results were positive, but several caveats were reported.

First, generalizing the method used by Hamylton et. al. (2012) on larger areas than one group of Seychelles reefs would be difficult. Indeed, nowhere exists large spatial coverage of detailed habitat maps. Second, when maps are available but come from different sources, significant product homogeneization may be needed. In fact, it is virtually impossible to systematize a comparison between different levels of mapping at large scale. The only data source available widely to test the surrogacy power of one level of maps to another is the Millennium Coral Reef Mapping Project (MCRMP). MCRMP created digital coral reef maps according to a worldwide geomorphological typology. Maps were created using a global coverage of very high resolution Landsat 7 ETM+ satellite images (Andréfouët et al., 2006). Although the 30 meters spatial resolution of those images do not authorize precise benthic cover description, integration of exposure to swell and depth information in the MCRMP typology increases the richness of this geomorphological classification (Andréfouët et al., 2006). The MCRMP typology is hierarchical and composed of 5 levels of geomorphological thematic description. The consistent hierarchy and mapping for most reefs worldwide offers the possibility to test how different levels of habitat descriptions could be surrogates of each other. However, it is important to consider that conclusion on habitat surrogacy may vary with the approach used for surrogacy measurement.

Indeed, conclusions on habitat surrogacy may vary depending on how surrogate efficiency is measured. This calls for clarifying the different types of surrogates commonly used in the literature. Surogates have been defined and tested using two main approaches. Namely, pattern-based surrogacy and selection based surrogacy approaches offer two distinct ways to measure how one data set can be used as a substitute for another. As reemphasized by Andréfouët et. al (2012) pattern-based surrogates are entities that have a statistical link (typically a good correlation) with the reference they substitute. Although those surrogates can be used for conservation, there is no guaranty that a network reserve design made according to the surrogate will be as effective as with the original data. Conversely, selection-based surrogates show their efficiency when used in a network design, and not by their statistical link with the original data. The somewhat counter-intuitive fact that good pattern-based surrogates are not necessarily good selection-based surrogates is inherent to the design, which often uses complementary criteria between locations (Andréfouët et al. 2012).

As selection based surrogacy is assessed through network design, it may be sensible to parameters forcing this design. Particularly, conservation objectives values used for network design may have influence on surrogacy, as they influe on design (Warman et. al. 2004a). In this study, we used MCRMP products of 19 contrasted countries to analyse surrogacy relation between different levels of geomorphological habitats. We used these two different surrogates evaluation approach, and then investigate on conservation objective influence on surrogacy effectiveness.

Materiel and Methods

1- Studied areas

The maps used for our analysis come from the Millennium Coral Reef Mapping Project, which is the only coral reef standardized maps available throughout the Pacific Ocean. We consider the reefs of 19 countries: Cook Islands, Federal State of Micronesia, Fiji, French Polynesia, Guam, Hawaii, Kiribati, Marshall, Northern Mariana, New Caledonia, Palau, Papua New Guinea, Samoa, Solomon, Tokelau, Tonga, Tuvalu, Vanuatu and Wallis and Futuna (Fig. 1). The 19 studied countries offer a gradient of number of L5 classes, number L4 classes and number of L3 classes, total coral reef area (km²) and number of planning units used for conservation planning (Table 1).

2- References and surrogates data (coral reef geomorphological levels)

Here, we aim to assess mutual surrogacy between three levels of geomorphological coral reef maps using a worldwide standardized map dataset. The maps come from the Millennium Coral Reef Mapping Project (MCRMP). The typology used in MCRMP is valid worldwide, and thus standardized for all the countries considered. In other words, this means that maps from different areas can be compared. This MCRMP hierarchical classification includes five levels of geomorphological thematic description, going from the coarsest description (Level 1: oceanic *vs* continental, Level 2: e.g. oceanic island, or continental fringing reef) to more precise description (Level 3: e.g. shelf patch reef complex, or ocean exposed fringing , Level 4: e.g. reef flat, terrace, pass or forereef) and Level 5.

For any given area, each level offers a different product when mapped (for example maps at levels 3, 4 and 5 for two areas, see Appendix 1). The first three levels (L1, L2 and L3) are summarized in Fig. 2. The finest level is 5th level, which is a unique combination of all the previous level information (e.g.: the reef flat of a fringing reef exposed to the ocean, in a oceanic island). This 5th level includes 795 units worldwide. These 795 classes describe all the reefs worldwide (but this does not mean that any given reef includes 795 classes (see Appendix 2, Millenium typology of Guam and Tokelau). In fact, for any given reef, the number of L5 classes includes 1 to 20 classes at most.

Here, we aim to study the surrogate potential of L4 as a substitute for L5, L3 as a substitute for L5 and L3 as a substitute for L4 using products from the 19 selected countries.

3. Surrogacy assessment methods

For every country, the coral reefs areas were gridded using a 5 by 5 kilometres grid. Each cell of the grid is a planning unit.

3.1. Pattern-based surrogacy

Pattern-based surrogacy was tested for each country. To assess surrogacy between two geomorphological levels, correlation was measured between class richness contained in each planning units for those two levels: non parametric Spearman correlation coefficient was calculated between the number of L3 and L5 classes, between the number of L4 and L5 classes, and between L4 and L3 classes in each planning units.

3.2. Selection-based surrogacy

Different scenario were tested with Marxan, a free software for conservation planning (Ball and Possingham, 2009) applying the "minimal set problem" to reserve design, or in other words, achieving a certain representation of biodiversity features for the minimum cost (McDonnel et al. 2002).

The scenarios, fairly simple, aims to include in the network a percent (10, 20 or 30%) of the surface area of each geomorphological class found in the studied country. The scenarios are run for every level of the MCRMP products considered here (L3, L4 and L5). In other word, inclusion of 10, 20 or 30% of each class composing a geomorphological level is targeted.

The "cost" of the design is proportional to the number of planning unit selected, forcing Marxan to found the best ratio between the conservation target achievement (10, 20 or

30% of the surface area of each geomorphological entity) and the number of planning units included in the network in order to minimize this cost. Each scenario was run 100 times, producing 100 reserves designs. Marxan typically provides two outputs from those 100 runs: 1/ the irreplaceability for each planning unit; and 2/ a best design. Irreplaceability is the selection frequency of each planning units. In other words irreplaceability is, for a conservation scenario, the number of times a planning unit has been selected on the final design. Irreplaceability is here calculated for 100 runs, thus its value range from 0 to 100. Conversely, the best design is the one among the 100 which reaches the lowest cost (See Appendix 3. for representation of irreplaceability and best design).

The boundaries length modifier (BLM) is a fairly standard planning parameter frequently used, allowing forcing or not the network to be compact. Here, we did not set any spatial constraints that could affect the primary geomorphological conservation objective. We wanted networks to be built upon criteria of habitat representativity first, and thus compacity was not used here.

For each conservation target (10%, 20% or 30% of entities included in reserve), effectiveness of surrogates was measured by calculating the overall correlation between the selection frequency of each planning units at the two different geomorphological levels. Non parametric Spearman coefficient was used to measure the correlations.

4. Factors influencing surrogacy potential

4. 1. Sensitivity to levels of description

In order to compare efficiency of the three surrogates considerate (L3 for L4, L3 for L5 and L4 for L5), we compared and tested means of their correlation coefficient with non parametric Kruskal Wallis and Mann-Whitney Wilcoxon test.

4. 2. Sensitivity to conservation planning parameters

The conservation target (10%, 20% and 30% inclusion of each geomorphological class) itself may have an influence on surrogacy effectiveness. Thus, the outputs for these different scenarios are explicitly compared and tested. Note that pattern based surrogacy is independent from a conservation target, which is a parameter specific to a reserve design process.

Results

1. Examination of pattern-based results

1.1. Detailed results

The correlations achieved for each combination of surrogate/reference levels (L3/L4, L3/L5 and L4/L5) are presented for each country in Fig. 3. The correlation between the number of L4 and L5 classes, all planning units included, is extremely high and significant for all countries. Correlation between L3 and L4, as well as correlation between L3 and L5 are generally high and significant ($p<0.001$), but there are variations between the studied countries.

1.2. Surrogate effectiveness, all countries included

The correlations achieved for each combination of surrogate/reference levels averaging all country, is presented in Fig.4. It allows highlighting tendencies on correlation between surrogates and references: means correlation is significantly higher between L4 and L5 (0.983) than between L3 and L5 (0.859) and between L3 and L4 (0.83). Mean correlation between L3 and L4 and between L3 and L5 are not significantly different.

2. Examination of selection-based results

2.1: Detailed results

The correlation achieved for each combination of surrogate/reference levels are represented for each country and each target value (10%, 20%, 30%) in Fig. 5. The correlation between irreplaceability of planning units is significant for the three combinations of surrogate/reference levels in almost all cases. However, the values of correlation coefficients are variable: between 0.37 and 0.98 overall. The only 2 cases for which correlation can not be established are: between L3/L4 and between L3/L5 for Tokelau with 10% target.

2.2: Surrogate effectiveness per country, all conservation objectives included

The correlations achieved for each combination of surrogate/reference, averaging all conservation objectives are presented for each country in Fig. 6. This figure highlights the fact that efficiency of surrogate can vary in function of the country. For example, L4 surrogate for L5 reference is the most efficient surrogate/reference combination for Tokelau and Tuvalu, but the less efficient for Samoa and Tonga.

2.3. Surrogate effectiveness, all conservation objectives included, all countries included

The correlations achieved for each combination of surrogate/reference, averaging all countries and all conservation objectives are presented in Fig. 7. It allows highlighting tendencies on correlation between surrogates and references: mean correlation is significantly higher between L4 and L5 (0.781) than between L3 and L5 (0.683) and between L3 and L4 (0.708). Mean correlation between L3 and L4 and between L3 and L5 are not significantly different.

2.4 Influence of conservation objectives per country, all surrogates included

The results achieved for 10%, 20% and 30% conservation targets, averaging all reference/surrogate combination, are presented in Fig. 8. According to this figure, conservation objectives influence surrogacy. Indeed, for many countries, correlations are slightly higher for higher representation thresholds. However, this trend is not systematic. For example, in Tuvalu, correlation actually decreases when conservation target increases.

2.5 Influence of conservation objectives, all surrogates included, all country included

Results achieved for 10%, 20% and 30% conservation targets, averaging all countries and all surrogate/reference combinations are presented in Fig. 9. It allows highlighting the influence of conservation objectives on surrogacy. Indeed, correlation means increases with more demanding conservation targets: it reach 0.677, 0.735 and 0.760 for respectively the 10%, 20%, and 30% target. If mean correlation for 30% target is significantly higher than mean correlation for 10% target, this is not the case between 10% and 20% target, and neither between 20% and 30% target.

3. Synthesis of selection-based vs pattern-based results

Results for selection-based surrogacy averaging all surrogates and all conservation targets, as well as result for pattern-based surrogacy averaging all surrogates are presented in Fig. 10. On this figure, we can obviously see that selection-based and pattern-based surrogates do not co-vary when looking at the diversity of countries. Indeed, countries with the lowest pattern based-correlation may have good selection-based surrogacy, while countries with the best pattern-based correlation do not necessarily diaply good results on selection-based surrogacy.

Discussion

1. Surrogacy between different levels of habitat description

To our knowledge, this is the first time that levels of habitat description are directly tested as surrogates to each others. Our results show very high potential of coarse geomorphological description levels as surrogates for more detailed geomorphological description levels for coral reefs. Indeed, for both surrogacy measurement tested, correlation obtain between levels tested is high and significant for almost every country. The only non significant correlation values are obtain for conservation-based surrogacy on Tokelau with 10% target, and can be explained by the very small number of planning units for this country (Spearman coefficient is less significant for small sample size). Between the three combinations of surrogate/reference tested (L3 for L4, L3 for L5 and L4 for L5), the better surrogacy is performed by L4 as surrogate for L5 reference. This is interesting, because as L4 and L5 are the levels of Millenium typology describing the most precisely, they may be linked more closely than coarse levels (L3, L2) to others habitat descriptors such as benthic cover, and thus to species composition (Dalleau et al., 2010).

However, as discussed by Grantham et. al (2010), effectiveness of surrogates may vary depending on the measurements used. In their study, they highlighted that values obtained for surrogates effectiveness by calculating Spearman correlation between irreplaceability of planning units are more significant that all values obtain with other measurement. Even if their method for evaluation of planning unit irreplaceability differs from the one we used, their results show the interest of using several measurement methods for the assessment of surrogacy. Thus, analyse of surrogacy between habitats levels with other methods, as incidental representation (Warman et. al, 2004b) or accumulation richness (Ferrier & Watson, 1997, Ferrier et. al, 2002) would allow enhancing our conclusions on efficiency of this surrogacy.

2. Effects of conservation planning parameters on surrogacy

Concerning the conservation objectives, our results suggest that the largest the target is, the better the correlation (for selection based surrogacy). However, this may be an artefact du to the higher probability of two planning units to be selected in design for both habitats levels tested when the total amount of planning units selected is more important (which is likely the case when target increases substantially).

For selection-based surrogacy, it would also be interesting to explore the effect of the conservation planning parameters that we have left stable here. The influence of boundaries length modifier and size of planning units in reserve design is undeniable (Nhancale & Smith, 2011). As selection-based surrogacy is inherently related to a reserve design, it would be interesting to investigate influence of BLM value and size of planning units on selection-based surrogacy. In this experiment, BLM was systematically null, in order to avoid spatial constraints and stay focus on habitats conservation objective. However, in conservation planning, a BLM value offering the best trade-off between reserve system boundary length and the total area of the reserve system, called optimal BLM value, is often used (Stewart & Possingham, 2005). As BLM value strongly constrained reserve design, it may influence the efficiency of selection-based surrogates. We explored that issue for selection based surrogacy values obtained between L3/L4, L3/L5 and L4/L5 with 20% conservation objective on Papua New Guinea. It appears that surrogacy measurement is relatively higth when BLM is null, decrease until the optimal BLM value and increase with BLM value when optimal BLM value is exceeded. In other words, there is a parabolic relationship type $x = y^2$ between surrogacy value and BLM value, with surrogacy in y reaching its minimum value for x equal to optimal BLM. This trend needs to be confirmed for the others countries. Further investigations regarding the influence of BLM value on surrogacy are advised.

Concerning the size of planning units, it would have been interesting to define their size depending on the country size, fragmentation and extent. Indeed, here, the smallest country (Tokelau) can be covered with only 21 planning units. In addition, this would have allowed avoiding “empty” planning units, like for Vanuatu, where only 8% of planning units areas we defined contained coral reefs (92% of remaining space cover land or marine non reef area). The influence of the size of planning units from one country to another warrants further investigations for patter-based and selection-based surrogacy, since correlation coefficient are calculated between planning units for both of those approach.

3. Selection-based surrogacy vs Pattern-based surrogacy

Results obtains with pattern-based approach are not necessarily transposable to conservation-based approach (Andréfouët et. al, 2012). Indeed, pattern-based measures are sensible to relationship between richness of reference and surrogate level of habitat description, when selection-based measures are more sensible to complementarity among classes contained in those levels (William et. al, 2006). Regarding our results of effectiveness for different habitats description levels considered as surrogate to each other, results obtained with conservation-based and pattern-based approach are here similar (means correlation is significantly higher between L4 and L5 than between L3 and L5 and between L3 and L4).

However, results obtained with conservation-based and pattern-based approaches do not co-vary when looking at the diversity of countries. Thus, similarities in effectiveness measurement with both approaches do not imply similar sensibility of these aproaches to parameters varying between country (ie number of classes in levels 3, 4 and 5, total coral reef area and number of planning units covering this area, cf. Table 1). Considering this, it would be interesting to further investigate the effect of each parameter separately, on pattern based measurement, and on selection based measurement. This may bring explaination on this non-covariance.

Influence on reserve design of spatial scale, features size (our classes), and planning unit size have been underscored by Warman et. al. (2004a) and Hess et al. (2006). As selection based result is, by definition, dependant on reserve design, it would be interesting to see if such parameters also influe on surrogacy. Surrogacy assessment between standardized levels of description on several countries offers possibility to identify trends in influence of countries parameters on surrogacy, hence the interest of additional investigation on this issue.

4. Prospect for conservation planning

Large scale conservation planning allowed avoiding the usual shortcoming of marine protected area when not thought and established as being part of a network (Agardy et al. 2011). Indeed, external drivers of change, including climate change, often overwhelm any progress made at smaller-scales and issues of representation and connectivity can not be resolved at local scale given the continuous and incremental pressure on ecosystems (Fieldman et al. 2012). Conservation of blocks of natural habitat large enough to be resilient to large scale perturbation and long term changes are advised to achieve conservation and sustainability on a grand scale (Bensted-Smith et. al, 2012). In particular, for coral reefs ecosysytems, importance of large scale networks of reserves on resilience have been highlighted by Underwood et al (2013) and Almany et al (2009). In this context, our results bring to the conclusion that the use of coarse geomorphological levels of habitats description for large scale conservation planning is useful and may be recommended. Indded, those levels are good surrogates to more precise description levels, themselves linked to habitat maps including biological information (Hamylton et. al., 2012). This relation between habitat and biological map had been studied and small scale (Seychelles Islans). If generalization of the method used by Hamylton et. al. (2012) on larger areas than one group of Seychelles reefs would be difficult, we can suppose that this relation between habitat and biological map is generally true for smaller scales considered separately. In other words, there is probably no constant relation between geomorphological maps and biological map at large scale, but at smaller scale, considering separately each portion composing the large scale, this relation exists. This means that conservation planning using geomorphological habitat description would allow protecting both species and habitat.

From a regional point of view, our results confirm the possibility to use different levels of habitat description as surrogate of each other for conservation planning. This opens new perspectives for design of reserve network at large scale. Indeed, coarse habitat descriptors are often mappable from remote sensing images, allowing to have spatially exhaustives data set at lower cost useable for conservation planning. Mapping habitat at large scale induces loss in precision. Thus, as our results highlight the performance of coarse habitat maps for conservation planning, we would advocate use of habitats maps to identify priority conservation areas in broad region.

To the initial question: what is the adequate level of habitat description to use as surrogate for species?, we can not give a systematic answer, but we can emphasis that this is not a real issue, considering that different levels of description can substitute themselves in conservation planning.

Conclusion

Study of different levels of habitats description as surrogates to each other with a worlwide typology of coral reef geomorphology leads to several conclusions: 1. different levels of geomorphological habitat description are good surrogates to each other 2. Sorrogacy between levels of geomorphlogical description depend on combinaison of level considerated and conservation target (for selection based surrogacy) 3. Similarity in conservation-based and patter-based results concerning surrogacy between levels does not imply that they are sensitive to the same parameters 4. From a conservation point of view, this study highlights the possibility to use coarse habitat description in the design of reserve networks. This outcome is especially interesting for large scale conservation planning, as it emphasised the interest of standardized data over precise data when broad area are considered.

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Figure caption

Fig.1. Excusive Economic Zones of Pacific countries. Are represented in grey countries for which MCRMP products are available.

Fig. 2 : Hierarchical classification scheme used for the Millenium mapping project. Three levels are represented; the main division is about oceanic and continental reef. Node (in italic) and blocks (colored) are the second and the third level in the classification hierarchy. The fourth level, not shown here, is made of 65 geomorphological units that enter in the composition of different nodes and blocks. A total of 795 unique classes are thus assigned. (Andréfouët et al.,2006).

Fig. 3 : Fig. 3 : Spearman correlation coefficients obtained for pattern based surrogacy. For each country, the correlation between L3/L4, L3/L5 and L4/L5 is represented. As all correlation coefficient are highly significant ($p>0.001$), significance levels aren't indicated. Countries are ranked in ascending order for L5 richness. Abbreviations: N.M : Northern Mariana, W&F : Wallis and Futuna, Cooks : Cooks Islands, F.P : French Polynesia, N.C: New Caledonia, P.N.G : Papua New Guinea.

Fig. 4. Representation of correlations obtained for pattern-based surrogacy between L3/L4, L3/L5 and L4/L5. Those correlations value are obtained by calculating the mean of correlation coefficient for all countries.

Fig. 5 : Representation of Spearman correlation coefficients obtained for selection-based surrogacy between L3/L4, L3/L5 and L4/L5 at each country. Abbreviations: N.M : Northern Mariana, W&F : Wallis and Futuna, Cooks : Cooks Islands, F.P : French Polynesia, N.C: New Caledonia, P.N.G : Papua New Guinea. Countries are ranked in ascending order for L5 richness. Fig 5.a, b, c respectively present those results for 10%, 20% and 30% conservation target. Minus sign indicate low significance levels (- - $p>0.01$, - $p>0.05$, nothing when $p<0.01$)

Fig. 6. Representation of correlations obtained for selection-based surrogacy between L3/L4, L3/L5 and L4/L5 at each country. Those correlation values are obtained by calculating the mean of correlation coefficient for 10%, 20% and 30% target. Abbreviations: N.M : Northern Mariana, W&F : Wallis and Futuna, Cooks : Cooks Islands, F.P : French Polynesia, N.C: New Caledonia, P.N.G : Papua New Guinea. Countries are ranked in ascending order for L5 richness.

Fig. 8. Representation of correlations obtained for selection-based surrogacy with 10%, 20% and 30% target at each country. Those correlation values are obtained by calculating the

mean of correlation coefficient for.the three surrogate/reference combinations: L3/L4, L3/L5 and L4/L5 Abbreviations: N.M : Northern Mariana, W&F : Wallis and Futuna, Cooks : Cooks Islands, F.P : French Polynesia, N.C: New Caledonia, P.N.G : Papua New Guinea. Countries are ranked in ascending order for L5 richness.

Fig. 9. Representation of correlation obtained for selection-based surrogacy with 10%, 20% and 30% conservation objectives. Those correlation values are obtained by calculating the mean of correlation coefficients for all surrogates and for all countries.

Fig. 10. Representation of correlation obtains with pattern-based and selection based surrogacy. For pattern based surrogacy, those correlation values are obtained by calculating the mean correlation coefficient for the three surrogate/reference combinations. For conservation based surrogacy, those correlation values are obtain by calculating the mean correlation coefficient for the three surrogate/reference combination, and for the three conservation objectives (10%, 20%, 30%). Abbreviations: S.B : selection-based, P.B : patter-based, N.M : Northern Mariana, W&F : Wallis and Futuna, Cooks : Cooks Islands, F.P : French Polynesia, N.C:New Caledonia, P.N.G : Papua New Guinea. Countries are ranked in ascending order for pattern based correlation..

Table caption

Table 1 : Goemorphological richness (number of classes in levels 3,4 and 5), coral reef area (km²) and number of planning units for each countries.

Table 1

Area	Number of classes in level 5	Number of classes in level 4	Number of classes in level 3	Coral reef area (km²)	Number of planning units
Tokelau	8	8	4	223	21
Tuvalu	18	15	8	3287	252
Marshall	20	14	10	14082	954
Northern Mariana	22	14	12	261	102
Kiribati	24	16	8	1184	130
Wallis and Futuna	24	14	11	934	134
Samoa	27	17	11	483	112
Guam	29	14	15	246	54
Cook Islands	36	18	17	868	115
Hawaii	46	23	19	14146	1191
Palau	56	20	21	2545	191
Vanuatu	56	25	19	1250	611
Tonga	64	24	21	5884	438
French Polynesia	66	30	20	16151	1366
Micronesia	70	36	22	15629	1208
Solomon	132	38	33	8854	1851
New Caledonia	174	42	29	36339	2197
Fiji	282	44	31	25727	2086
Papua New Guinea	334	47	35	27062	4765

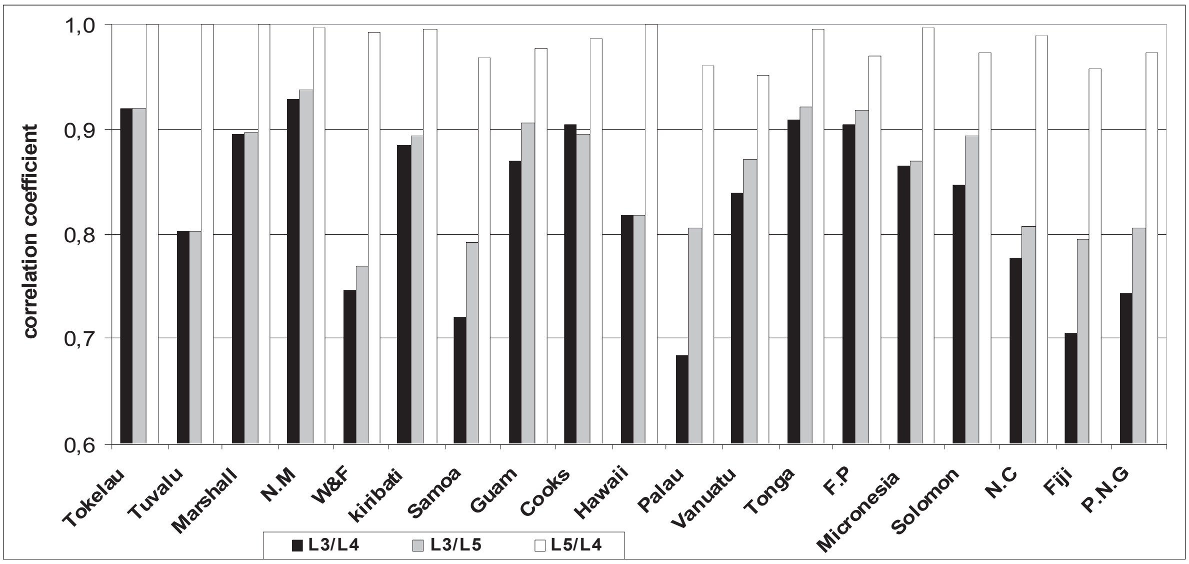
Fig.1.


MEXICO
CLIPPERTON
HAWAII
JOHNSTON ATOLL
NORTHERN MARIANA ISLANDS
WAKE ISLAND
GUAM
MARSHALL ISLANDS
PALMYRA ATOLL
PALAU
FEDERATED STATES OF MICRONESIA
HOWLAND AND BAKER ISLANDS
KIRIBATI (GILBERT ISLANDS)
NAURU
JARVIS ISLAND
EQUATOR
PAPUA NEW GUINEA
KIRIBATI (PHOENIX ISLANDS)
TUVALU
TOKELAU
KIRIBATI (LINE GROUP)
SOLOMON ISLANDS
WALLIS & FUTUNA
SAMOA
COOK ISLANDS
AMERICAN SAMOA
CORAL SEA
VANUATU
FIJI
NIUE
FRENCH POLYNESIA (POLYNESIE FRANCAISE)
NEW-CALEDONIA (NOUVELLE-CALEDONIE)
TONGA
AUSTRALIA
PITCAIRN ISLAN
LORD HOWE
PACIFIC OCEAN
Exclusive Economic Z
TASMAN SEA
0
1 000 km

Fig. 2.

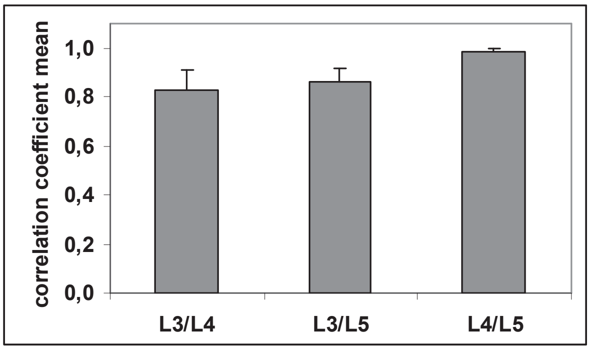

Oceanic Reefs
Atoll
Drowned atoll
Lagoon
Rim
Patch
Bank
Drowned bank
Bridge
Lagoon
Barrier
Patch
Uplifted Atoll
Island
Land
Non reefal water bodies
Coastal Barrier
Outer Barrier
Multiple Barrier
Imbricated Barrier
Barrier-Fringing
Coastal/fringing Patch
Intra-lagoon Patch
Intra-seas Patch
Shelf Patch
Ocean Exposed Fringing
Intra-seas Exposed Fringing
Lagoon Exposed Fringing
Shelf Reefs
Continental (shelf) Reefs
Atoll
Drowned atoll
Lagoon
Rim
Patch
Bank
Drowned Bank
Bridge
Lagoon
Barrier
Patch
Uplifted Atoll
Island
Land
Non reefal water bodies
Coastal Barrier
Outer Barrier
Multiple Barrier
Imbricated Barrier
Barrier-Fringing
Coastal/fringing Patch
Intra-lagoon Patch
Intra-seas Patch
Shelf Patch
Ocean Exposed Fringing
Intra-seas Exposed Fringing
Lagoon Exposed Fringing
Shelf Reefs
Patch
Coastal/fringing Patch
Intra-lagoon Patch
Intra-seas Patch
Shelf Patch
Intra-shelf Barrier
Coastal Barrier
Outer Barrier
Multiple Barrier
Imbricated Barrier
Barrier-Fringing
Outer-Shelf Barrier
Coastal Barrier
Outer Barrier
Multiple Barrier
Imbricated Barrier
Barrier-Fringing
Fringing
Ocean Exposed Fringing
Intra-seas Exposed Fringing
Lagoon Exposed Fringing
Shelf

Fig. 3.



correlation coefficient
1,0
0,9
0,8
0,7
0,6
Tokelau
Tuvalu
Marshall
N.M
W&F
kiribati
Samoa
Guam
Cooks
Hawaii
Palau
Vanuatu
Tonga
F.P
Micronesia
Solomon
N.C
Fiji
P.N.G
L3/L4
L3/L5
L5/L4

Fig. 4.



correlation coefficient mean
1,0
0,8
0,6
0,4
0,2
0,0
L3/L4
L3/L5
L4/L5

Fig. 5.

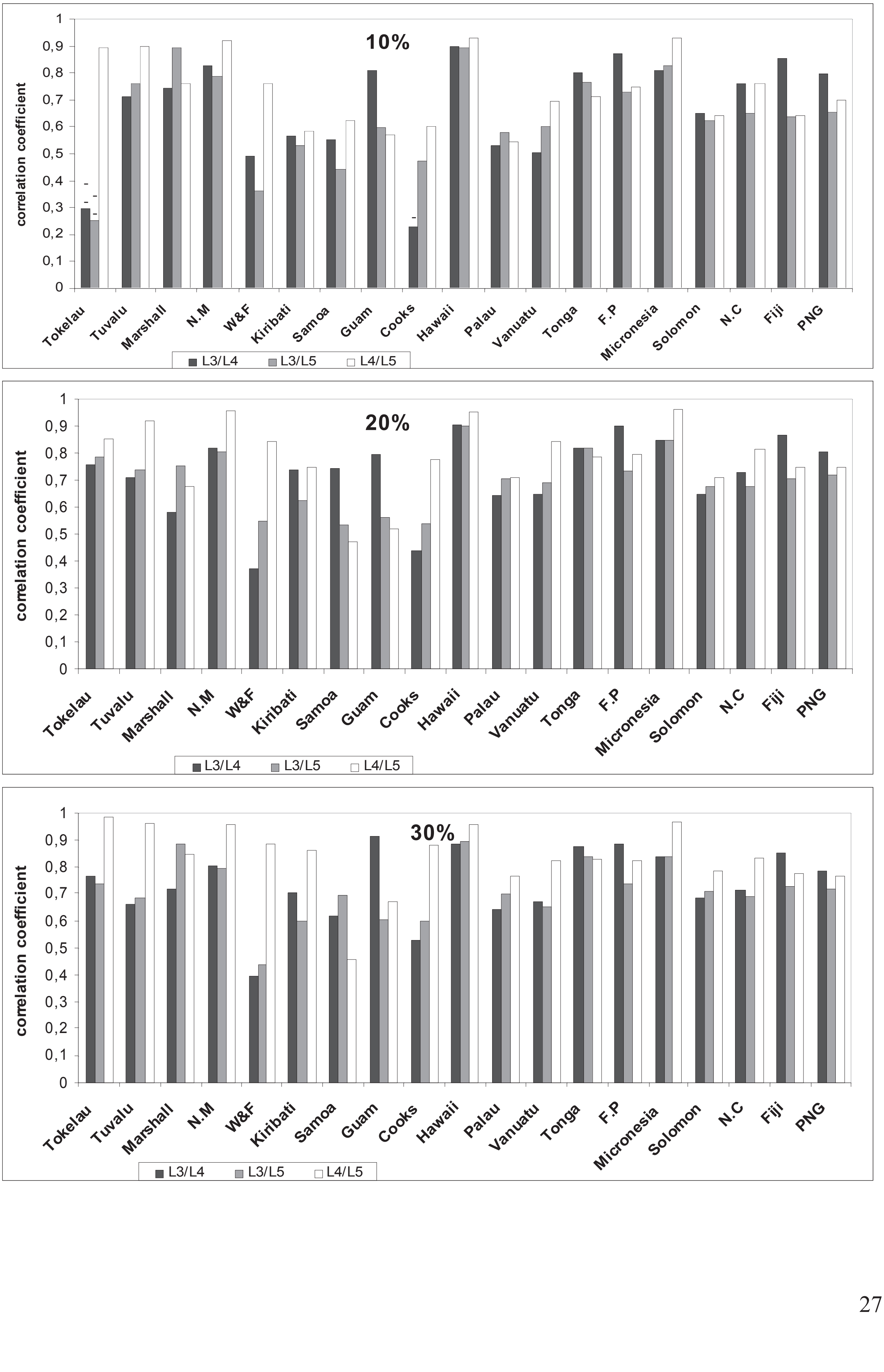
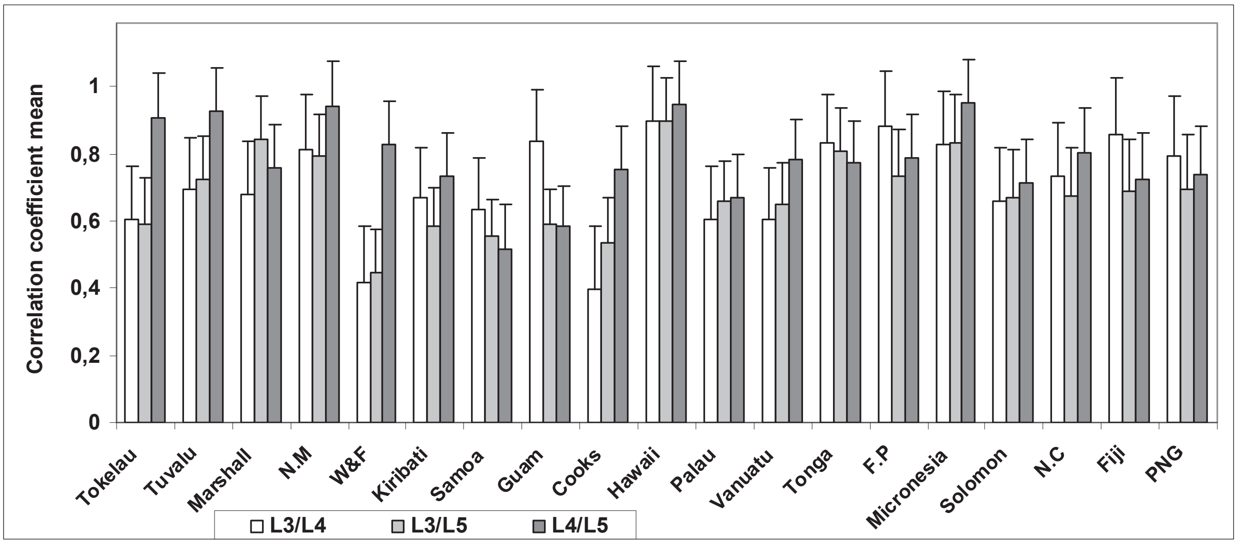
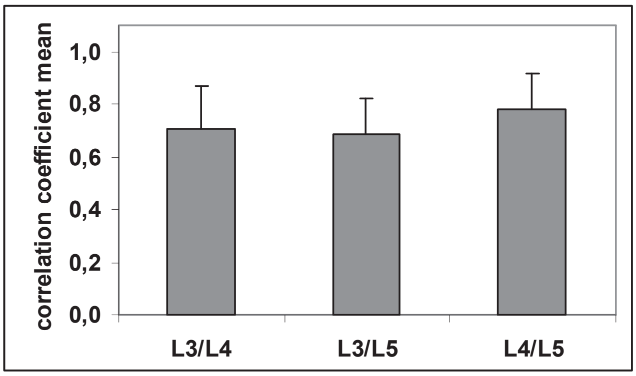

10%
20%
30%
correlation coefficient
Tokelau
Tuvalu
Marshall
N.M
W&F
Kiribati
Samoa
Guam
Cooks
Hawaii
Palau
Vanuatu
Tonga
F.P
Micronesia
Solomon
N.C
Fiji
PNG
L3/L4
L3/L5
L4/L5

Fig. 6.



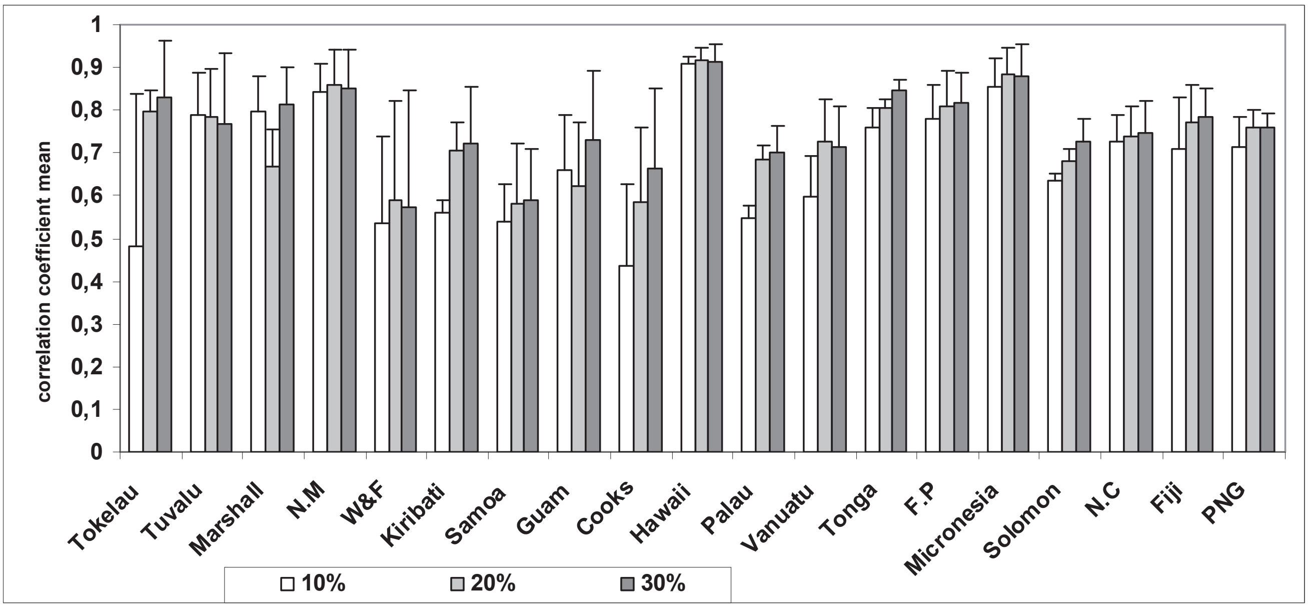
Correlation coefficient mean
1
0,8
0,6
0,4
0,2
0
Tokelau
Tuvalu
Marshall
N.M
W&F
Kiribati
Samoa
Guam
Cooks
Hawaii
Palau
Vanuatu
Tonga
F.P
Micronesia
Solomon
N.C
Fiji
PNG
L3/L4
L3/L5
L4/L5

Fig. 7.



correlation coefficient mean
1,0
0,8
0,6
0,4
0,2
0,0
L3/L4
L3/L5
L4/L5

Fig. 8.



1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
correlation coefficient mean
Tokelau
Tuvalu
Marshall
N.M
W&F
Kiribati
Samoa
Guam
Cooks
Hawaii
Palau
Vanuatu
Tonga
F.P
Micronesia
Solomon
N.C
Fiji
PNG
10%
20%
30%

Fig. 9.

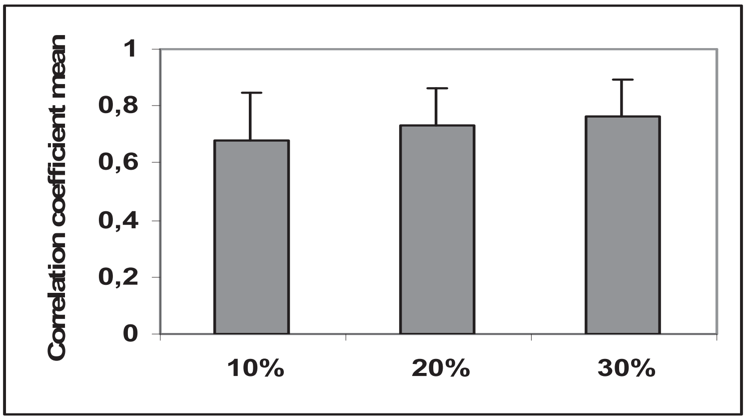
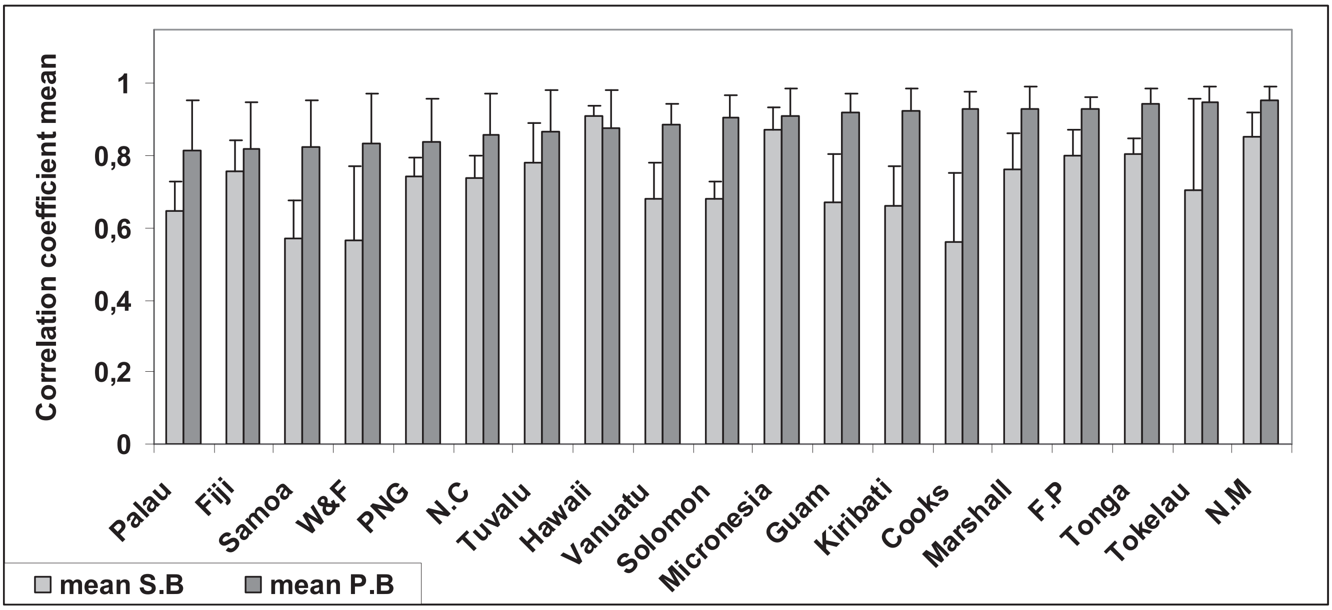


Fig. 10.



Correlation coefficient mean
1
0,8
0,6
0,4
0,2
0
Palau
Fiji
Samoa
W&F
PNG
N.C
Tuvalu
Hawaii
Vanuatu
Solomon
Micronesia
Guam
Kiribati
Cooks
Marshall
F.P
Tonga
Tokelau
N.M
mean S.B
mean P.B

Appendix caption

Appendix 1 : maps of MCRMP products.

Appendix1a : MCRMP products at L3 levels for Louisiade Archipelago (Papua New Guinea) and for Panapompom and Panaeti Island (Louisiade archipelago).

Appendix1b : MCRMP products at L4 levels for Louisiade Archipelago (Papua New Guinea) and for Panapompom and Panaeti Island (Louisiade archipelago).

Appendix1c : MCRMP products at L5 levels for Louisiade Archipelago (Papua New Guinea) and for Panapompom and Panaeti Island (Louisiade archipelago).

Appendix 2 : Exemples of Millenium classes contained in a defined area

Appendix 2a. : Millenium Typology for Guam

Appendix 2b. : Millenium Typology for Tokelau

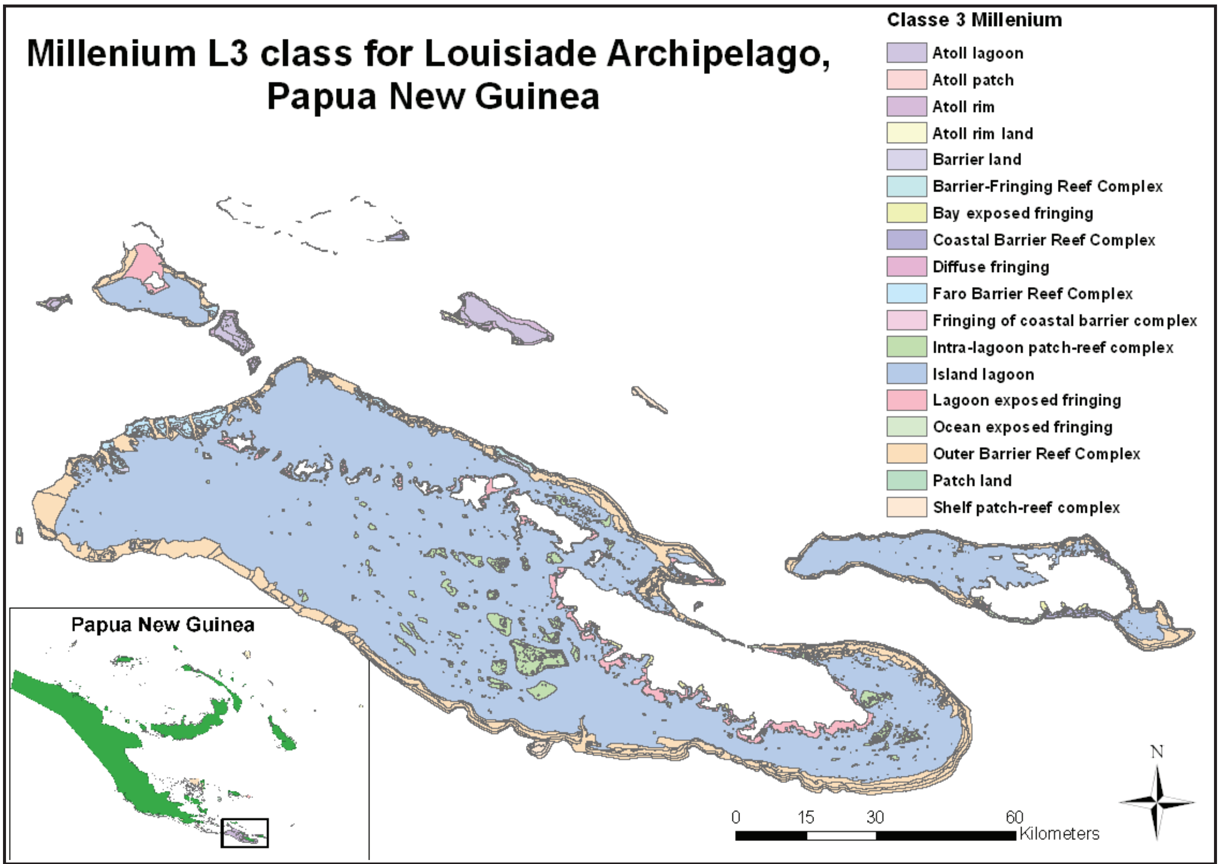
Appendix 3 : Selection based results for D'Entrecasteaux reefs (New Caledonia).

Appendix 3.1. a,b,c,d respectively represents, for L3 level, irreplaceability for 10% target, irreplaceability for 30% target, best design for 10% target, and best design for 30% target.

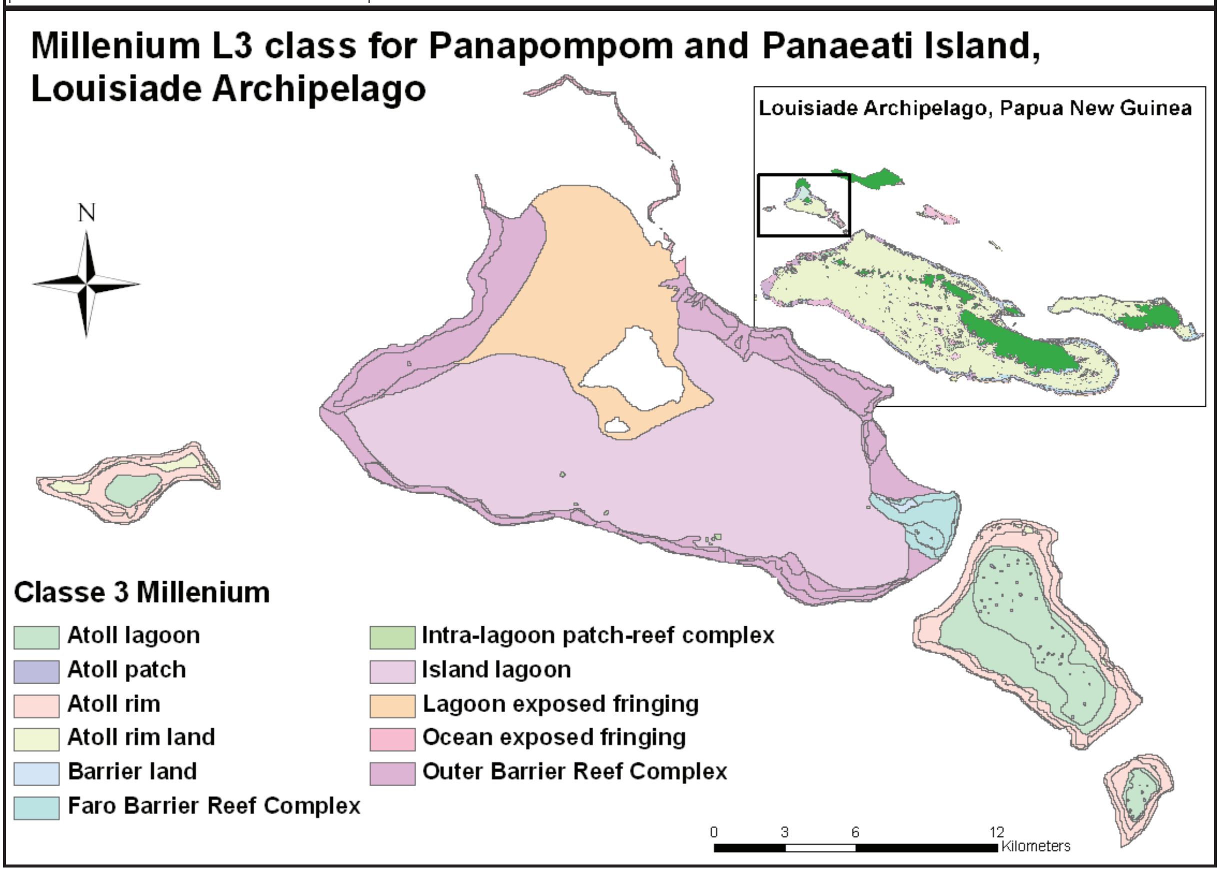
Appendix 3.2. a,b,c,d respectively represents, for L4 level, irreplaceability for 10% target, irreplaceability for 30% target, best design for 10% target, and best design for 30% target.

Appendix 3.3. a,b,c,d respectively represents, for L5 level, irreplaceability for 10% target, irreplaceability for 30% target, best design for 10% target, and best design for 30% target.

Appendix 1a

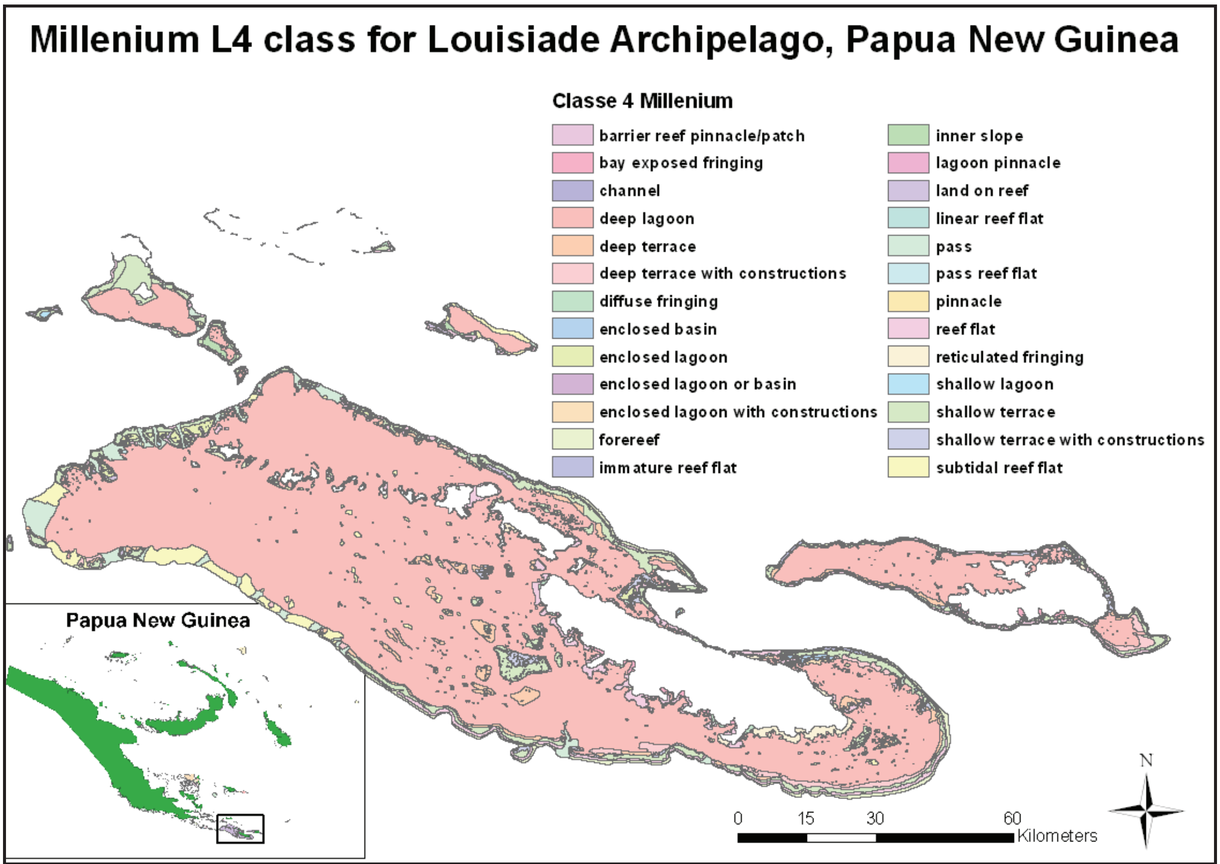


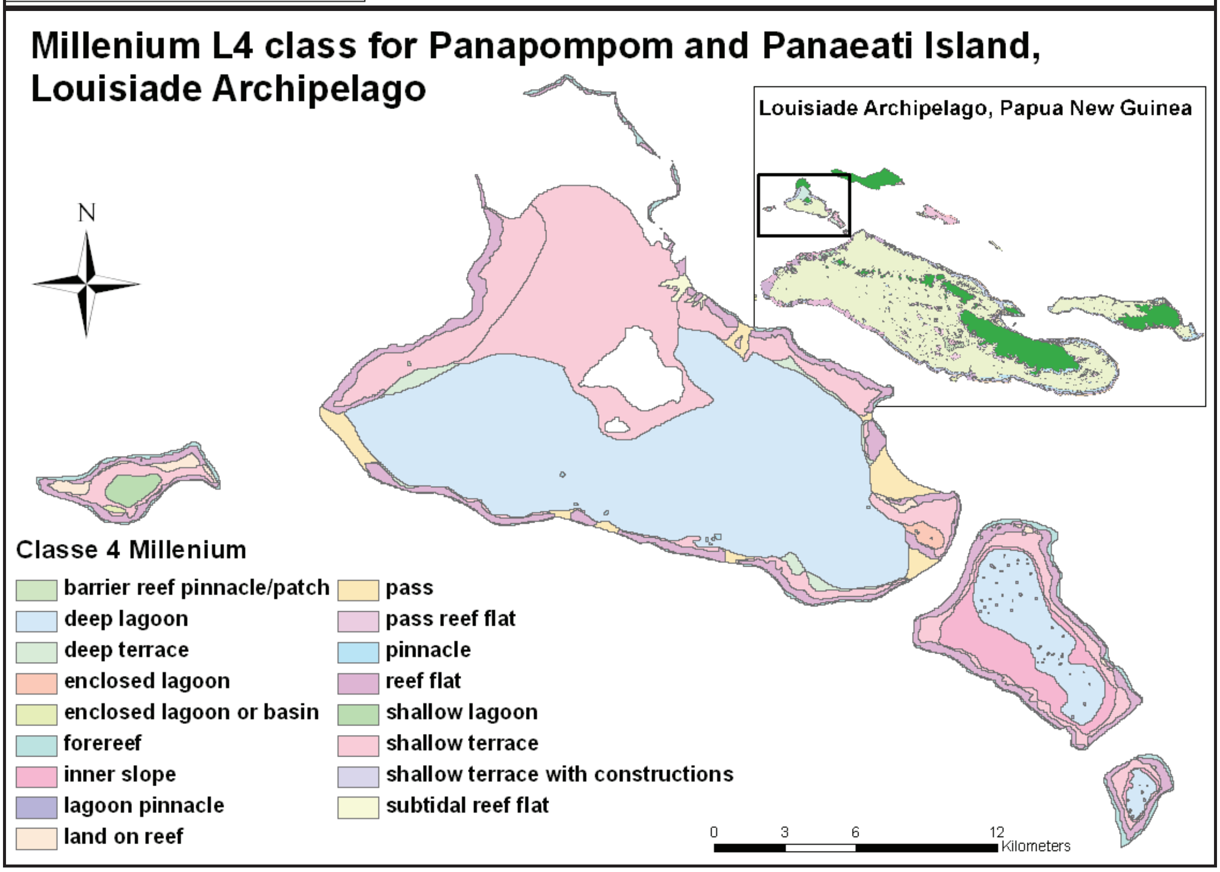
Millenium L3 class for Louisiade Archipelago, Papua New Guinea
Classe 3 Millenium
Atoll lagoon
Atoll patch
Atoll rim
Atoll rim land
Barrier land
Barrier-Fringing Reef Complex
Bay exposed fringing
Coastal Barrier Reef Complex
Diffuse fringing
Faro Barrier Reef Complex
Fringing of coastal barrier complex
Intra-lagoon patch-reef complex
Island lagoon
Lagoon exposed fringing
Ocean exposed fringing
Outer Barrier Reef Complex
Patch land
Shelf patch-reef complex
Papua New Guinea
N
0 15 30 60
Kilometers



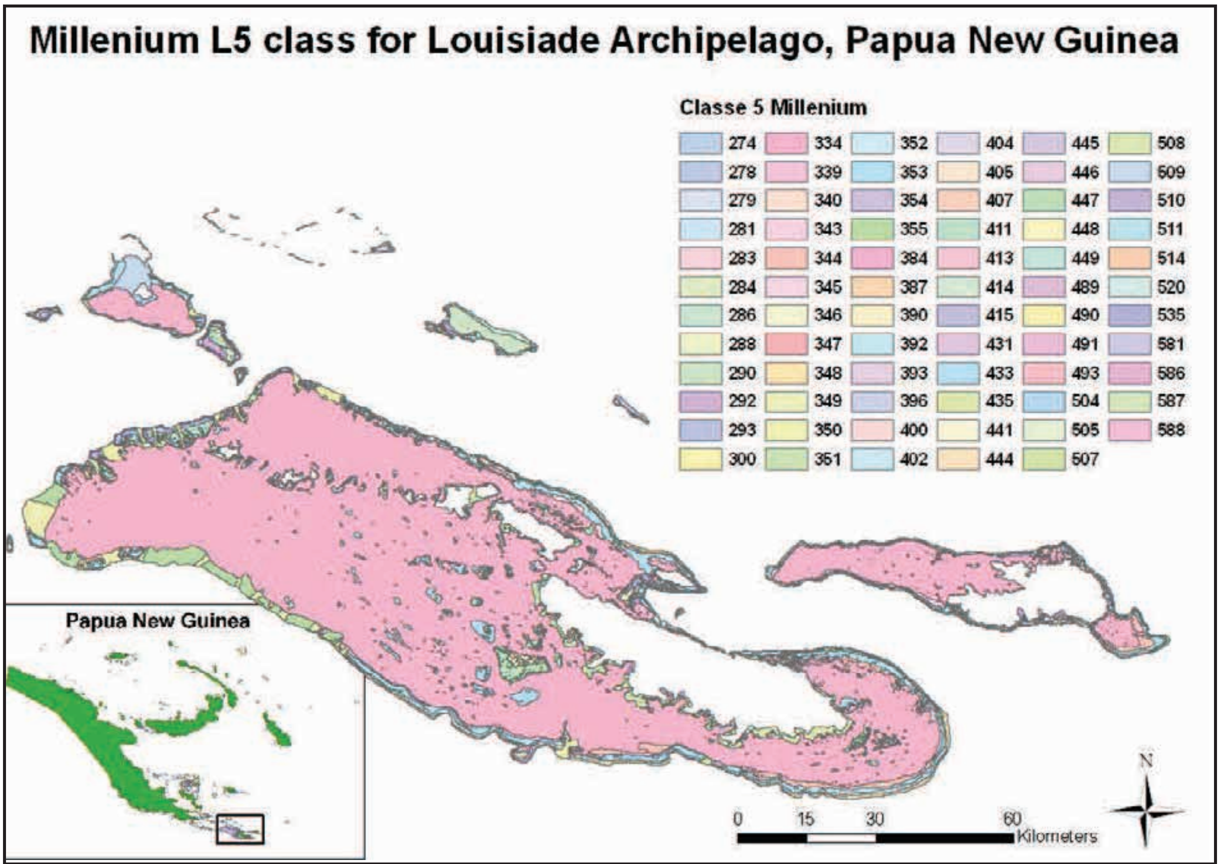
Millenium L3 class for Panapompom and Panaeati Island, Louisiade Archipelago
Louisiade Archipelago, Papua New Guinea
N
Classe 3 Millenium
Atoll lagoon
Atoll patch
Atoll rim
Atoll rim land
Barrier land
Faro Barrier Reef Complex
Intra-lagoon patch-reef complex
Island lagoon
Lagoon exposed fringing
Ocean exposed fringing
Outer Barrier Reef Complex
0 3 6 12
Kilometers

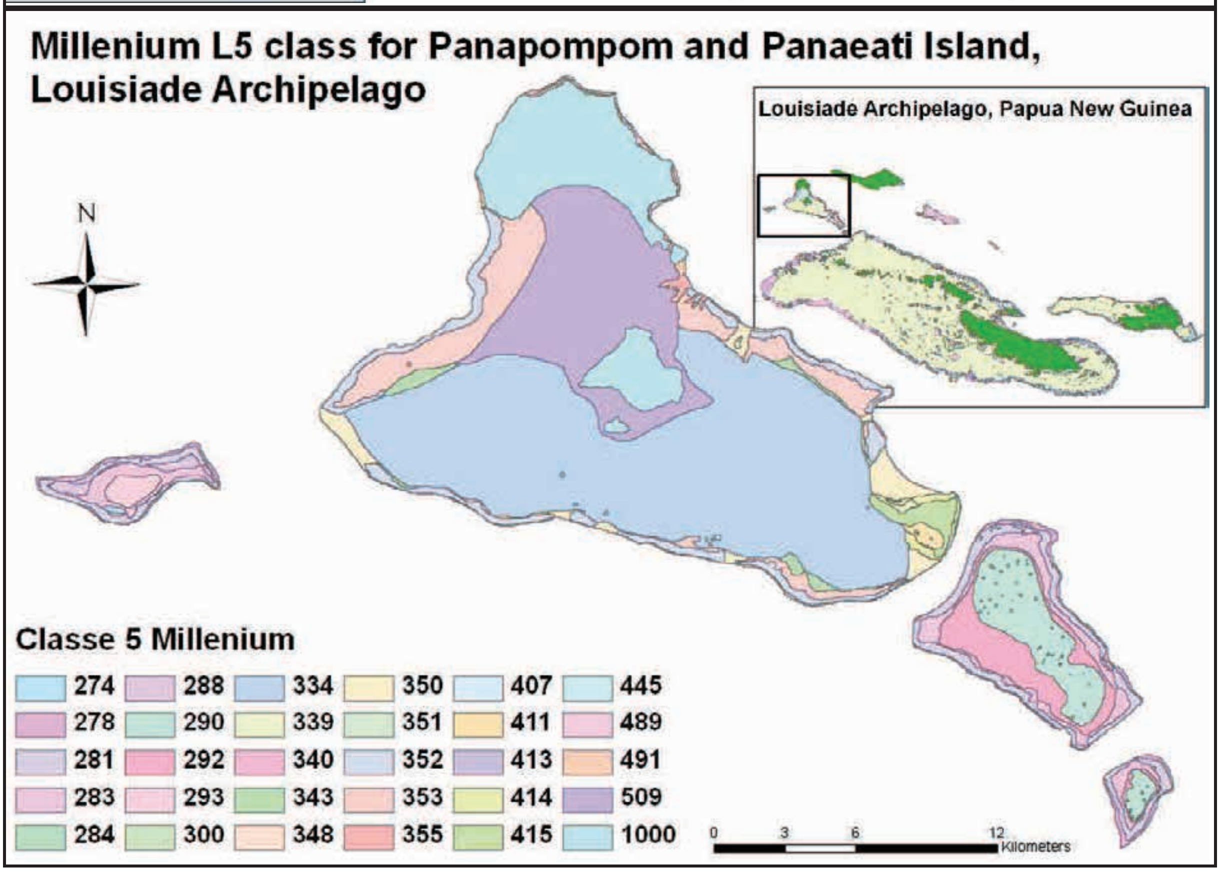
Appendix 1b


Millenium L4 class for Louisiade Archipelago, Papua New Guinea
Classe 4 Millenium
barrier reef pinnacle/patch
bay exposed fringing
channel
deep lagoon
deep terrace
deep terrace with constructions
diffuse fringing
enclosed basin
enclosed lagoon
enclosed lagoon or basin
enclosed lagoon with constructions
forereef
immature reef flat
inner slope
lagoon pinnacle
land on reef
linear reef flat
pass
pass reef flat
pinnacle
reef flat
reticulated fringing
shallow lagoon
shallow terrace
shallow terrace with constructions
subtidal reef flat
Papua New Guinea
0 15 30 60
Kilometers
N


Millenium L4 class for Panapompom and Panaeati Island, Louisiade Archipelago
Louisiade Archipelago, Papua New Guinea
N
Classe 4 Millenium
barrier reef pinnacle/patch
deep lagoon
deep terrace
enclosed lagoon
enclosed lagoon or basin
forereef
inner slope
lagoon pinnacle
land on reef
pass
pass reef flat
pinnacle
reef flat
shallow lagoon
shallow terrace
shallow terrace with constructions
subtidal reef flat
0 3 6 12
Kilometers

Appendix 1c


Millenium L5 class for Louisiade Archipelago, Papua New Guinea
Classe 5 Millenium
274 334 352 404 445 508
278 339 353 405 446 509
279 340 354 407 447 510
281 343 355 411 448 511
283 344 384 413 449 514
284 345 387 414 489 520
286 346 390 415 490 535
288 347 392 431 491 581
290 348 393 433 493 586
292 349 396 435 504 587
293 350 400 441 505 588
300 351 402 444 507
Papua New Guinea
0 15 30 60 Kilometers
N


Millenium L5 class for Panapompom and Panaeati Island, Louisiade Archipelago
Louisiade Archipelago, Papua New Guinea
N
Classe 5 Millenium
274 288 334 350 407 445
278 290 339 351 411 489
281 292 340 352 413 491
283 293 343 353 414 509
284 300 348 355 415 1000
0 3 6 12 Kilometers

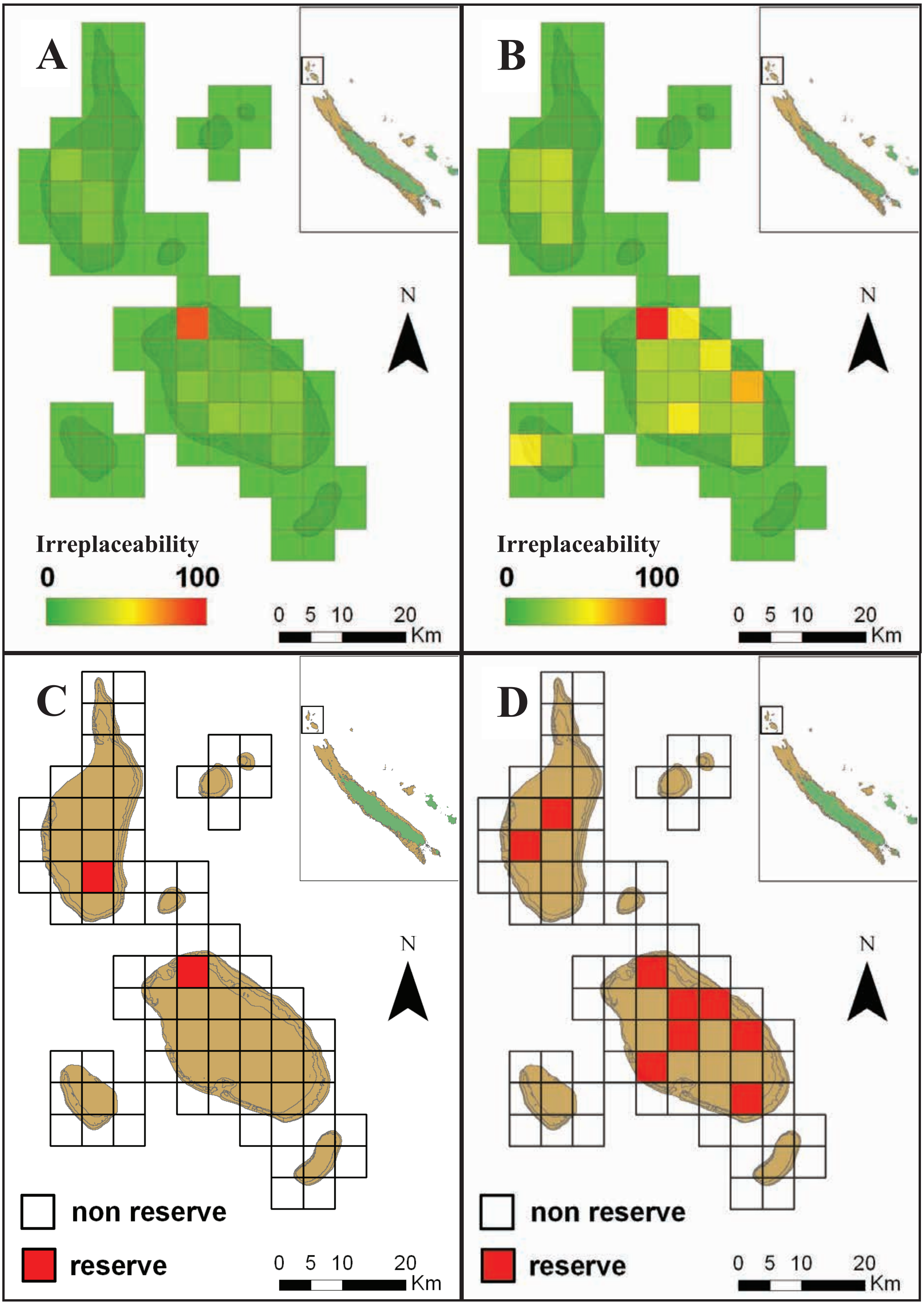
Appendix 2a.

L1_ATTRIB	L2_ATTRIB	L3_ATTRIB	L4_ATTRIB	L5
oceanic	Oceanic Bank	Drowned bank	drowned bank	40
oceanic	Oceanic Bank	Bank lagoon	deep terrace	52
oceanic	Oceanic Bank	Bank lagoon	deep terrace with constructions	53
oceanic	Oceanic island	Island lagoon	deep lagoon	67
oceanic	Oceanic island	Barrier land	land on reef	72
oceanic	Oceanic island	Outer Barrier Reef Complex	deep terrace	76
oceanic	Oceanic island	Outer Barrier Reef Complex	forereef	81
oceanic	Oceanic island	Outer Barrier Reef Complex	pass	83
oceanic	Oceanic island	Outer Barrier Reef Complex	reef flat	85
oceanic	Oceanic island	Coastal Barrier Reef Complex	enclosed lagoon with constructions	119
oceanic	Oceanic island	Coastal Barrier Reef Complex	forereef	120
oceanic	Oceanic island	Coastal Barrier Reef Complex	pass	123
oceanic	Oceanic island	Coastal Barrier Reef Complex	reef flat	125
oceanic	Oceanic island	Coastal Barrier Reef Complex	shallow terrace	126
oceanic	Oceanic island	Patch land	land on reef	164
oceanic	Oceanic island	Intra-lagoon patch-reef complex	reef flat	179
oceanic	Oceanic island	Intra-lagoon patch-reef complex	subtidal reef flat	182
oceanic	Oceanic island	Shelf patch-reef complex	forereef	210
oceanic	Oceanic island	Shelf patch-reef complex	reef flat	215
oceanic	Oceanic island	Ocean exposed fringing	forereef	222
oceanic	Oceanic island	Ocean exposed fringing	pass	223
oceanic	Oceanic island	Ocean exposed fringing	reef flat	224
oceanic	Oceanic island	Ocean exposed fringing	shallow terrace	226
oceanic	Oceanic island	Lagoon exposed fringing	reef flat	240
oceanic	Oceanic island	Lagoon exposed fringing	shallow terrace	242
oceanic	Oceanic island	Bay exposed fringing	bay exposed fringing	243
oceanic	Oceanic island	Diffuse fringing	diffuse fringing	244
oceanic	Oceanic island	Fringing of coastal barrier complex	diffuse fringing	245
oceanic	Oceanic island	Shelf slope	undetermined envelop	267
main land	main land	Main Land	main land	1000

Appendix 2b.

L1_ATTRIB	L2_ATTRIB	L3_ATTRIB	L4_ATTRIB	L5
oceanic	Oceanic atoll	Atoll rim	enclosed lagoon or basin	7
oceanic	Oceanic atoll	Atoll rim	forereef	11
oceanic	Oceanic atoll	Atoll rim	reef flat	14
oceanic	Oceanic atoll	Atoll rim land	land on reef	21
oceanic	Oceanic atoll	Atoll lagoon	deep lagoon	23
oceanic	Oceanic atoll	Atoll lagoon	deep lagoon with constructions	24
oceanic	Oceanic atoll	Atoll lagoon	inner slope	25
oceanic	Oceanic atoll	Atoll patch	lagoon pinnacle	33

Appendix 3.1.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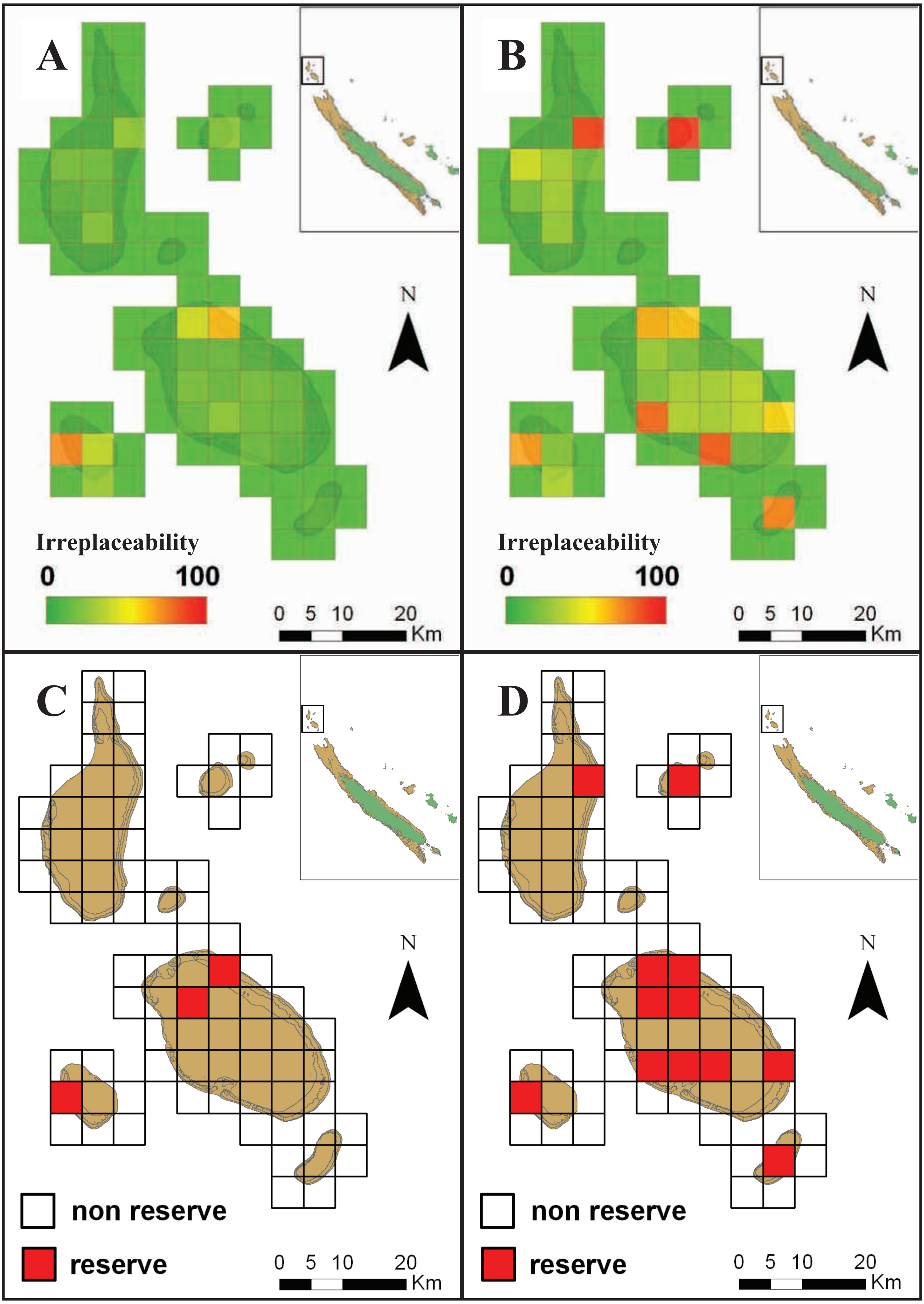
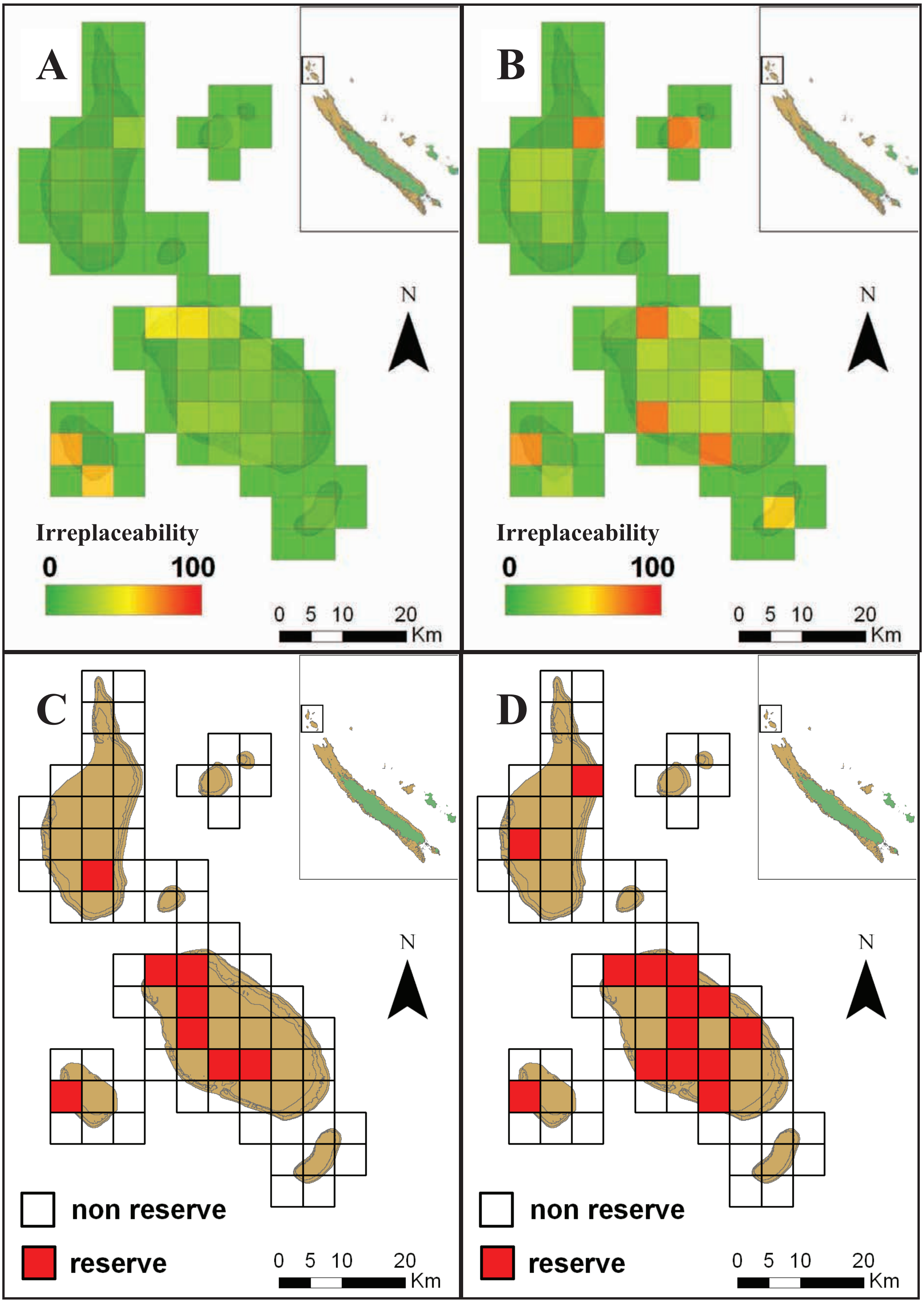
Irreplaceability
0
100
0 5 10 20
Km
N
B
Irreplaceability
0
100
0 5 10 20
Km
N
C
non reserve
reserve
0 5 10 20
Km
N
D
non reserve
reserve
0 5 10 20
Km
N

Appendix 3.2



A
Irreplaceability
0
100
0 5 10 20
Km
N
B
Irreplaceability
0
100
0 5 10 20
Km
N
C
non reserve
reserve
0 5 10 20
Km
N
D
non reserve
reserve
0 5 10 20
Km
N

Appendix 3.3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Irreplaceability
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Km
B
N
Irreplaceability
0
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0 5 10 20
Km
C
N
non reserve
reserve
0 5 10 20
Km
D
N
non reserve
reserve
0 5 10 20
Km