Coral Reefs (1997) 16: 225–230

Coral Reefs

New estimates of global and regional coral reef areas

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Accepted: 3 April 1997

Abstract. Global and regional coral reef area statistics are of considerable value in fields ranging from global environmental change to fisheries to conservation. Although widely quoted, Smith's 1978 figure of 600 000 km^2 is only an approximate calculation. The World Conservation Monitoring Centre has prepared a new estimate of reef coverage by mapping emergent reef crest and very shallow reef systems. These data were rasterised, using 1 km grid squares, as a means of reducing errors arising from variation in scale. Global and regional reef coverages were calculated from the resultant grid. The total global area is estimated at 255 000 km^2, considerably lower than many previous estimates. Variation in reef area estimates is, in part, a function of variation in reef definition.

Introduction

Estimates of reef area are useful for many purposes, including, for example, the calculation of carbon budgets and calcification rates (Smith 1978; De Vooys 1979; Crossland et al. 1991; Opdyke and Walker 1992; Kleypas in press), and also the modelling and calculation of fisheries statistics (McManus 1989; McManus et al. 1995; Munro 1996). The future availability of more accurate estimates of reef areas at regional, national and local scales will undoubtedly be of further use in such work as coastal resources management, planning and legislation, in the study of conservation status and in the establishment of priority areas for conservation. Such figures will also provide a powerful tool in broader studies and modelling of biological and geological processes, including studies of biogeography and biodiversity, and the biological and geological evolution of reefs.

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A number of early authors produced maps showing the distribution of reefs world-wide (Darwin 1842; Joubin 1912; Emery et al. 1954), but it was not until the 1970s that significant efforts were made towards the generation of estimates of global reef area (Table 1). Two broad approaches have been used in the generation of these estimates: one involves the direct calculation of reef area using existing reef maps (Newell 1971; De Vooys 1979); the other involves the calculation of reefal shelf area using more predictive techniques (Milliman 1974; Smith 1978; Copper 1994; Kleypas in press). There are practical difficulties, associated with scale, in using existing reef maps. Newell (1971) based his calculations on the consideration of a 1 : 10 000 000 global map, producing a figure of 150 000 km^2, but suggested this should be increased by a factor of ten to achieve a more accurate estimate. De Vooys (1979) used much larger-scale marine charts, but based his estimates on a sample of only five such charts, and a subsequent multiplication of the resulting figure.

Table 1. Estimates of global coral reef area, 1971–1996

Area ($\times 10^3$ km^2)	Reference
150 to 1 500	Newell 1971
1 440	Milliman 1974
617	Smith 1978
112	De Vooys 1979
1 500	Copper 1994
584 to 3 930	Kleypas in press
255	Spalding and Grenfell this paper

To date the most widely quoted figures for global and regional reef area are those derived by Smith (1978). These were derived from estimated areas of shallow ocean (above 30 m) and estimates of the proportion of reef frontage within 10° 'squares' of latitude and longitude, a method which combined predictive elements with the use of a hard copy map. Considerable advances in computer technology, together with the development of very large digital global datasets now provide opportunities to refine reef area calculations, using either map-based or predictive techniques. Kleypas (in press) provides an attempt at the latter, predicting reef occurrence based on global environmental data of sea surface temperature, salinity, water depth, water clarity, and solar irradiance. This study presents a new global assessment of the total area of coral reefs using maps of reef areas and geographic information systems (GIS) technology.

Methods

Since 1994, staff at the World Conservation Monitoring Centre in the UK have been compiling a global coral reef dataset, under a Coral Reef Mapping Initiative, on an ARC/INFO GIS (Spalding 1995, in press). Sources for this dataset vary considerably in age, quality, scale and in reef definition. Each of these factors, but most particularly the latter two, present considerable difficulties in the derivation of statistical outputs which are comparable between countries.

Mounsey (1991) provides a review of some of the difficulties and consequent weaknesses inherent in the generation of a multi-national, multi-source GIS. Although many of these same weaknesses are undoubtedly inherent in the global coral reef database, the current analysis concerns only a single data-layer. Hence there are no problems of data mismatch between layers, while, for reasons outlined later, a number of other potential errors which might arise are avoided or reduced.

A list of the source materials, by county, is given in ReefBase (1996). The majority of sources were 'hard copy' published or unpublished maps, from which the reefs were transferred to the GIS by digitising. Although errors are likely to arise at this stage, they are mostly minor operator errors, affecting positional accuracy and boundary representation (Fisher 1991). In the current work, such errors are largely lost in the subsequent generalisation and regionalisation of the data. In some cases the source material was digital, derived from processed remote imagery.

Source maps range from navigational charts to national topographic map series, while, more occasionally, specialist coral reef or shallow substrate maps have been used. With the exception of the latter categories, the original data sources rarely provide a definition of the mapped 'reefs'. Although this lack of attribute definition seems to be a weakness it is usually possible, with a knowledge of reef systems, to elucidate simple definitions for most maps. The majority of sources plot, as 'reefs', marine carbonate structures clearly visible from the air or sea (hence of navigational interest). These 'reefs' are typically presented as lines marking emergent or near-emergent 'reef crest' or 'shallowest reef area', and in many of these, the lines themselves demarcate polygonal areas or may be connected to the land, thus enclosing an area of 'reef-flat' or 'shallow lagoon'.

The remaining, and undoubtedly most significant, weakness with the global coral reef dataset concerns the variation in scale, coupled with the different format of the spatial data layer (lines and polygons). While there are exceptions, the majority of reefs in the global database were prepared from source maps at scales between 1 : 250 000 and 1 : 1 000 000. In order to minimise the influence of this variation it was necessary to devise a method which would harmonise and 'smooth' these data. This had to be done whilst minimising data loss, in order to derive results that were both valid with respect to the data sources, and scientifically relevant to coral reef work. A technique was devised which effectively rasterised the data, generalising them into pixels of 1 km square, as a means of reducing or factoring out the influence of scale from subsequent areal calculations. Similar techniques are widely used in the generalisation of pre- and post- classification thematic layers, allowing for the combination of data from different sources (Lunetta et al. 1991).

The data were archived in ARC/INFO software, and one of the first tasks was to produce a single 'best' global coverage from the numerous datasets available (for a number of countries two or even three data layers were available showing coral reefs). This reef dataset was re-projected onto an equal area projection prior to analysis. Using the GRID module of ARC/INFO, a 1 km grid system was then overlaid onto this reef projection and the grid squares with reefs present were counted, in an automated process. The choice of grid-size has a very significant bearing on the resulting area statistics: sample tests using grids of side 500 m, 1000 m and 2000 m typically showed increases in reef area by a factor of 1.4 to 1.9 for every doubling of the grid side (quadrupling the grid area). The decision to use a 1 km^2 grid was based on both the practical constraints imposed by the data, and on geomorphological and ecological arguments:

1. With only a few exceptions, the smallest scale of the source data is 1 : 1 000 000. At this scale, map resolution will typically allow differentiation of sites 500 m or more apart (i.e. 0.5 mm on the map). The use of a 1 km grid square represents the conversion of all data to a low resolution (about 1000 m) which lies within the same order of magnitude as the lowest resolution data of the source material. This grid-size thus minimises loss of data while preventing errors inherent in the re-sampling of the small-scale datasets to a finer resolution than the original source.

2. In geomorphological terms a 1 km^2 grid assumes that, on average, a reef which is drawn as an arc has a 500 m influence in all directions, while reefs marked as polygons have an average influence of 500 m from their outer edges. These generalisations are considered to be reasonable, especially given the knowledge that what has been mapped is, in most cases, the reef crest, and that in many areas this is usually associated with shallow to steep reef-slopes on one side and, on the other side, reef flats or lagoons (often containing back reef or lagoonal patch reef type structures). Future work could attempt to factor in regional differences in coral reef geomorphology, as a means of refining the results.

There remain inevitable weaknesses arising from the variability in the data. Large-scale, high resolution data are likely to show an increased number of very small reefs. This will tend to increase the total reef area for those countries with high resolution sources, although with the use of the grid, small reefs may amalgamate within grid squares. They will only thus significantly enhance reef area where they stand in considerable isolation from other reefs. A small number of reefs within the global dataset have been mapped at lower resolutions than 1 : 1 000 000. For the most part this will tend to mean a loss of representation of small reefs and a simplification of reef demarcation, leading to an underestimation of reef area. The opposite might be expected to occur, however, if reefs are presented as polygons which, of necessity, tend to exaggerate reef area at these scales.

Results

The global map of coral reefs used for this work is summarised in Fig. 1. This shows a complete global reef coverage, although the problems of variation in definition, age and scale of the data sources, discussed above, remain. Using the 1 km^2 grid, the estimate of global coral reef area is some 255 000 km^2. Further breakdown of this figure into area estimates for regions of biogeographic or political significance is provided in Tables 2 and 3. This global estimate represents only 41% of Smith's original estimate (Smith 1978), and his regional breakdown estimates are also provided in Table 2 for comparison. At the regional level these two sets of area estimates show some interesting variations which are most clearly expressed when the data are presented in percentage terms rather than actual area terms, as shown in Fig. 2. Table 3 provides figures for some alternative regions which are of interest for political or biogeographic purposes, but which were not originally covered by Smith (1978).

Tests looking at the grid size showed this to have considerable influence on the resulting area calculation.

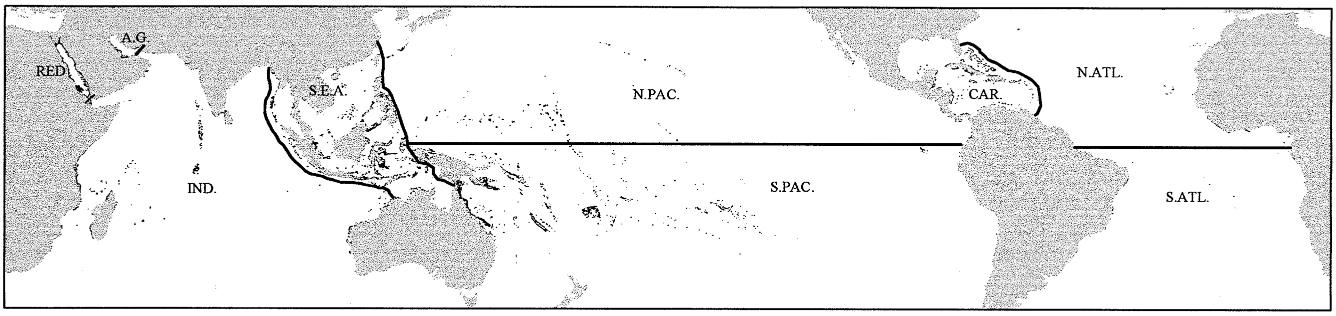

Fig. 1. The global distribution of coral reefs, together with the regional boundaries as used in Table 2. (*N.PAC.*, North Pacific; *S.PAC.*, South Pacific; *CAR.*, Caribbean; *N.ATL.*, North Atlantic; *S.ATL.*, South Atlantic; *RED*, Red Sea; *A.G.*, Arabian Gulf; *IND.*, Indian Ocean; S.E.A., South east Asia)

Table 2. Global and regional coral reef areas, rounded to the nearest thousand, with a comparison with the figures generated by Smith (1978). Regional boundaries are shown in Fig. 1

Region	Area × 10^3 km^2	Smith's (1978) area estimate × 10^3 km^2
Red Sea	17	27
Arabian Gulf (Persian Gulf)	3	12
Indian Ocean	36	146
South East Asia (Asiatic Mediterranean)	68	182
Northern Pacific	17	76
Southern Pacific	91	77
Caribbean	20	57
Northern Atlantic	2	32
Southern Atlantic	1	8
TOTAL	255	617

Table 3. Additional regional reef areas obtained from the 1 km^2 grid for commonly used biogeographic regions

Region	Area × 10^3 km^2 (percentage of world total)
Indo-Pacific	232 (91.0%)
Atlantic	23 (9.0%)
Western Pacific (including Hawaii)	105 (41.2%)
Eastern Pacific	3 (1.2%)
Wider Caribbean	21 (8.2%)
Lesser Antilles	2 (0.8%)
West Africa	1 (0.4%)

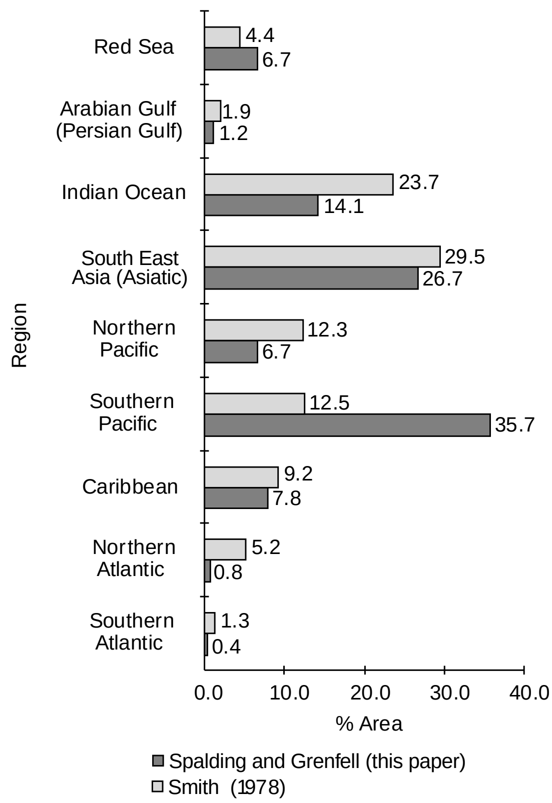

Fig. 2. A comparison of the regional reef areas obtained by Smith (1978) with those prepared for the current work. Areas are expressed in percentage terms to show, more clearly, the regional differences between the two sets of estimates

Reef areas derived using a grid of 0.5 × 0.5 km were typically between 30 and 45% lower than those areas calculated using a 1 × 1 km grid. These same results were likewise between 30 and 50% lower than those areas calculated using a 2 × 2 km grid. In order to analyse further the influence of scale, simple tests were run on three different countries for which duplicate datasets were available at different scales: figures for the Maldives derived from the 1 : 1 000 000 dataset were only some 4% smaller than those derived from a 1 : 300 000 dataset; for the Philippines the 1 : 1 000 000 dataset generated a figure 7% larger than a 1 : 250 000 dataset; while for the Seychelles the 1 : 1 000 000 produced a figure nearly 35% smaller than the high resolution figure derived from a mixed-source dataset. A similar test was also undertaken for data from the Great Barrier Reef which showed a much larger difference: the area derived from the 1 : 1000 000 dataset was 47% lower than that derived from the 1 : 250 000 dataset, however closer inspection of the dataset appeared to show that this difference arose largely from a differences in attribute definition, rather than scale.

Discussion

Thematic cartography has typically recognised three basic components of maps: space, attribute and time (Chrisman 1991). With the current dataset we have considered potential weaknesses in the first two elements, namely the scale problems (spatial) and definition problems (attribute). Time as a component has largely been ignored because, although the source maps for the dataset cover a wide range of ages, the largely physical definition of reef which has been assumed, together with the low resolution of the final analysis will largely negate any temporal influences on reef distribution over a time scale of perhaps 3–4 decades. This would not be the case if reef health or quality were being considered.

Alteration of the grid square area produced some notable variation in resulting area estimates. Using the maximum variation suggested above (either doubling or halving the side of the grid) would still lead to a global estimate ranging between 134 000 and 485 000 km^2: figures that are still substantially lower than those produced by most previous authors. In the current work a 1 km^2 grid is most likely to produce consistent and accurate results considering the resolution of the data sources and the fact that, in most cases, 'reefs' in this dataset approximate to reef crest or shallow reef areas. The 1 km^2 grid extends this narrow definition of a reef by assuming that these reefs have a 0.5 km influence in all directions from their perimeter.

The comparison of area estimates for particular countries using different data sources showed some interesting results. The variation which was shown is likely to be a composite effect of both varying scale and varying reef definition in the different sources. Although the number of potential case-studies was limited by data availability the results suggest that scale may not be a major influence where it varies over less than one order of magnitude. By contrast, the results from the Seychelles (where a 1 : 1000 000 dataset was compared to a mixed resolution dataset with some data at 1 : 50 000), suggest that at such resolutions the influence of scale may greatly affect the resulting statistics. If this is indeed the case then it seems likely that the global area estimate presented in this work is an under-estimate. Unfortunately, at the present time it seems likely that 1 : 250 000 is the highest consistent resolution available for mapping coral reefs and that higher resolutions are unavailable for large areas of the globe (Spalding, in press). This being the case, the current method remains the best alternative and, as high resolution data is very limited in the dataset (less than 5% of reefs have been mapped in this dataset at scales of 1 : 100 000 or better), they are unlikely to have a great influence on the global or regional totals.

The results from the case-study on the Great Barrier Reef showed an even greater variation between the results from derived from a 1 : 1 000 000 dataset and those from a 1 : 250 000 dataset. Closer inspection of the two datasets showed that the lower resolution source omits many reefs, not as a result of scale differences, but from a difference in reef definition. Cursory examination of satellite and aerial images shows that the high resolution dataset includes some slightly deeper structures which, although visible from the air are not likely to break the surface. These reefs were not included in the 1 : 1 000 000 dataset. The Great Barrier Reef is possibly exceptional, certainly in its overall dimensions, but it illustrates the problem of differing attribute definition, which is very difficult to control with any multi-source dataset, but particularly when attribute definitions are poor or unavailable.

The relative differences noted between the regional figures estimated in this work and those generated by Smith (1978) are worthy of comment. For most regions there is a notable consistency between the two sets of percentage estimates. Three regions, however, stand out as being quite different between the two studies. Smith (1978) showed similar areas of reef in the Northern and Southern Pacific regions, while the present paper suggests that the Northern Pacific contains only 6.7% of the world's coral reefs while the Southern Pacific contains 35.7%. The current estimate is likely to be more correct as the latter region includes not only the majority of the Pacific islands, but also the vast reef areas associated with Papua New Guinea and the Great Barrier Reef; north of the equator there are fewer islands. In the Indian Ocean again the current dataset differs widely from Smith's (1978), suggesting only 14% of the world's reefs occur here, as against nearly one quarter (23.7%). Although the Indian Ocean contains many very important reef areas, the region does not include the vast reef areas associated with the Red Sea, South East Asia or the Pacific. Finally, there are discrepancies in the area of the non-Caribbean Atlantic reefs, with Smith suggesting a total of 6.5% of the global total, while our figures suggest only 1.2%. As the only significant coral reef areas in this region are those of Bermuda, Brazil and the poorly developed structures in the central and eastern Atlantic it seems likely that 6.5% is a considerable exaggeration.

Although error and inaccuracy undoubtedly play a role in these and all previously calculated reef area statistics, reef definition also has a considerable role to play. Figure 3 provides some examples of possible reef definition and clearly shows that reef area figures could vary by a full order of magnitude depending on the definition of coral reef that was adopted. For this particular study we have focused on the shallow, physically well developed reefs, approximating to those marked C in Fig. 3. This definition was imposed upon us by the data. The only reef areas that have been consistently mapped around the world are the very shallow reefs, reef flats and reef crests, while the 1 km^2 grid approximately extends this definition to cover parts of the reef slope and lagoon as indicated by the C in Fig. 3. This definition covers the areas of highest productivity, in many cases having the highest percentage coral cover and the highest calcification rates; these areas are often the most economically important for reef tourism, and for coastal defence, although also presenting the greatest navigational hazards. Even fisheries science, which typically uses a wider definition of coral reef, often provides harvest statistics for reef-flat, or shallow areas of active coral growth separately from wider reef fishery statistics, recognising the very high yields arising from these areas.

The reef area estimates of Smith (1978) used quite a different definition of reef, more akin to the reef marked B in

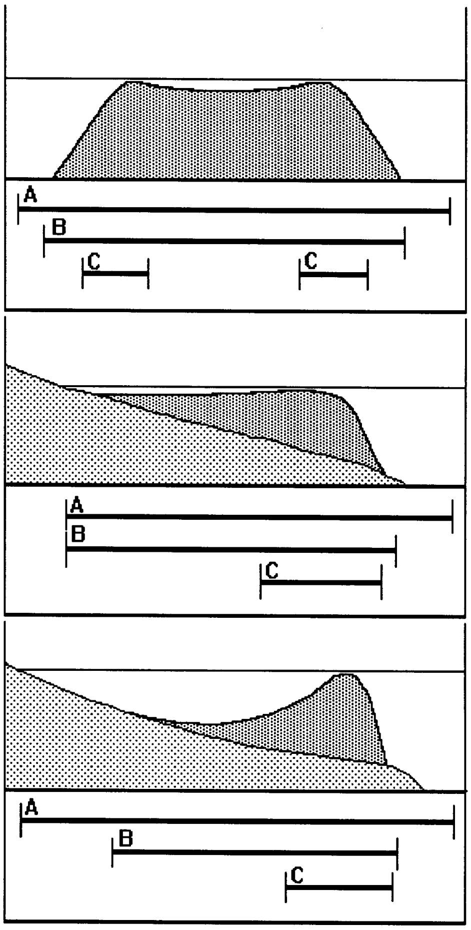

Fig. 3. Diagrammatic view of differing reef definitions for an atoll, fringing and barrier reef. *A*, *B*, and *C* represent different reef definitions: *A* extended reef area, of interest to fisheries; *B*, integral reef area, of interest to geologists, coastal planners; *C*, near-surface reefs, of interest for tourism, navigation, studies of maximal productivity, coastal defence

Fig. 3. This area could only be very roughly estimated, using a global reef map, bathymetric area figures and predictive techniques (estimating shelf area to a depth of 30 m for those regions with coral reefs). In this work Smith (1978) estimates that 90–95% of his total reef area comprises reefs with 'slow' calcification rates. These would equate to less actively growing and deeper reef areas. As our own estimate is more closely tied to the shallow reef areas we would expect a much higher proportion of our total reef area to be associated with faster rates of calcification. Given these differences in definition there is actually a surprising degree of similarity between the results of Smith (1978) and the current work. Where there are differences it seems likely that the more recent dataset provides more reliable results, although some discrepancies are likely to remain based on the differences in reef definition.

A number of workers use reef definitions which extend well beyond the classic reef types illustrated here, and even beyond the definition indicated A in Fig. 3. Munro (1996), for example, describes a reef for the purposes of reef fisheries as "an area in which the presence of reef building (hermatypic) corals largely precludes the commercial-scale use of mobile fishing gears such as trawls and seine nets". Such a definition includes, for example, sparse and occasional coral communities on submerged banks and slopes and, using such a definition, Munro estimates the total non-trawlable coralline shelf area of the western Atlantic alone to be some 660 000 km^2. While such areas of 'reefal shelf' are not reefs in the classic Darwinian sense they obviously are important in fisheries and may play a significant role in the maintenance of biodiversity. The reef area estimates under preparation by Kleypas (in press) will, to some extent, deal with these 'extended reefs', although there are undoubtedly many problems with such estimates. Over vast areas of the world the composition of the benthic substrates remains poorly known and unmapped. Similarly there are no detailed bathymetric datasets which cover the relatively shallow shelf areas at the global level. For measuring these extended reefs at the global level, predictive estimates remain the most viable method.

Acknowledgements. Thanks are due to Richard Luxmoore, for the original methodology, Jeremy Eade who trialled the methodology, and to the GIS staff at WCMC who have helped develop the first detailed digital coral reef coverage of the world: Corinna Ravillious; Simon Blyth, Mary Edwards, Jonathan Rhind, Annabel Lee and Ivor Wheeldon. Thanks are also due to the many organisations and individuals which have helped in the development of the global coral reef GIS: space does not permit us to acknowledge these individually, although a full list of sources is available on ReefBase (1996). Tom Spencer and Stephen Smith commented helpfully upon earlier drafts of this paper.

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