Science in Chagos

What we know and what we need to know

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Introduction

Chagos is a British Territory of about 55 islands totalling 55km^2 of land, spread over 10,000 km^2 of reefs (Fig 1). It is the site of the greatest marine biodiversity in the UK and its Territories, and it is the most remote reef system in the Indian Ocean. The near-absence of direct, local, human impacts and their overall condition has identified them as a key scientific reference site, and has led to their inclusion in the Pew Trusts Ocean Legacy series of four locations of major global importance[1].

This paper accompanies a more general colour document designed to promote awareness of the need to conserve and protect Chagos, a need which has become urgent in a period of global environmental deterioration and climate change. It presents a selection of extracts taken from over 100 papers published by more than 50 scientists. It demonstrates the importance of understanding the science of a region affected by climate change only, without local development impacts. It identifies immediate research targets to improve the knowledge base.

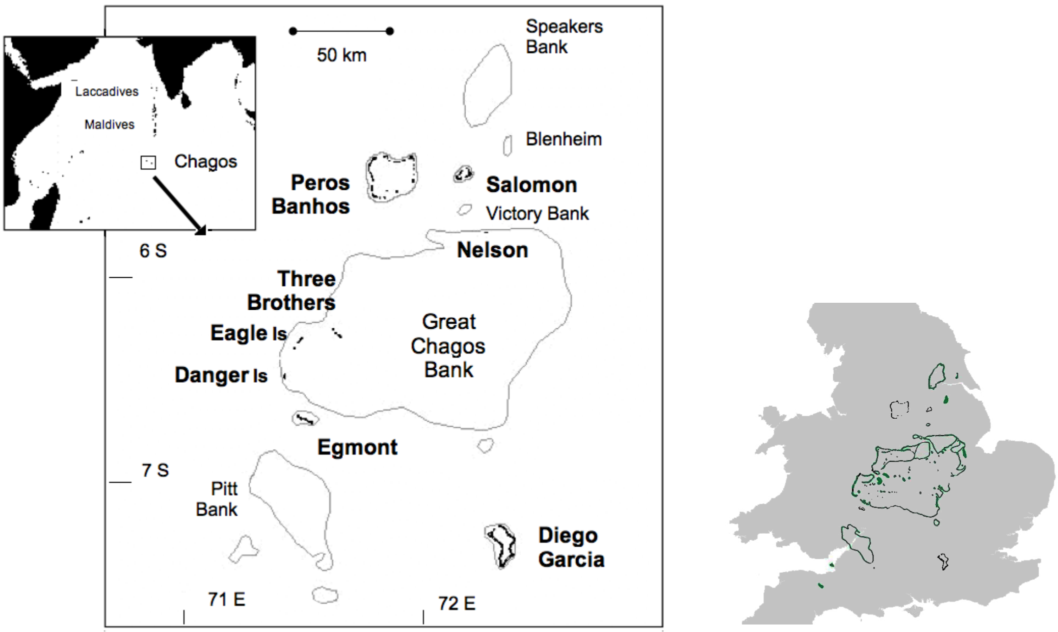

Fig 1. Left. Site map and location of Chagos. Atolls and banks with land are in bold, remainder are shallow and submerged reefs. **Right**: The relative size of Chagos and the UK.

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Stepping stone in the Indian Ocean?

A key point is whether Chagos is important. Three main issues determine this: is it big enough to matter; is it located where it would matter if it was big enough; and is there evidence that it acts as a stepping stone for species?

GIS work has determined the distribution of reef substrate with depth[2] (Fig 2). In the exceptionally clear waters of this region, peak reef diversity is 20 m depth, with high coral cover extending to 60 m deep[3]. Depending on what cut-off is adopted, there are at least 9,000 km^2 of reef substrate within the photic zone. In this archipelago, all examined areas of lagoon sea floors support more coral-covered hard substrate than they do soft sediments[4].

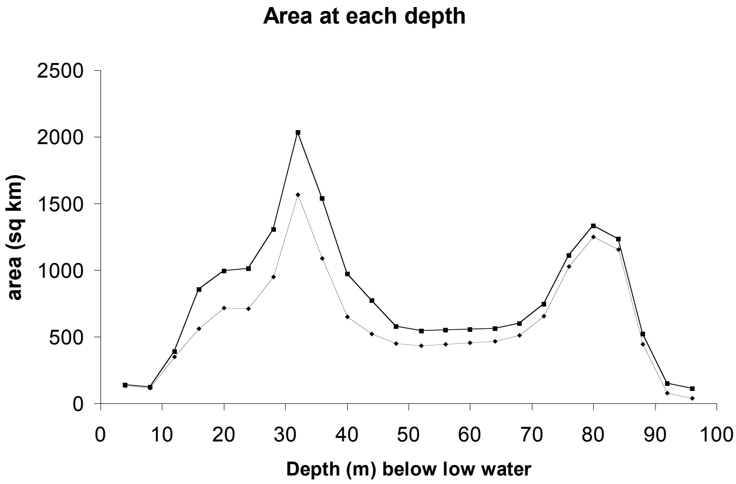

Fig 2. Depth distribution of sublittoral substrate with depth in Chagos to 100 m depth, calculated by GIS from six sets of Admiralty charts. Top line is all banks and atolls, bottom line is 5 main atolls only (including Great Chagos bank).

In this region, currents flow east or west, depending on season and annual location of the Inter-Tropical Convergence Zone. Chagos lies roughly central in any east-west movement of species, between the Indonesian very high diversity region and shores of the western Indian Ocean. There is substantial reef substrate down-current of Chagos. The South Equatorial current usually exceeds 1 kt (Fig 3).

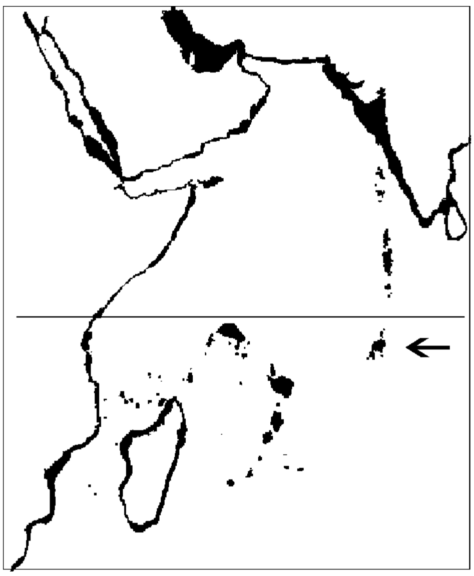

Fig 3. Shaded black shows areas of reef substrate or potential substrate lying within the photic zone in the western and central Indian Ocean. Arrow points to Chagos. Horizontal line represents the Equator. Most shores are fairly steep-to, so reef zones appear thin at this scale. Large expanses between Chagos and African coast are the Mascarenes and Seychelles banks, with the large Nazareth Bank, Saya de Malha Bank and Cargados Carajos shoals.

There is substantial shallow substrate to act as a stepping-stone in terms of Indian Ocean species movements, and substantial 'target' reef to receive exported larvae.

An early attempt to examine whether or not species movements occurred used a GIS technique and species lists of, in this case, corals[5]. Substitution of geographic distances (km) in a GIS with 'distances' measured by species similarity coefficients, showed an Indian Ocean which was 'squeezed' in an East-West direction, and even a Red Sea (a known coral reef larvae 'trap') which became inverted, pointing towards the central Indian Ocean. This provided strong indications that Chagos did act as a stepping stone in an East-West direction, but it could not add a time element; is the East-West connection facilitated frequently, or only rarely since the Holocene?

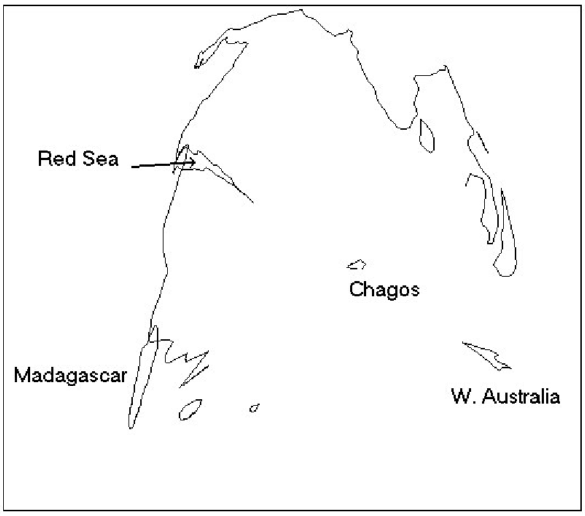

Fig 4. 'Rubber sheeting' of the Indian Ocean, achieved using a 3rd order polynomial procedure, where geographical distances were replaced by 'biological distances', namely similarity coefficients of corals from 24 locations with those of Chagos.

DNA techniques now permit considerable improvement on this rather crude first estimate. In 1996, 2006 and 2008, samples were collected for DNA analyses of 24 species of reef fishes, numerous marine invertebrates including corals and crustaceans, coconut crabs, two turtle species[6] and several birds. Few results are available yet, but it has been shown so far for the turtles that Chagos populations do indeed have a strong affinity with those to the west particularly and, depending on the species, a weaker connection with populations in the north or east, but, so far, numbers of samples are limited. For the one crustacean examined to date[7], populations within the Indian Ocean are genetically similar despite the long distances between them (but that these separated from Pacific groups, probably from the late Pleistocene).

Early indications bear out the stepping-stone hypothesis. Results are in preparation by participants from institutions in six countries, which should supply information on the biogeographic role of this archipelago for both reef and key island species.

Ocean warming effects

Chagos reefs are one of very few locations where effects of climate change can be measured without being confounded by effects from localized and direct human influences such as shoreline alterations, sewage, industrial pollution and extensive over-fishing. The Indian Ocean was the region where the greatest impact occurred from the extreme warming event in 1998, so considerable work has been done on past and forecast sea surface temperatures (SST) of this region, and on mortality and subsequent recovery of reef communities from that time.

SSTs for Chagos (Fig 5 left) show a rising trend, beginning in the 1970s, forecast to continue rising to the later part of this century[8]. Important too is the probability, in each future year, of a recurrence of the lethal temperatures of 1998 (Fig 5 right). With current trends, about one year in every two will see these temperatures by 2030. In corals, the principal reef builders, average age of reproduction is about five years old, so the date when the probability of mortality occurs more frequently than once every five years may be more important; this is predicted by about 2020.

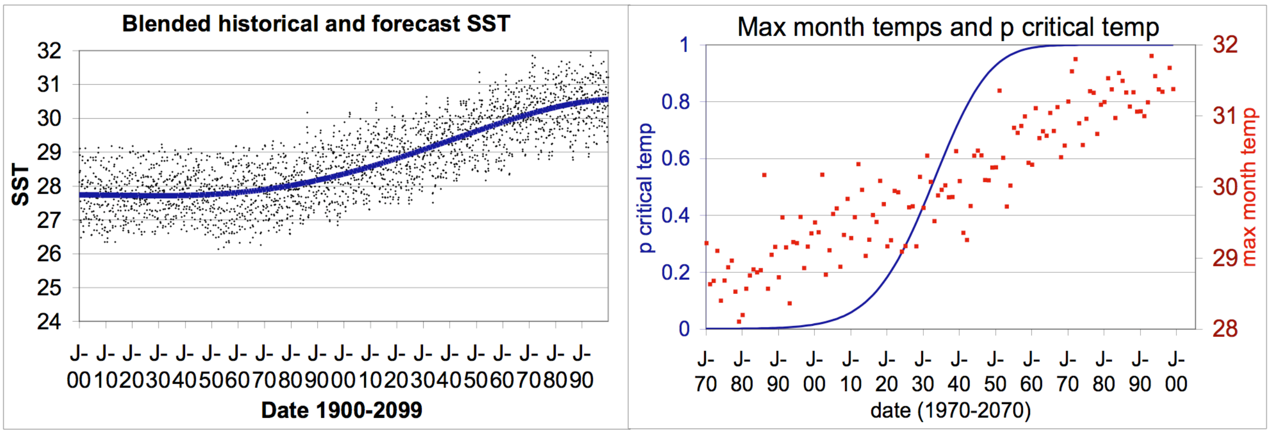

Fig 5. Left: Historical SST (HadISST1) and forecast SST (HadCM3) blended to show confluent trend for Chagos 1900-2099. **Right**: Dark line is probability of seeing a recurrence of 1998 temperatures. Left hand y-axis shows probability Dots and right y-axis: warmest month temperatures.

The above curves are derived from relatively coarse satellite data. In 2006 twenty temperature loggers were deployed at depths to 25 m in four atolls, recording at 2 hour intervals. The first six were retrieved from Diego Garcia in 2008. A four month clip from 25 m depth is shown in Fig 6.

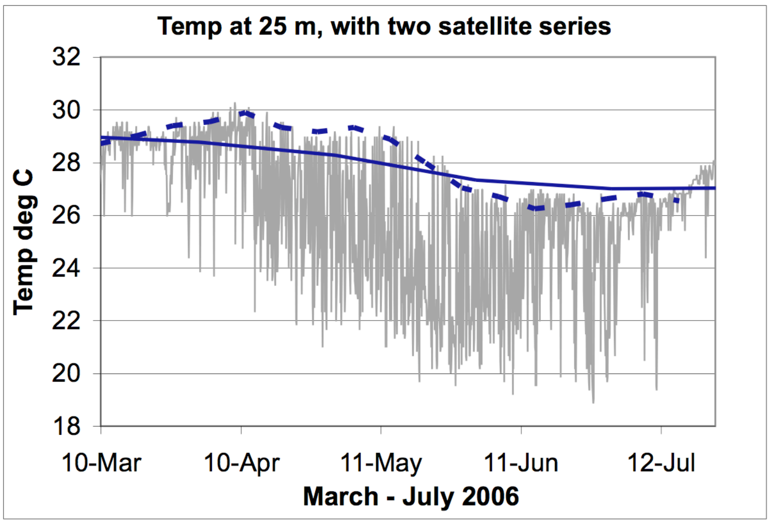

Fig 6. Water temperatures: one example (from 25 m depth) of six available. Grey trace shows logger data, taken at 2 hourly intervals, north Diego Garcia. Solid trace is HadISST1 temperature data, which is averaged over 1 month and over a 1x1 degree square of latitude and longitude. Dashed trace is high resolution AVHRR data (8 day, 1 km^2 resolution).

Satellite data, especially AVHRR, has remarkable accuracy and advantages, but clearly fails to reflect the frequent plunges in temperature at depth. The magnitude of these, and their occurrence toward the end of the seasonal warming period, may provide an important temperature refuge for reef life. These are clearly important features; the data from all six traces is available for download[9]. The plunges increase with depth and have a cycle of 2-4 days. These temperature patterns may prolong or increase the survivability of reefs in a warming world beyond that predictable in conventional ways using satellite data only.

Work needed is firstly to retrieve the remaining 14 loggers and determine whether these plunges occur on other Chagos atolls, whether they occur in the deep lagoons, whether episodes of bleaching without mortality occurs during the periods of cool water influx, and whether they affect the survivability of these reefs. This has great importance to the selection of reefs for protection and conservation in future, given that so many other designated, protected areas in the Indian Ocean have afforded little or no protection from warming (next sections).

Coral mortality from warming

Warm SSTs overwhelmed most of the Indian Ocean in 1998, killing most stony corals in Chagos and the rest of the Indian Ocean. Soft corals were also severely depleted, both in terms of cover and taxonomically. Affected depths extended to a minimum of 15 m in Chagos' northern atolls to >30 m in the southernmost Diego Garcia atoll (Fig 7). Substantial areas of denuded substrate were left, covered only by films of filamentous algae and micro-organisms. Strikingly, macro-algae did not take over the vacated reef substrate, as occurred in most areas of the world where reefs suffer nutrient enrichment, coastal development and overfishing of herbivores[10]. Unusually, large expanses of space remained bare of macro-organisms for several years. Erosion of dead colonies and bare substrate then became substantial, and continued at least until coral cover began to recover[11].

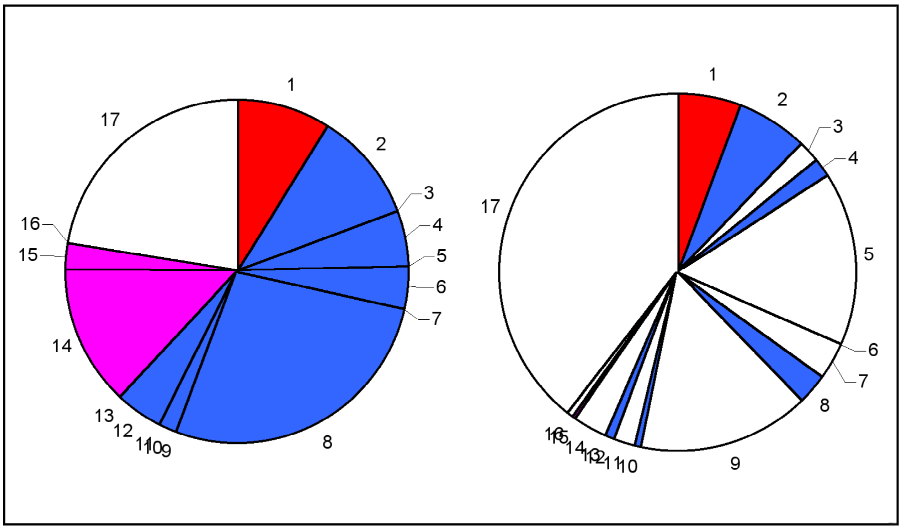

Fig 7. Reef cover values from before (**left** 1996) and after (**right** 1999) the 1998 warming event, to 5 m depth. Key: 1: Red algae, 2: *Porites* live, 3: *Porites* dead, 4: digitate coral live, 5: digitate coral dead, 6: table coral live, 7: table coral dead, 8: other coral live, 9: other coral dead , 10: *A. palifera* live, 11: *A. palifera dead*, 12: *Heliopora* live, 13: *Heliopora* dead, 14: Soft coral, 15: *Millepora* live, 16: *Millepora* dead, 17: bare substrate.

In several respects, Chagos was typical in the degree it suffered compared with 20 other sites in the Indian Ocean[12] and the degree to which it was affected was approximately average (Fig 8). It is the extent and rapidity of its subsequent recovery which is exceptional. Because coral survival in Chagos reefs increased with depth, the average loss was approximately 50%. Rapid consequences resulting from the loss of coral cover included the increased erosion of reef substrate, and, most importantly, the loss of 3-dimensional structure (Fig 8 right).

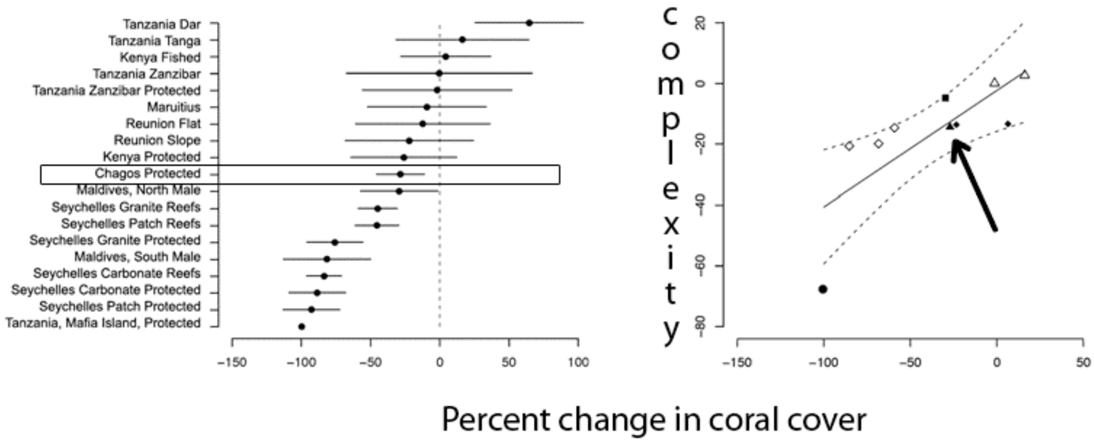

Fig 8. Coral mortality in Chagos in an Indian Ocean context. (**Left**) Change in live coral cover at 20 biogeographical locations: Chagos is marked by the box. Bootstrapped 95% confidence intervals indicate whether mean change departs significantly from zero. Locations ordered by magnitude of coral decline. (**Right**) Correlation between change in live coral cover and change in structural complexity across the region: arrow points to Chagos.

Coral recovery and trajectories

Recovery in Chagos since 1998 has been rapid, even though there have been additional warming events in 2003 and 2005, which caused severe and extensive bleaching, but minimal subsequent coral mortality in both those cases[13].

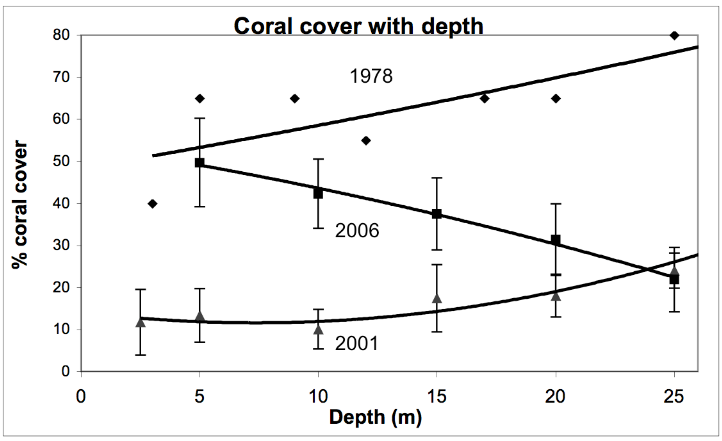

Fig 9. Coral cover with depth on seaward reefs of Chagos in 1978, 2001 and 2006, showing the loss seen in 2001 and recovery in 2006. Bars are 95% CIs; data to compute CIs for 1978 are lost, so mean points is shown instead to give an idea of scatter. (Data for 2006 is for all observed sites; a similar plot in (ref 13) showed the pattern for northern atolls only.

Different atolls embarked on differing trajectories of recovery. Obvious possibilities for this depend on differing larval recruitment patterns and differing ability of atolls to produce larvae and retain them once locally produced. Space was not limiting in any atoll after the 1998 mortality, and it is likely that chance and stochastic factors initially governed what corals recovered where. Fig 10 shows the greatest similarity between adjacent atolls, and greatest differences between more distant pairs, so localized current patterns and temperature refuges are likely also to be important.

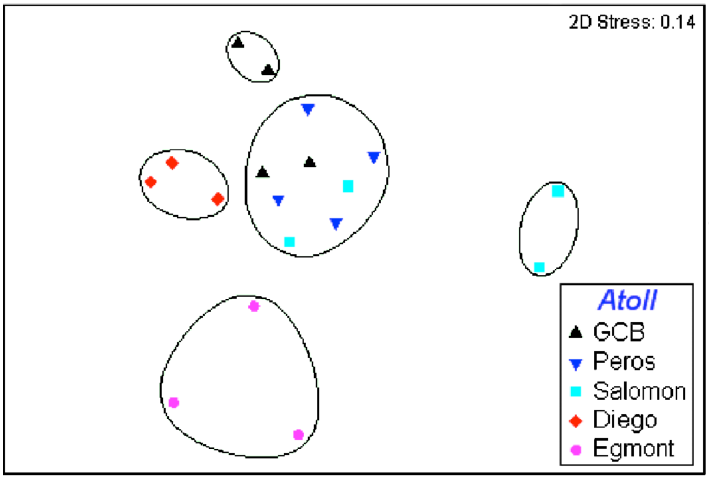

Fig 10. MDS ordination of sites from all atolls on benthic community data from 5 m depth. Index is Bray Curtis, grouping boundaries are 60% similarity

Greater understanding of what factors drive recovery are needed, which will have clear practical application to conservation of reef systems around the Indian Ocean. Present 'marine protected areas' do not appear to confer any particular protection to impacts from climate change[14], and choice of where effort should be placed for marine ecosystem conservation and protection needs to be much better informed, given limited resources available for conservation. For example, reefs subject to frequent temperature drops due to ocean swell exposure and upwellings might be more resilient, and hence perhaps should be better targeted for protection.

Coral cover has been restored in shallow water, but present benthic communities differ in two important respects from the pre-1998 condition. They are at present primarily encrusting, lacking the 3-dimensional canopy structure in most areas due to the young age of the returning corals. Secondly, as seen in Fig 10, the benthic communities differ between sites. Community structure may be converging, but this remains unknown. Partly, this appears to be influenced by active depth selection by those coral larvae which settle in each location[15], a feature readily observable in Chagos seaward reefs because of their (temporarily) extensive quantity of unoccupied substrate. Given that conservation efforts for the Indian Ocean aim to encompass as many different types of community as possible, an important question is whether a convergence of community type between sites within the archipelago will later occur, in the absence of further massive mortalities, and whether further mortalities will act to keep the present substantial differentiation in place?

Fore- and hindcasting of coral population trajectories

For meaningful conservation efforts in this ocean, it is important to keep track of 'trajectories' of reef health or degradation. When access to sites is easy and regular, documentation of key statistics (such as cover, diversity etc.) can show trajectories and trends over time. To detect or understand trajectories on isolated and infrequently visited reefs, and then by different researchers, is much harder. Simple tools for rapidly gathering information that allows extrapolation and reconstruction of trajectories (i.e. forecasting and hindcasting) have been developed, based on phototransects, that allow trajectories of coral populations in the Chagos Archipelago, to be made.

Some trajectory information is available: some coral zones disappeared while others regenerated very well. However, due to the area's extreme isolation, much information is lacking of key population parameters which will tell us about regeneration, such as information on recruitment rates, growth dynamics, and even differential survival/regeneration rates on ocean facing reefs versus lagoons. Because Chagos (at least its northern atolls) contains some of the world's last uninhabited reef areas unimpacted by human habitation, its value is of increasing importance in this respect also. By extracting size-class information from phototransects, and making certain assumptions about recruitment and life-history characteristics, we can regress a governing life-stage transition matrix from the ensemble of phototransects. From this governing matrix, key parameters, such as fertility, recruitment and survival are being extracted and estimated with reasonable certainty. At present, enough information exists to reconstruct the dynamics of several of the most important genera, including fore- and hindcast general coral cover. Future work must concentrate on finer sampling that will also focus on keystone species groups such as acroporids, pocilloporids, faviids and poritids.

While coral cover is low, competitive interactions between species are clearly of minor importance, but possibly restoration of cover may be reflected by increasing numbers of coral interactions. It is suggested that competitive interactions are a returning influence on the emerging (and different) community structures. Some of the earliest work on aggressive interactions between corals was performed in Chagos[16]. When benthic cover was severely depleted following the 1998 mortality, little influence by pairwise interactions and competitive dominance on community structure would be expected while cover remained low, but, by 2006, cover was restored sufficiently for interactions to again become a significant driver of community structure. A dominance/competitive hierarchy re-established itself after only 8 years, to a degree sufficient to influence community structure seen on the reef[17]. The importance of this varies between reefs according to which species initially recruited, and the importance also is likely to change with time as communities evolve.

Partly in an attempt to map these events, a very high resolution photographic system was developed[18] in which over 1,000 frames were photographed to create a mosaic covering 68m^2 (Fig 12).

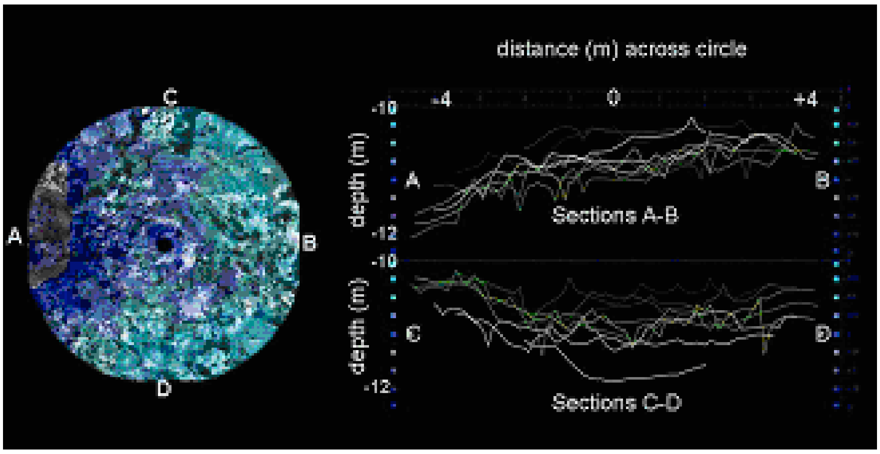

Fig 12. Reef topography produced from reef maps by calculating radial distances between frame centres, which indicates relative distance of reef surface from camera.

With 3-D structure widely assumed to underpin the high diversity of coral reefs, this technique is being used to determine 3-dimensional structure, or rugosity, over this scale (10 m diameter) by means of calculating distances between adjacent frame centres for the >1,000 frames in each image. The need is to extend and automate the technique.

Because visits to the archipelago have been relatively few, video transects have also been used to archive reef condition.

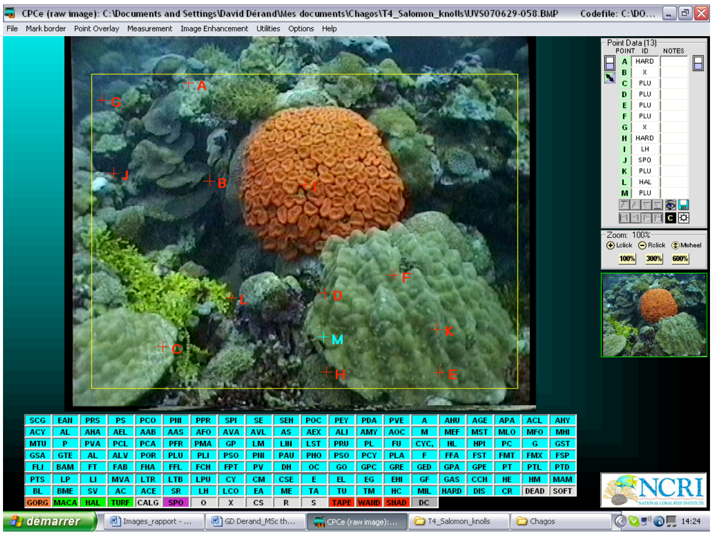

Fig 13. 'Coral Point Count' software applied to a processed image from Salomon knolls. High hard coral cover showing the visually mature state of the reef slope (Salomon atoll) in 2006. In this example, cover values are calculated by random scattering of points (red letters on screen).

To date two series have been taken, one for the series of requirements noted, and a second which focused on diseases in corals.

Lagoon responses

Chagos atoll lagoons are unusually rich in corals, having high proportions of hard substrate. Some lagoons are extremely sheltered and enclosed while others have very high exposure, to the point of even supporting rudimentary, calcareous algal spur and groove structures[19], features which usually are associated with high exposure reefs, and which indeed are well developed on many of the ocean-facing reefs of this archipelago.

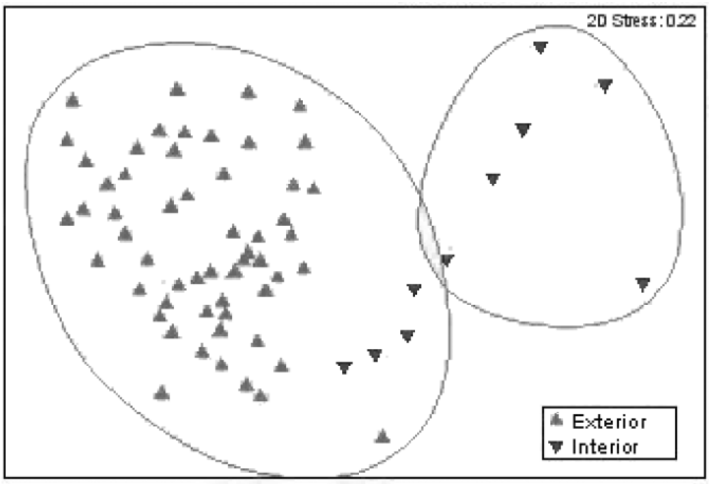

Fig 11. MDS ordination of samples (all atolls) based on coral cover at 15 m depth. Bray-Curtis grouping of samples, with groups delimited at 50% similarity.

Lagoonal coral recovery responses are shown with those of the ocean facing reefs (Fig 11). Lagoonal sites are not grouped as clearly as ocean-facing sites, and there is a ‘trail’ of lagoon sites whose character increasingly becomes oceanic in nature.

Fish responses to climate change in Chagos

Responses of Chagos fishes with the reefs following the 1998 bleaching event was examined as part of a large Indian Ocean wide study of the impacts of that bleaching event. Reef benthic cover, structural complexity and the diversity and abundance of reef fishes were quantified before and after (2005-2006) the 1998 bleaching event at 66 sites in 7 countries. Many of these countries included sites in no-take marine protected areas, and Chagos represented a large *de facto* protected zone. Impacts of the bleaching event on coral cover were greatest in the low latitude island countries of Seychelles, Maldives and Chagos. Chagos displayed an impressive recovery from severe bleaching in that time period (Fig. 14B). Across the region there was a gradient of coral loss (Fig. 14A,B) against which to test secondary effects such the consequences of this on fish. It was apparent that where coral had been lost, structural complexity of the reef had also declined (Fig. 14C), leading to changes to various components of the fish community. Declines were evident for overall species richness, and coral feeding and small planktivores were affected. Small bodied fish (<20cm) also declined across the region. Only the mixed diet feeders were completely unaffected, with the small bodied herbivores also declining.

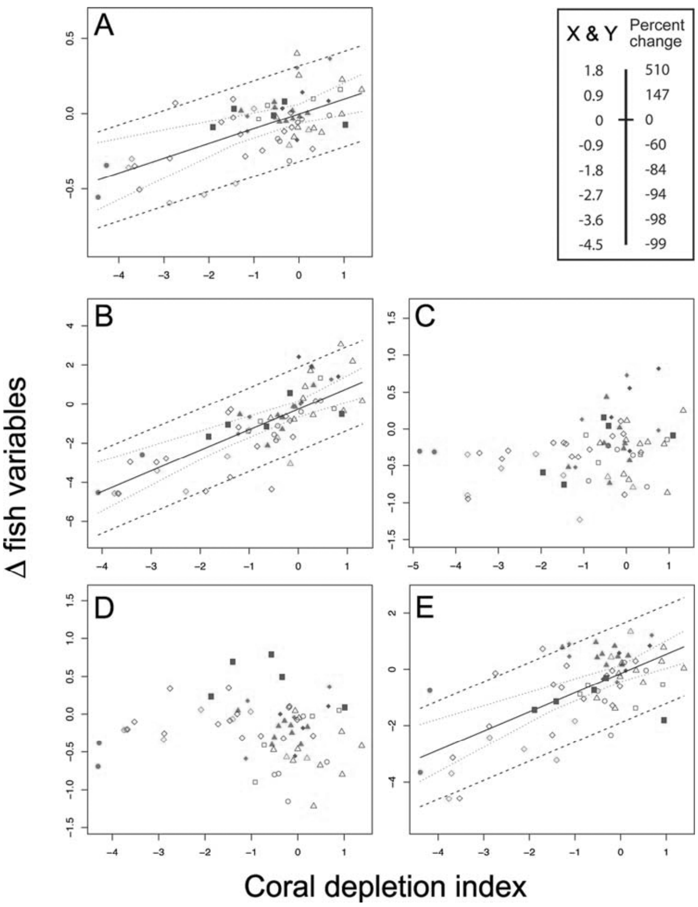

Fig 14. Change in fish groups in response to coral decline. Continuous model Bayesian meta-analysis of relationships between decline in coral cover and change in (A) species richness of fish assemblages, and (B) abundance of obligate corallivores, (C) herbivores, (D) mixed diet feeders, (E) planktivores. Scale as converted to percent change indicated in top right panel. Linear trend lines only presented where significant model fits were recorded. Inner dashed line represents 95% credible interval on the regression and outer dashed line represents the 95% prediction interval. Sites include Mafia Island, Seychelles, Maldives, Kenya, Tanzania, Reunion, and Mauritius as well as Chagos.

Importantly, Chagos was a pillar of stability in the region, with sites showing comparatively little change in status through the bleaching event. The highly diverse and abundant fish life, and subsequent rapid recovery of corals, confirmed Chagos as a unique location. The study highlighted the importance of depth refuges of live coral cover in Chagos to reseed shallower reefs after a large bleaching event, and showed that in the absence of other human impacts, coral reefs and associated fish assemblages can be very resilient to impacts of climate change. The need to reduce local stresses and manage the resilience of the system as a whole in other locations is evident.

In 2006, the feeding specialization of coral feeding butterflyfish in Chagos was assessed[20], which allowed for an assessment of the susceptibility of different species to coral loss. Multiple individuals of 3 species, *Chaetodon trifascialis*, *Chaetodon trifasciatus* and *Chaetodon auriga*, were monitored on reefs in Diego Garcia. *C. trifascialis* was the most specialized feeder, targeting almost exclusively *Acropora* corals, and only consuming 4 genera of corals overall. *C. trifasciatus* also only ingested coral, but had a more diverse diet, targeting 14 coral genera. *C. auriga* was the least specialized, with approximately 55% of its diet being live coral, the remainder being benthic algae and small invertebrates. It had earlier been found that the inner Seychelles islands had lost ~90% of their live coral cover in the 1998 bleaching event with corresponding effect on these butterflyfish; the feeding specialization identified in the Chagos study was reflected in the patterns of decline of these species, with *C. trifascialis* almost disappearing, *C. trifasciatus* displaying substantial declines and *C. auriga* displaying very small and unsubstantial changes. The study highlighted the consequences of feeding versatility in dictating species vulnerability and ultimately abundance following climate change impacts.

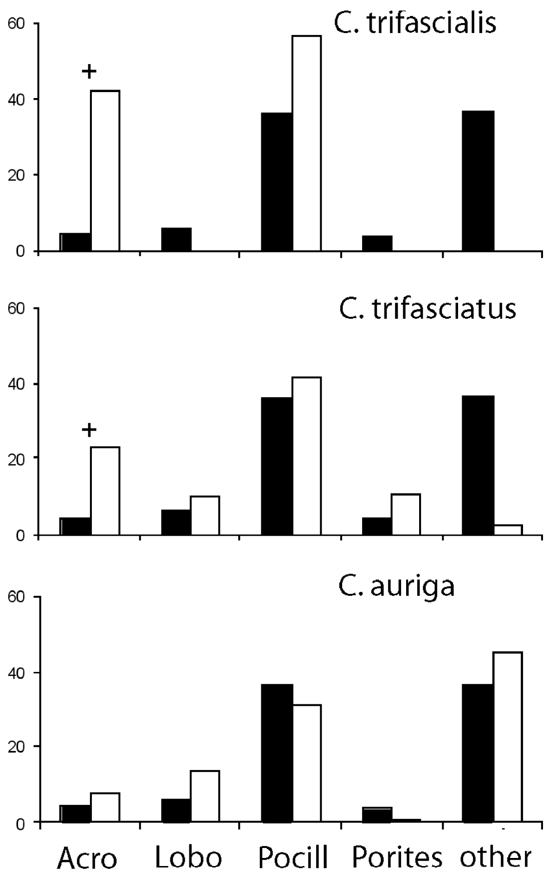

Fig 15. Feeding selectivity of *Chaetodon trifascialis*, *C. trifasciatus* and *C. auriga* in Diego Garcia. Data are only presented for the four coral genera most preferentially consumed. Black bars indicate percent resource availability, open bars indicate percent feeding bites on that resource. + indicates positive selectivity on that resource by the fish.

Acclimation by zooxanthellae clades

A key question is whether corals have the ability to acclimate or adapt to rising SST. Amongst zooxanthellae, Clade C is the overwhelmingly dominant form in corals and, in the last few years, several authors have concluded that Clade D, which is more resistant to warming, is possibly increasing in abundance and frequency of its occurrence. Clade D appears to perform less well in 'normal' conditions, which may be why it has not become more common than appears to be the case.

The focus has been almost entirely on the possible increase in Clade D, but remarkable results from Chagos[21] show a differing path of acclimation. No Clade D has yet been found in this archipelago. However, Clade A is surprisingly common in some genera. Clade A is more tolerant of strong light.

Bleaching episodes in Chagos occur during Feb-April when winds may be light or nil for long periods. Bleaching during warm seasons is known to result not only from raised temperatures but also from co-occurring strong illumination. Lack of wind during the warm season results in a flat sea, through whose glassy surface more illumination penetrates. Many examples were reported after 1998 where corals which were only partly killed had live tissues on shaded portions only, and it was estimated that illumination at depth during these periods was considerably greater than in conditions of normal waves. Acclimation appears here to be taking the route of greater light tolerance. Clade A is known primarily from the Caribbean to date, and this response and possible method of acclimation adds a new dimension. Clade A was detected in substantial abundance in the most sensitive *Acropora* and related *Isopora* (formerly called *Acropora palifera*), but not in others to date.

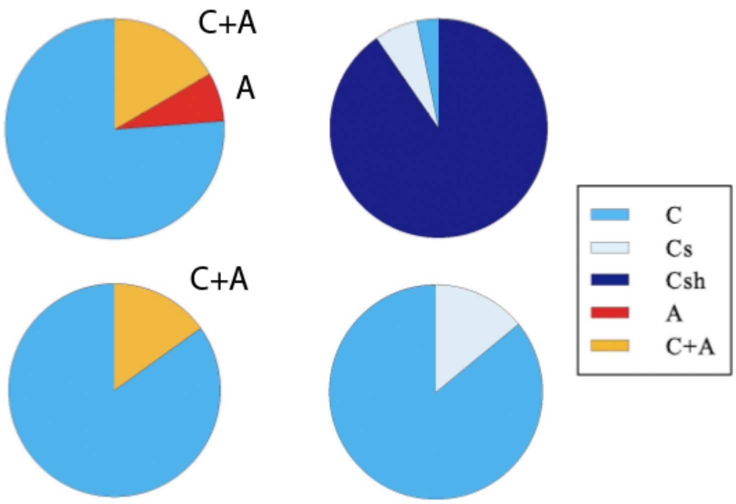

Fig 16. Proportions of different zooxanthellae clades in Chagos corals. Diversity of *Symbiodinium* as determined by PCR-RFLP from four species: **top left**: *Acropora muricata*, **top right** *Seriatopora hystrix*, **bottom left** *Isopora palifera*, **bottom right** *Stylophora pistillata*. Three species of *Pocillopora* were all Clade C and not shown here.

Water exchange, clarity and sand budgets

Localised water exchange, especially of cool water, may be assumed to underlie the ability of these reefs to resist warming. Chagos lagoon temperatures may exceed ocean surface temperature by 2 ^{o}C on cloud-free, windless days[22].

The persistence of the islands themselves in conditions of sea level rise and in times of reduced (even temporarily) limestone production is a key question needing more attention. Some work has been carried out in Diego Garcia. This atoll is particularly enclosed, ideal for estimating lagoonal water and material exchange on a daily (tidal) basis. Its lagoon covers 122 km^2 of which approximately half is rich or potentially rich coral habitat. With an average tidal range of 1 m, daily water exchange is 240 x106 m^3 d^{-1}.

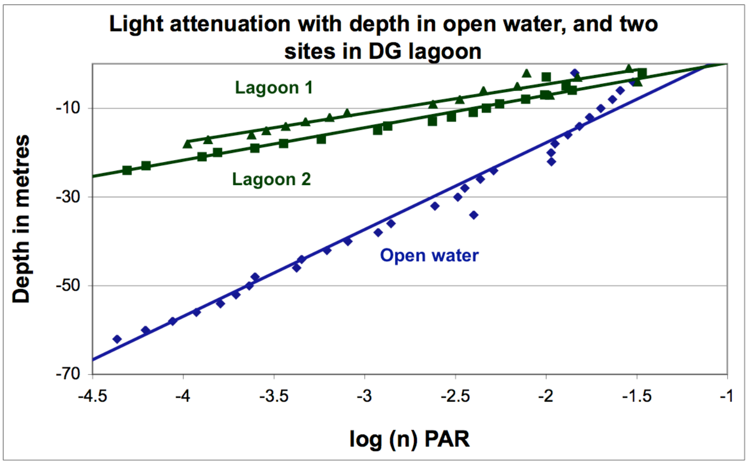

Fig 17. Light attenuation with depth in open Chagos waters, and in two central parts of the lagoon. x-axis is log of difference between surface light and that at each depth at the time of measurements. (PAR: Photosynthetically Active Radiation)

The open water transparency is close to maximum theoretical levels, reflecting the nutrient-poor state of the central Indian Ocean. From differences in water clarity in adjacent ocean and flooding water, and that in ebbing water (Fig. 17), it is calculated that daily removal of particulate material was 600 tons – 4,800 tons/ day. Allowing some sediment in incoming tides, this is conservatively revised down to 500 – 4,000 tons day^{-1} or between 219,000 -1.4 million tons y^{-1}. In a healthy reef system with stable shores and islands in equilibrium, limestone production approximately equals limestone attrition and, in Diego Garcia lagoon, limestone production on coral reefs appears to be remarkably similar to quantities removed on outgoing tides. In the northern atolls which are more open in nature, lagoon water clarity is greater than it is in Diego Garcia, permitting greater coral growth in deeper water.

For production and attrition in a lagoon to balance, other elements of reef condition must be optimal, namely the balance of coral-algae, and removal of both by grazing and rasping organisms. These calculations have been used to assess erosion in Diego Garcia, which is now marked in some important areas. Similar calculations are needed to estimate rates and amounts of erosion of other islands in the archipelago, however, these calculations will be more complex due to the more open structure of the atolls. Studies of sediment structure and balance between algae, foraminifera, coral and other organism derived carbonate sediments are needed. At a number of sites throughout Chagos, apparent rise in sea levels and accompanying erosion of beach sand has destroyed both vegetated land and what appears to have once been important turtle nesting habitat

Several atolls in the archipelago are swash atolls, consisting of reefs just below the surface, without land formations. These reefs are largely unstudied, but could provide valuable information of how atolls may change in structure in response to inundation by sea level rise and extreme loss of sediments due to erosion.

Reef geomorphology from remote sensing

Some of the earliest trials of the 1970s which calibrated orbiting sensors for marine use were carried out in the very clear waters of Chagos[23] and this has been taken much further recently. In 2006, a section of reef in northern Diego Garcia was studied to ascertain how well the much finer topography of the submerged platform can be derived from satellite. Again, the exceptionally clear waters of the central Indian Ocean offer the opportunity to map the distribution of seabed topography and habitat at the scale of the whole archipelago using remote sensing data. The key to the usefulness of this strategy is that it must yield reliable information about the seafloor with only minimal investment in fieldwork, as opportunities to visit many of the world's remote reef systems, such as Chagos, are difficult.

Commercial imagery with sub-metre spatial resolution is readily available for Diego Garcia from both the IKONOS and QuickBird satellites and will likely expand to cover large swaths of the Chagos Bank in the coming years. A bathymetry survey was conducted (Fig. 18) using an acoustic transducer acquiring a depth sounding three times a second along the track of a small boat. These data were combined with a derivation of bathymetry directly from an IKONOS satellite image that relies on the predictable extinction of light between spectral bands. The method was shown to be robust down to a depth of 15 metres (inset Fig. 18), at which point there are too few photons returning from the seabed to be reliably detected in the longer wavelengths of the satellite sensor.

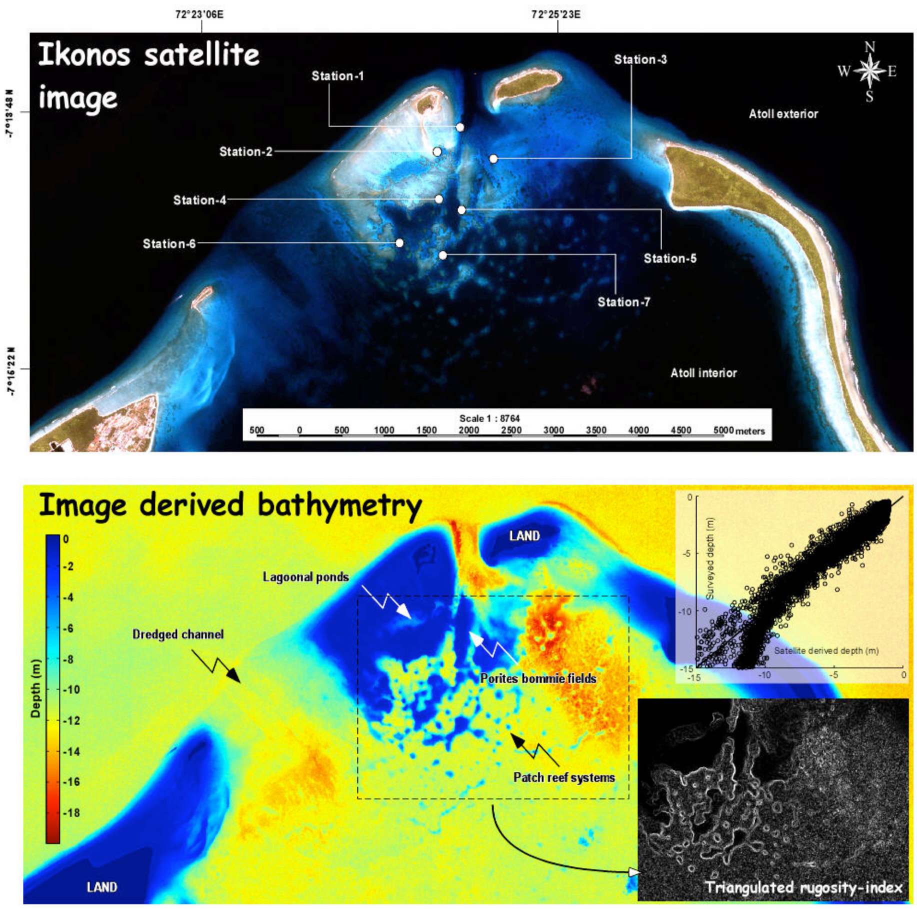

Fig 18. Satellite-derived bathymetry for the northern tip of Diego Garcia

The seafloor topography model derived from the satellite data is capable of resolving the geomorphology of the reef (Fig 19). The expansive reef flats that have built around the series of small islands is shown to become fragmented with distance leeward from the atoll rim, before finally transitioning into a network of semi-coalesced patch reefs rising from the lagoon floor. A dredged shipping channel through the major break in the atoll rim is clearly visible in the satellite bathymetry.

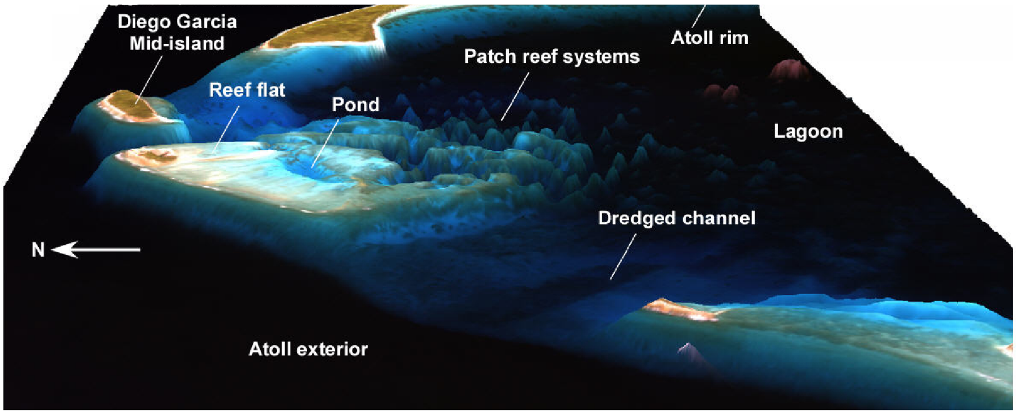

Fig 19. 3-D representation of the marine topography of study area derived from satellite. The intricate patch reef system on the lagoonal side of the rim has a rugosity index of 15:1. This highly complex area represents critical habitat for many guilds of reef fish

Estimates of fish diversity from remote sensing

The topographic map can then be used as the basis to derive metrics of seabed roughness that in turn can be used to forecast the distribution, abundance, and diversity of fishes[24]. The basis of this predictive ability lies in the fact that certain guilds of fish favour seafloors which offer set characteristics of rugosity and faunal coverage. To construct a predictive model it is also necessary to map the distribution of ecological assemblages that cover the seabed. Coupled with some on-ground knowledge, the character of the benthos can be derived from the satellite data since different assemblages display separable signatures in albedo and texture (Fig 20).

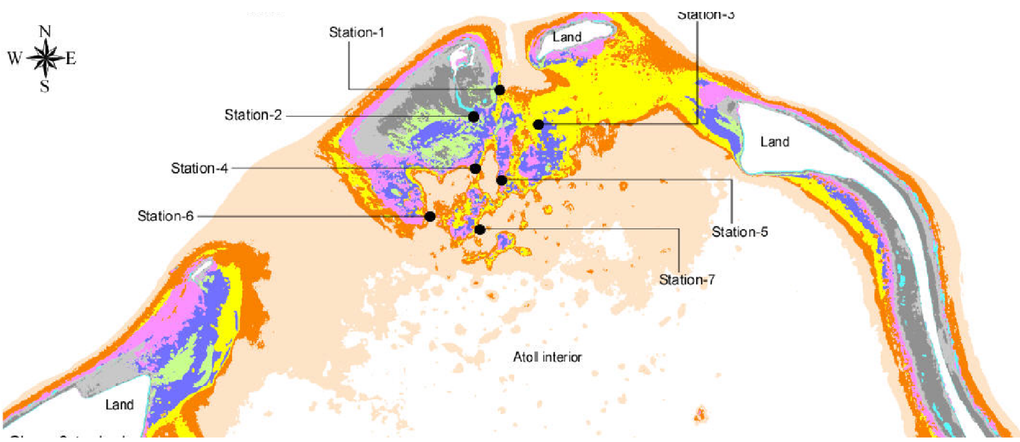

Fig. 20. Habitat map for the study area derived from IKONOS satellite imagery and ground-verification. Nine ecologically relevant categories were deemed adequate to represent the ecological and geomorphological diversity of the area. Overall accuracy of the map was 78% when tested against an independent ground control set.

Validation for the predictive model was provided by replicated counts of fish within the study site during 2006. A total of seven stations were visited (Fig 21) with four replicate fish counts conducted at each. The degree to which reef fish respond to the roughness and complexity of the seafloor was assessed by extracting metrics of rugosity and assemblage diversity across numerous scales within the satellite imagery (Fig 21b).

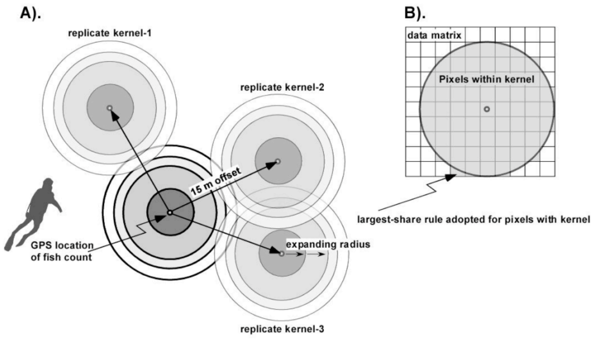

Fig 21. A). Seafloor character was assessed within expanding circular kernels to a radius up to 400 m, operating atop of satellite-derived rugosity and diversity datasets. 3 replicate kernels were surveyed at each measurement station. B). A largest-share rule was employed such that pixels subtended by the periphery of the circular kernel were considered for analysis providing >50% of their area was within the boundary.

The study successfully showed that remote sensing can be used to assess habitat complexity over 3 orders of magnitude (from spatial scales of 50 to 125,000 m^2). Monte Carlo simulation revealed that for areas exceeding 5,000 m^2, satellite-derived seabed complexity was a poor predictor of fish, but, over lesser distances, diversity and abundance of certain fish communities showed strong relations to the remotely sensed parameters. The study suggests that remote sensing is capable of predicting habitat complexity at a scale relevant to fish over expansive areas. The clear and shallow waters of Chagos are well poised for the further application of satellite mapping to understand the geomorphological diversity of the archipelago's reefs, their current status, and their susceptibility to erosion under scenarios of rising sea level.

Pollution and water quality

Pollutant concentrations in both biota and seawater have been analysed in several locations[25,26]. In the late 1990s a range of organic and inorganic substances proved to be detectable only in very low quantities, with the possible exception of copper which was attributed to the use of copper-based pesticides during plantation days of over 25 years earlier. In 2006, specific biocides including Irgarol, which is used as an anti-fouling agent, were assessed in Diego Garcia harbour along with a programme of screening for a wide range of other common substances. Levels found were exceptionally low and mainly undetected at the parts per billion or even parts per trillion levels[27]. For all substances assessed, these waters appear to be the cleanest so far reported in the world.

In contrast, possibly because of ocean gyres, there is much flotsam and jetsam on all the shores of northern islands[28]. With no inhabitants, there is no rubbish clearance, as occurs in some other atoll groups in this ocean. It is suggested that at some sites the densities of such debris has now become sufficient to impede nesting turtles.

Invasive and introduced species

The Convention on Biological Biodiversity ranks non-native species introductions as one of the most significant threats to biodiversity. Most Chagos islands were transformed to copra plantation between the 1700s to 1970, when the flora became coconut dominated. The progress of coconut domination is clear from a comparison of Eagle Island, where copra harvesting ceased in 1935, with the eastern arm of Diego Garcia where harvesting ceased in the 1970s. Eagle Island exhibits reduced diversity and chaotic coconut thickets, while some habitats such as *Typha* swamp and peat area have totally disappeared under coconuts since 1975. Diego Garcia supports a large population of breeding boobies in the frequent remaining native hardwood trees, compared with few nests and rare and senescent hardwoods on Eagle, despite similar rat populations on each island. However, several very small islands contain remnants of native Indian Ocean island forest which, with protection and regeneration, could be used to re-colonise the other islands (Fig 22).

Fig 22. *Pisonia* forest on North Brother, Great Chagos Bank.

However, following the development of Diego Garcia from about 1970, which contains 50% of the total land area of the archipelago, plant species introductions have risen alarmingly[29] (Fig 23). Introduced species now greatly outnumber the native species of flora, with both showing a clear island size effect.

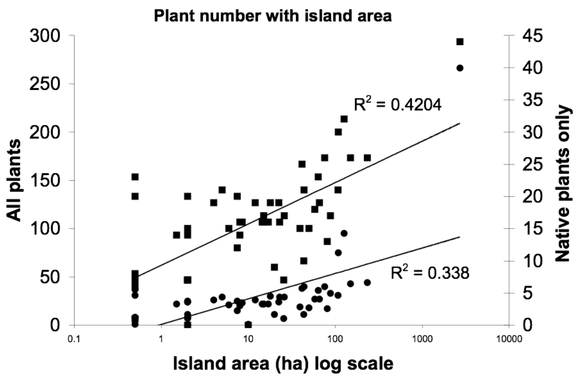

Fig 23. **Left**: Number of introduced plant species recorded on Diego Garcia. Right: Number of plant species plotted against island size for native plants only (circles, right y-axis) and all plants (squares, left y-axis).

In contrast to the severely affected islands, marine species have apparently not been introduced to any significant degree. There have been no marine species invasions. The IUCN's Global Marine Programme[30] assessed marine introductions in 2006, focusing on the harbour area of Diego Garcia and including most other atolls also. The taxonomic focus was on groups known to translocate, and samples included scrapings from hard substrates and sediment cores for identification of dinoflagellate cysts and infauna. Sampling was also photo-documented extensively. From approximately 1500 samples, no introduced species were discovered. An analysis of sampling strategy and site selection is being carried out to verify whether this may account for the lack of detection, but the results appear to be the first survey of this kind that has not detected any introduced or cryptogenic (of unknown origin) species.

Bird life

Seabird populations of the Indian Ocean are thought to be at a fraction of their historical levels and subject to widespread and numerous threats[31]. Chagos contains 10 Important Bird Areas (IBAs), as defined by Birdlife International. Populations of birds fluctuate, and the fact that visits are very infrequent, and usually at the same time of year, has meant that these changes are not properly documented. Furthermore, estimates of total populations are further limited by lack of understanding of breeding phenology.

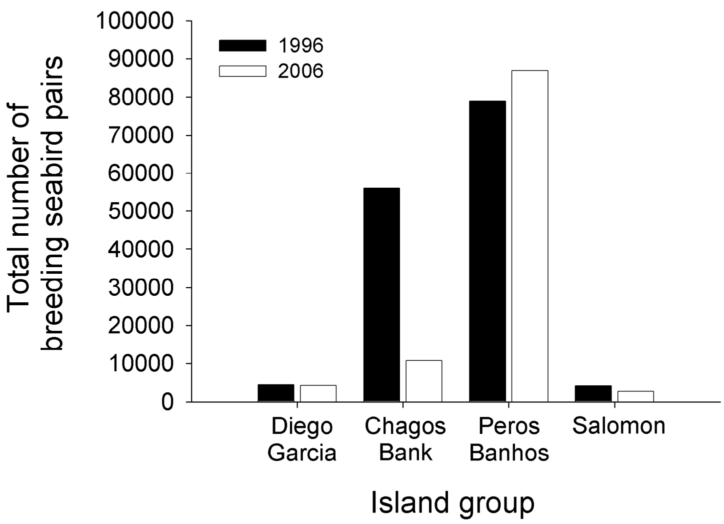

Fig 24. Total number of breeding pairs of seabirds on the four main island groups in 1996 and 2006.

Estimates suggest marked decadal changes in populations of some species. Nine species have apparently declined in numbers. The marked drop in the islands of the Great Chagos Bank is attributed to reductions in tern numbers or to their relocation, but several other species also have apparently declined, with some being lost to specific atolls. Conversely, eight species, notably Frigate and Booby species have increased in numbers, and several islands gained new breeding species. The IBAs have been re-evaluated, and two additional IBAs have been proposed. Important now is re-evaluation of bird populations at different times of the year, along with better estimates of the lengths of their breeding seasons, in order to better determine numbers.

Exploitation and poaching

The military base of Diego Garcia is on the archipelago's southernmost and most distant atoll, leaving the remaining 99%, which is uninhabited, located closer to some of the populated areas of the Indian Ocean. There is one BIOT Protection Vessel to patrol the entire >650,000 km^2. Unsurprisingly, poaching is a continuing issue, as evidenced by up to approximately 3 to 5 arrests made each year of poachers, mainly from Sri Lanka, and from information gained from data and scientists in Sri Lanka itself.

Sea cucumbers (Beche de Mer) are one target organism. Surveys carried out in 2006 showed a marked difference in densities between the militarized atoll and the 'open' atolls to the north (Fig 25)[32]. Given the approximate sizes of boats and GIS estimates of area, this depletion appears to equate to approximately 500 boat loads in total. Densities of sea cucumbers estimated in 2002 at several sites[33] were re-examined in 2006, showing heavy depletion over this time at those sites. Data on sea cucumber imports and re-exports in Sri Lanka itself, provided by local scientists, also suggest substantial numbers of boats poach each year in Chagos waters.

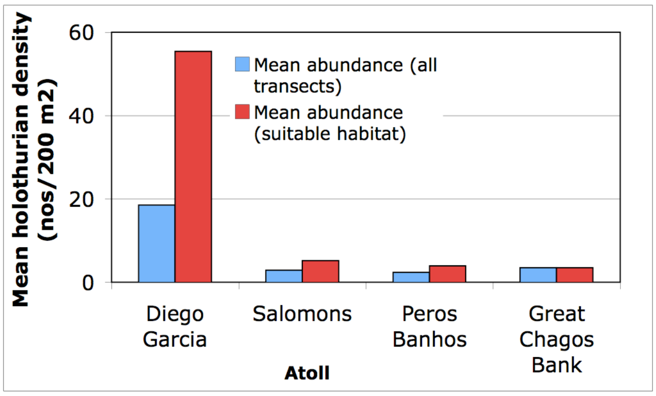

Fig 25. Sea cucumber densities in four atolls.

Shark numbers, likewise, have collapsed over the past few decades (Fig 26) in line with the trends seen throughout the Indian Ocean[34] despite some clear fisheries regulations. The collapse mostly occurred before fisheries protection was in place, and there has been no recovery since. Observations in 2008 in Diego Garcia also show frequencies of 0.25 sharks per dive, suggesting the depressed numbers continue, but this atoll was not surveyed in earlier dates so the point is not graphed.

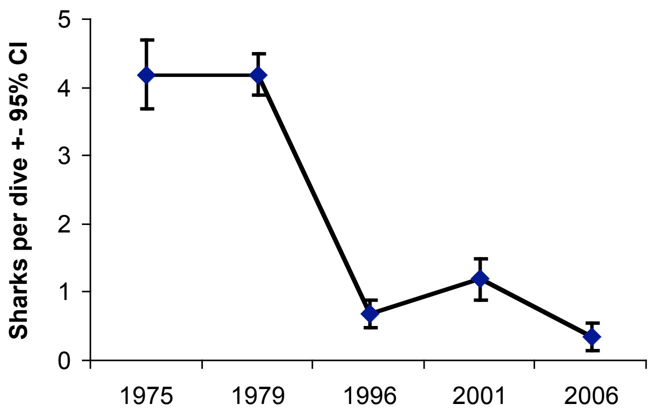

Fig 26. Change in relative abundance of reef associated sharks per scientific research dive, 1975-2006.

In addition to population declines, frequencies of some species have changed: silvertip sharks increased slightly in abundance from 1996, whereas blacktip and whitetip reef sharks were rarely encountered in 2006. Poaching which specifically targets sharks and Beche de Mer, is the most likely cause of these changes. These data highlight that shark populations, even in remote marine areas, are vulnerable to distant fishing fleets.

Turtle populations are now subject to less exploitation than during the period when the islands were used for copra, when inhabitants relied heavily on hawksbill shell as an export item and on green turtle meat for subsistence[35]. Declines in recorded shell exports between 1904 and 1946 (Fig. 27) probably reflect corresponding declines in hawksbill populations, but this chart represents only the tail end of over 150 years of exploitation. Annual exports of hawksbill shell in the early 1900s, representing at least 200-300 individual turtles, would be equivalent to a significant portion of the total annual nesting population a century later. Today some 300-700 hawksbills and 400-800 green turtles are estimated to nest annually.

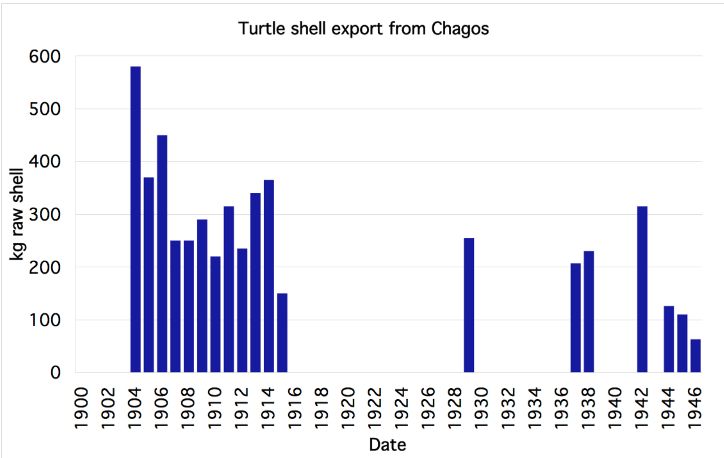

Fig 27. Decline in exports of turtle shell from Chagos from the early 1900s to the end of records in 1946.

Turtles have been protected throughout Chagos since the 1970s, with enforcement more effective at Diego Garcia than in the outer islands. Population surveys conducted over the last decade indicate that, in the outer islands, hawksbill nesting numbers have been stable and those of green turtles may have increased; while at Diego Garcia, nesting numbers for both species have increased as have numbers of foraging turtles at Turtle Cove.

Geochemistry and global climate teleconnections

The location of Chagos in the central Indian Ocean means it occupies an important gap in global monitoring networks of atmospheric gases, seawater pH and several other measurements of great importance. Significant work has been done on the proxies Sr/Ca and $\delta^{18}O$ from coral cores collected in 1996 (Fig 28). Coral Sr/Ca ratios are stationary with local SST, and show a warming of 0.3 °C since 1950 [36]. This, with $\delta^{18}O$, has been used as a proxy for rainfall also, and has shown links with the movement of the Inter-Tropical Convergence Zone. Up to the 1970s an alternation existed between wet and dry spells lasting 15-20 years, but after that time the variability of this region became annual, with a strong coupling to the Pacific El

Niño. This supported evidence that there has been, in the last 20 years, a major change in the coupled El-Niño-monsoon system.

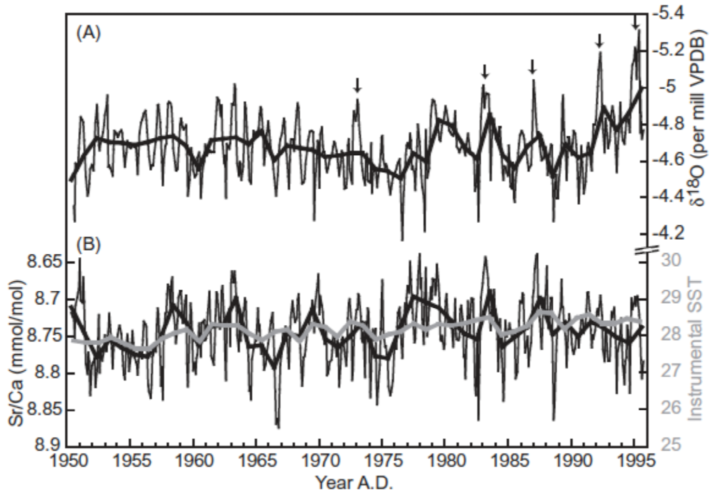

Fig 28. Bimonthly time series of $\delta^{18}O$ measured in a coral core (thin line) and annual means (thick line). Arrows mark El Niño events of 1972–1973, 1982–1983, 1987, 1992, and 1994–1995. B: Monthly time series of Sr/Ca measured in the core (thin line) and annual means (thick black line). Annual mean sea surface temperature (SST) record is shown for comparison (thick grey line).

The central location of Chagos thus also provides a valuable site for global climatic monitoring and modelling. These results show great potential for resolving the teleconnections and interactions between the monsoon cycle in the Indian Ocean and the Pacific's El Niño[37].

Research targets identified and still needed…

Still needed is work in three main categories. Firstly, given the now accepted importance of this reef system to the UK, to the Indian Ocean, and globally in terms of biodiversity, much more regular monitoring is required. This is needed to permit the UK to fulfil its obligations under several charters, including the Biodiversity Convention. Second is work related to global issues. It is one of very few global locations where climate change effects are not complicated by direct forms of pollution and coastal development. The archipelago's geographical location also means it fills a gap in global programmes. The third category covers work which should be done if the already recognized high ecological value of Chagos is to be restored. A detailed list of about 30 needed projects have recently been published elsewhere[38].

In summary: Needed now are repeated measurements of coral cover, community structure and juvenile recruitment to estimate extent and timing of recovery from previous climate change impacts, and repeated measurements of reef fish, both as indicators of responses to climate change and as a reference point for global comparisons. Reefs should display ecological integrity at and between each trophic level, but research is needed to assess whether key species are represented at functional levels (e.g. Is ocean acidification effecting basal levels of food webs; are there sufficient top predators, etc.). Monitoring of the internationally important seabird and marine turtle populations and their responses to environmental change and fluctuations needs to be upgraded, as does monitoring for marine diseases and species introductions.

Micro-atoll and shoreline erosion measurements are needed. Most important is acquisition of data on past, present and future sea levels in these small islands, along with the ability of these islands to maintain themselves. Particularly needed is the establishment of an ocean water alkalinity data series to measure acidification, along with continuation of direct temperature measurements at several depth intervals.

For global environmental research, geochemistry cores of reefs and corals are needed to develop historical temperature records over the past 3-4 centuries, for referencing future changes, and for linkage with regional data sets derived from other geochemistry cores, for work on, and calibration of, global climate oscillations. Measurements are needed of atmospheric gases for calibration of those geochemistry cores, and to fill the huge gap in global coverage that exists in the Indian Ocean. Genetic studies need to be continued to establish the biological connectedness of Chagos with the rest of the ocean, and to understand its role as a stepping stone and as a source of biological replenishment for depleted, inhabited areas in the west of the ocean.

There is an unparalleled opportunity for restoration of ecosystems in Chagos. Mapping of island vegetation, soil structure and stability is now possible, along with eradication of invasive species, particularly rats, on key islands. 'Keyhole' re-introduction of native hardwoods and associated species, initially beneath the coconut shade, will need to be used to re-establish a more varied indigenous vegetation over time, together with appropriate habitat management of open areas to bring back ground-nesting bird species to such areas. There is an increased chance of successfully eradicating rats once coconut vegetation is at manageable levels. Turtle nesting areas can also be improved through regular rubbish clearance.

Building on the completed GIS, there is a need to complete archipelago-wide mapping of shallow-water habitats using satellite imagery, including identification of highly vulnerable areas such as spawning sites, nursery areas and breeding grounds of key species. It is also possible to extend the GIS to map island areas at high risk of erosion and likely inundation.

These programmes are needed to further define the global and ocean-wide conservation value of the archipelago, including as a biodiversity refuge and as a natural heritage area. Programmes would not act in isolation, but would be collaboratively connected with other programmes which currently exist, and which usually are struggling, in other parts of this ocean, especially in western Indian Ocean islands and on the African coast.

Existing, piecemeal conservation efforts in the tropical oceans are, by and large, failing. The world-wide, well documented declines in both quality and quantity of reefs are testament to that, while at the same time human needs are increasing. Overall, reefs are not generally keeping up with rates and extent of depletion. However, for most aspects, this is uniquely not the case in Chagos, so the latter offers unparalleled and crucial opportunities. There is scope in Chagos to not only collaborate with other countries and multi-national programmes, but also to show the way ahead and use scientific knowledge obtained from Chagos for the benefit of many.

References and Notes

1 http://www.globaloceanlegacy.org/

2 Dumbraveanu, D. and Sheppard, C.R.C. 1999. Areas of substrate at different depths in the Chagos Archipelago. In: Sheppard, C.R.C. and Seaward, M.R.D. (eds.). *Ecology of the Chagos Archipelago*. Occasional Publications of the Linnean Society of London. Vol 2. pp 35-44.

3 Sheppard, C.R.C. (1980). Coral cover, zonation and diversity on reef slopes of Chagos atolls, and population structures of the major species. *Marine Ecology Progress Series* 2:193-205.

4 Sheppard, C.R.C. (1981). The reef and soft substrate coral fauna of Chagos,Indian Ocean. *Journal of Natural History* 15:607-621.

5 Sheppard, C.R.C. 1999. Corals of Chagos, and the role of Chagos reefs in the Indian Ocean. In: Sheppard, C.R.C. and Seaward, M.R.D. (eds.). *Ecology of the Chagos Archipelago*. Occasional Publications of the Linnean Society of London. Vol 2. pp 53-66.

6 Mortimer, J.A. & Broderick, D. 1999. Population genetic structure and developmental migrations of sea turtles in the Chagos Archipelago and adjacent regions inferred from mtDNA sequence variation. Pp. 185-194, In Sheppard, C.R.C. and Seaward, M.R.D. (eds). *Ecology of the Chagos Archipelago*. Linnean Society Occasional Publications 2.

7 Williams ST, Knowlton N, Weight LA, 1999. Indo-pacific molecular biogeography of the coral- dwelling snapping shrimp Alpheus lottini (Decapoda: Caridea: Alpheidae. Pp. 195-206, In Sheppard, C.R.C. and Seaward, M.R.D. (eds). *Ecology of the Chagos Archipelago*. Linnean Society Occasional Publications 2.

8 Sheppard, C.R.C. 2003. Predicted recurrences of mass coral mortality in the Indian Ocean. *Nature* 425:294-297.

9 http://template.bio.warwick.ac.uk/staff/csheppard/csdownload.htm

10 Sheppard, C.R.C. 1999. Coral Decline and Weather Patterns over 20 years in the Chagos Archipelago, central Indian Ocean. *Ambio* 28:472-478.

11 Sheppard C.R.C., Spalding M, Bradshaw C, Wilson S. 2002. Erosion vs. recovery of coral reefs after 1998 El Niño: Chagos reefs, Indian Ocean. *Ambio*. 31:40-48

12 Graham NAJ, McClanahan TR, MacNeil MA, Wilson SK, Polunin NVC, Jennings S, Chabanet P, Clark S, Spalding MD, Letourneur Y, Bigot L, Galzin R, Öhman MC, Garpe KC, Edwards AJ, Sheppard CRC (2008) Climate warming, marine protected areas and the ocean-scale integrity of coral reef ecosystems. *PLoS ONE* 3(8): e3039: doi:10.1371/journal.pone.0003039

13 Sheppard CRC, Harris A, Sheppard ALS (2008) Archipelago-wide coral recovery patterns since 1998 in the Chagos Archipelago, central Indian Ocean. *Marine Ecology Progress Series* 362:109-117.

14 Graham NAJ, McClanahan TR, MacNeil, MA, Wilson, SK, Polunin NVC, Jennings S, Chabanet P, Clark S, Spalding, MD, Letourneur Y, Bigot L, Galzin, R, Ohman MC, Garpe KC, Edwards AJ, Sheppard CRC, 2008. Climate Warming, Marine Protected Areas and the Ocean-Scale Integrity of Coral Reef Ecosystems. *PLoS One* 3(8): e3039 pp9.

15 Harris A, Sheppard CRC. 2008. Status and recovery of the coral reefs of the Chagos Archipelago, British Indian Ocean Territory. In: Obura O, Tamelander J, Linden O (eds). *CORDIO Status Report 2008*. pp 61- 70.

16 Sheppard, CRC. (1979). Interspecific aggression between reef corals with reference to their distribution. *Marine Ecology Progress Series* 1:237-247.

17 Turner, JR. (in prep). Recovery of benthic community structure on the reef slopes of Chagos Atolls following bleaching mortality events. *Marine Ecology Progress Series*.

18 Turner JR. Gibbs R. 2008. Imaging coral community structure at high resolution over large areas on the reef terraces of the Chagos Archipelago. Procedings 11th International Coral Reef Symposium, Fort Lauderdale, Florida USA. In press.

19 Sheppard CRC. 1981. The groove and spur structures of Chagos atolls and their coral zonation. *Estuarine Coastal and Shelf Science* 12:549-560.

20 Graham NAJ (2007) Ecological versatility and the decline of coral feeding fishes following climate driven coral mortality. *Marine Biology* 153: 119-127.

21 Yang SY, Obura D,, Sheppard C, Chen CA 2009. High incidence of phylotype A and among-reefal variation of *Symbiodinium* diversity in seven common scleractinian species at the Chagos Archipelago, Indian Ocean. *Marine Ecology Progress Series* In press.
22 Pugh, DT | Rayner, RF. 1981. The Tidal Regimes of Three Indian Ocean Atolls and Some Ecological Implications*. Estuarine, Coastal and Shelf Science*. 13:389-407.
23 Doak, E.L., Lyzenga, D.R. and Polcyn, F.C. 1979. *Bathymetry by landsat in the Chagos Archipelago.* Environmental Research Institute of Michigan pp. 31.
24 Purkis SJ, Graham NAJ, Riegl BM (2008) Predictability of reef fish diversity and abundance using remote sensing data in Diego Garcia (Chagos Archipelago). *Coral Reefs* 27:167–178.
25 Readman, J.W., Tolosa, I., Bartocci, J., Cattini, C., Price, A.R.G., Jolliffe, A., 1999. Contaminant levels and the use of molecular organic markers to characterize the coastal environment of the Chagos Archipelago. In: Sheppard, C.R.C. and Seaward, M.R.D. (eds.). *Ecology of the Chagos Archipelago*. Occasional Publications of the Linnean Society of London. Vol 2, 297–304.
26 Everaarts, J.M., Booij, K., Fisher, C.V., Maas, Y.E.M., Nieuwenhuize, J., 1999. Assessment of the environmental health of the Chagos Archipelago. In: Sheppard, C.R.C. and Seaward, M.R.D. (eds.). *Ecology of the Chagos Archipelago*. Occasional Publications of the Linnean Society of London. Vol 2, 305–326.
27 Guitart C, Sheppard A, Frickers T, Price ARG, Readman JW. 2006. Negligible risks to corals from antifouling booster biocides and triazine herbicides in coastal waters of the Chagos archipelago. *Marine Pollution Bulletin* 54 : 226–246
28 Price ARG, Harris A. 2009. Decadal changes (1996-2006) in coastal ecosystems of the Chagos archipelago determined from rapid assessment . Aquatic Conservation. In Press
29 Topp JMW. Sheppard CRC. 1999. Higher Plants of the Chagos Archipelago, central Indian Ocean In: Sheppard, C.R.C. and Seaward, M.R.D. (eds.). *Ecology of the Chagos Archipelago*. Occasional Publications of the Linnean Society of London. Vol 2. pp 225-240.
30 http://www.iucn.org/about/work/programmes/marine/
31 McGowan A, Broderick, AC, Godley BJ 2008. Seabird populations of the Chagos Archipelago: an evaluation of IBA sites and a need for monitoring. *Oryx* 42: 424-429
32 Price ARG, Harris A, McGowan A, Venkatachalam AJ, Sheppard CRC. 2009. Assessment of holothurians (sea cucumbers) in Chagos, British Indian Ocean Territory: abundance, illegal harvesting and conservation prospects. Aquatic Conservation. In press.
33 Posford Haskonig 2002. *Feasibility study of resettlement to the Chagos Archipelago*. 3 volumes, Foreign and Commonwealth Office, London.
34 Graham NAJ, Spalding MD, Sheppard CRC. 2009. Reef shark declines in remote atolls highlight the need for multi-faceted conservation action. *Biological Conservation* in submisison.
35 Mortimer, J.A. & Day, M. 1999. Sea turtle populations and habitats in the Chagos Archipelago. Pp. 159-172, in Sheppard, C.R.C. and Seaward, M.R.D. (eds). *Ecology of the Chagos Archipelago*. Linnean Society Occasional Publications 2.
36 . Pfeiffer M, Timm O, Dullo W-C, Garbe-Schönberg D. 2006. Paired coral Sr/Ca and δ18O records from the Chagos 2 Archipelago: Late twentieth century warming affects rainfall variability in the tropical Indian Ocean. *Geology* 34: 1069–1072.
37 Pfeiffer M, Dullo W-C, Zinke J, Garbe-Schonherg D. 2008. Three monthly coral Sr/Ca records from the Chagos archipelago covering the period of 1950-1995 AD: reproducibility and implications for quantitative reconstructions of sea temperature variations. *International Journal of Earth Science*, In Press.
38 Sheppard CRC, Graham N, Harris A, Hillman C, Hilton G, Jones R, Price A, Purkis S, Raines R, Riegl B, Sheppard ALS, Spalding M, Tamelander J, Topp JMW, Turner J. 2009. Objectives for Science in Chagos. *Chagos News* 33:12-14. also available at www.chagos-trust.org.