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Diversity

The full extent of the global coral reef crisis

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Coral reefs around the world are largely in decline (Bellwood et al. 2004; Bruno & Selig 2007; De'ath et al. 2012), putting the roughly 7.5% of humanity that depends on them in jeopardy. Diagnoses of the extent of reef decline and debate about the causes, which collectively define the global coral reef crisis, are based largely on local-scale estimates of shallow-water reef condition measured as the percentage of living coral veneer per unit area of reef (i.e., coral cover) (Hughes et al. 2011; Sweatman & Syms 2011; Sweatman et al. 2011). Coral cover is a popular metric for reef monitoring because it can be determined rapidly in the field and because it has been recorded, with varying degrees of quality, for over 50 years (Bellwood et al. 2004; Bruno & Selig 2007). Other ecological metrics, such as species and functional trait composition and reef structural complexity, are likely better for documenting reef condition (Graham et al. 2015) but take substantial time to measure consistently and over the broad scales required for global assessment.

Regardless of the ecological metric used, they are measured at small and standardized scales and therefore paint only a relative picture (e.g., per unit reef area) of whether the world's reefs are declining or expanding over the long term (e.g., the decadal to millennial periods over which climate change will unfold). Capturing the full picture of how coral reefs globally are faring requires knowledge of the absolute amount of consolidated reef structure upon which these ecological estimates apply at broader spatial scales. Consolidated reef is hard calcium carbonate substrate largely made up of skeletons of dead corals that either currently supports living coral or is suitable for coral to grow upon (e.g., it includes consolidated reef that is currently covered by coral competitors, such as macroalgae, but could support coral recruitment and growth in their absence). However, the global extent of this valuable resource remains elusive.

To accurately quantify global-scale trends in coral reef condition over the next century, local-scale ecological estimates such as coral cover must be integrated with broader-scale estimates of total consolidated reef extent. Taken on its own, a local-scale change could be misleading (Fig. 1). As an illustration, sequential estimates of high percent forest cover at the interior of the Amazon rainforest, taken in isolation, paint a rosy picture of ecosystem health. But considering the deforestation and fragmentation occurring at its edges, for example, results in a dismal and more accurate overall picture. Similarly, one must consider the total extent of consolidated reef available for corals to grow upon. Deepwater reefs, which we now know are much greater in extent than traditionally thought, are considered less susceptible to climate change and may potentially act as refuges for some coral species (Bridge et al. 2013). However, the processes for gathering extent data for deep reefs are laborious and take substantial time to complete (Harris et al. 2013). Conversely, the amount of shallow-water consolidated reef that exists on Earth (up to approximately 5–10 m deep) can now be quantified over large areas and with great accuracy with multi-spectral satellite imagery with 1 m or less spatial resolution and manual measurement or existing automated spatial analytical modules (e.g., Naseer & Hatcher 2004).

Proof that such an endeavor is feasible lies in The Millennium Coral Reef Mapping Project (http://www.imars.usf.edu/MC). This initiative used 30-m spatial resolution satellite imagery collected around the year 2000 to develop a global map of the world's coral reefs. The utility of such a tool, even at this relatively coarse spatial resolution, is highlighted by the discovery from a separate project using the same Landsat-7 ETM+ imagery that the island nation of the Maldives actually has half the previously assumed consolidated reef area (Naseer & Hatcher 2004). Such use of satellite imagery is in line with recent calls for biodiversity researchers and conservation practitioners to take better advantage of the opportunities afforded by remote sensing data (Turner

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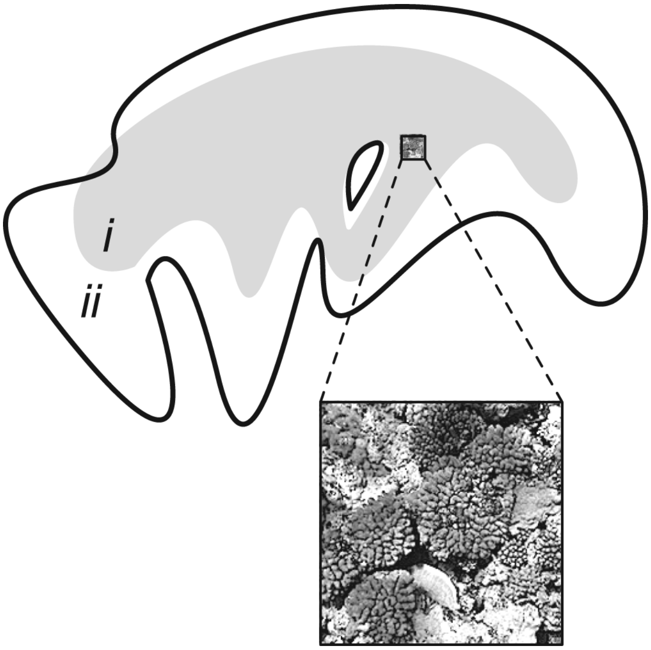

Figure 1. Consolidated reef extent and small-scale ecological metrics. A hypothetical areal schematic of a coral reef showing current consolidated reef area (shaded region i), historical reef area (outlined region ii), and the ecological characteristic of reef (square), which is typically measured using replicate small-scale samples. If consolidated reef area decreased by 50% while coral cover declined from 50% to 25% (i.e., a 50% reduction), the absolute amount of live coral remaining would be a much more marked (12.5% of the historical amount). Conversely, if the consolidated reef grew from area i to area ii over this period, absolute coral cover would remain unchanged, despite a 50% loss in cover.

et al. 2015). These recent technological advances can provide what we believe to be the critical missing piece in the global coral reef crisis, the amount of consolidated reef, but they have yet to be applied to the puzzle.

Unlike ecological reef characteristics, consolidated reef extent is often assumed to be a static figure akin to the area of a nation (e.g., Spalding & Grenfell 1997). However, consolidated reef is sensitive to environmental conditions and disturbances (Hopley et al. 2007), including physical breakage due to natural (e.g., storms, tsunamis) and human activity (e.g., blast fishing, ship groundings, coral mining, trampling) (Fox & Caldwell 2006; Madin & Connolly 2006) and ocean acidification (Manzello et al. 2008). Many natural processes are slow (e.g., vertical accretion rates of millimeters per year [Perry et al. 2012]) and can be influenced by the type of organism covering the reef substrate (e.g., reef-building corals versus non-reef-building algae). Because of its slow nature, reef accretion generally occurs only at detectable levels over time scales longer than most ecological field studies (Rasser & Riegl 2002). It is therefore unsurprising that consolidated reef extent has rarely been considered in assessments of coral reef condition. However, other natural processes such as sedimentation and storm damage can also be dynamic, changing reef areas significantly over surprisingly short periods (Lewis 2002; Blanchon 2011; Bridge et al. 2011). Likewise, human disturbances such as ship groundings and destructive fishing can reduce consolidated reef extent nearly instantaneously (Fox & Caldwell 2006).

The overlap of short and long time scales of change in reef extent mean that consolidated reef extent must be monitored at the highest possible spatial resolution (i.e., ≤ 1 m) in order to detect significant changes in the shortest possible time. Quantifying such changes would provide an improved representation of reported and predicted coral reef decline in the tropics and growth in poleward regions. Furthermore, relative to changes in live reef cover, recovery from loss of consolidated reef structure is predicted to take far longer (Rasser & Riegl 2002; Fox & Caldwell 2006; Blanchon 2011). As a result, loss of consolidated reef is far more insidious for coral reef recovery than is loss of live coral that leaves the structural reef matrix intact; consolidated reef loss may therefore have a disproportionately large impact on current and future conditions of coral reefs.

To establish a baseline against which future changes can be assessed, a global assessment of coral reef extent should be included in the list of global coral reef conservation priorities. A global-scale, coordinated, and long-term monitoring program coordinated by an international nongovernmental organization (e.g., International Union for Conservation of Nature or other relevant body) should be established to quantify these changes, especially in shallow-water reefs for which the technology to do so already exists. Because the main processes that determine the amount of consolidated reef generally operate over relatively long time scales, assessments could occur regularly but infrequently (e.g., every 5 to 10 years) to limit costs (or, ideally, they could occur more frequently if sufficient resources were available). A 2014 survey of satellite imagery for 1372 individual reefs within the Great Barrier Reef showed that high spatial resolution (i.e., ≤ 2 m) imagery was freely available in Google Earth for approximately 44% of these reefs (E. M.P.M, unpublished data). Assuming the same percentage applies to the approximately 255000 km^2 of global reef area (Spalding & Grenfell 1997) and a cost of approximately US$1700/225 km^2 imagery panel (DigitalGlobe 2014), we estimate a total cost of just under US$1 million to acquire the remaining high resolution imagery to cover this shortfall. This cost is likely to decrease over time as satellite imagery becomes less expensive and more imagery is acquired and incorporated into Google Earth and other open access platforms. In any case, this estimated cost pales in comparison with the estimated US$375 billion/year in goods and services that coral reefs provide globally (U.S. Commission on Ocean Policy 2004).

It is imperative that assessments of reef status incorporate ecological metrics (e.g., coral cover) and consolidated reef area, lest they lead to inaccurate conclusions. For the relatively small number of reefs for which both data types currently exist, methods for integrating ecological metrics and consolidated reef extent can be developed now and outputs can be revisited in the future to discern trajectories of change. For the remaining areas of the world, estimates of reef extent should be gathered urgently. For many of the world's reefs, this can be done by anyone with access to the internet through the use of the freely available, high-resolution imagery in Google Earth. Such efforts may be possible in a large-scale citizen science program. For the remaining reefs, commercial satellite imagery can generally be purchased at relatively low cost. Consolidated reef area is disappearing before our eyes (e.g., through blast fishing in the Indo-Pacific [Fox & Caldwell 2006]). Yet this disappearance cannot be visualized or quantified over large scales. The tools to solve this problem exist and are relatively inexpensive. It would be irresponsible not to apply them to a critical global conservation problem.

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