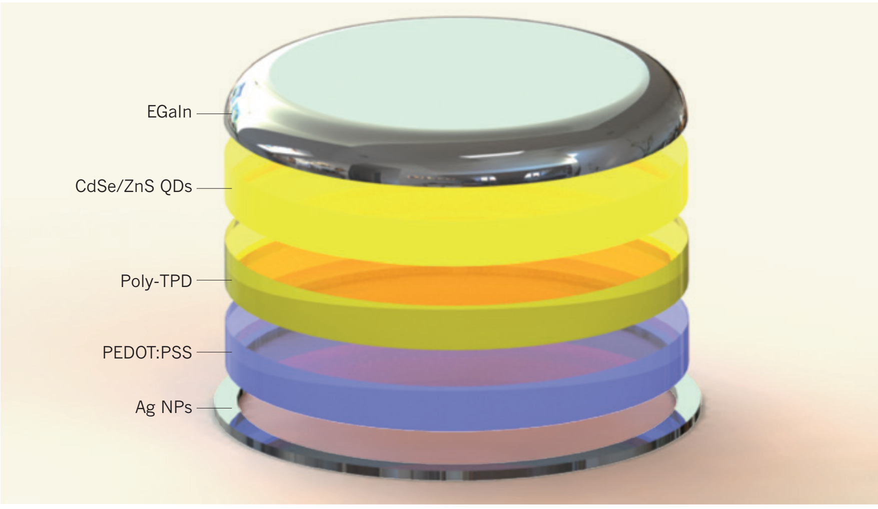



**Figure 1 | Fully 3D-printed quantum-dot-based light-emitting diodes (QD-LEDs).** The QD-LEDs reported by Kong and colleagues[1] consist of five layers: a conductive ring of silver nanoparticles (Ag NPs) that surrounds a transparent anode layer composed of poly(ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS); a hole-transport layer made of poly[*N*,*N*′-bis(4-butylphenyl)-*N*,*N*′-bis(phenyl) benzidine) (poly-TPD); a light-emitting layer composed of cadmium selenide/zinc sulfide quantum dots (CdSe/ZnS QDs); and a cathode layer composed of eutectic gallium indium (EGaIn). The diameter of the printed QD-LEDs is approximately 2 mm. (Figure adapted from ref. 1.)

The printed devices exhibit brightness, an essential metric of device performance, that is 10- to 100-fold below that of the best solution-processed QD-LEDs[3,8]. However, substantial improvements in device performance are likely to be possible by introducing an electron-transport layer (which was absent in the current architecture), such as one composed of zinc-oxide nanoparticles, and further optimizing the printing process.

The 3D-printing method used by the authors represents a simple, but sophisticated, approach for patterning functional materials. Demonstrated applications of this technique include printing electrodes that interconnect solar-cell and LED arrays[11], 3D antennas[12] and rechargeable microbatteries[13]. Although microbatteries rely on multi-material 3D printing of interdigitated cathode and anode layers, Kong and colleagues' study is much more impressive, because up to six, as opposed to two, different materials must be printed sequentially to create their devices.

One intriguing question that arises is whether fully 3D-printing electronic devices is the best approach for creating mass-customized electronics. Another viable strategy would be to combine 3D printing with automated pick-and-place machinery that places electronic components accurately and repeatably to generate objects with embedded circuitry and devices[11]. LEDs are commercially available that have lateral dimensions akin to those demonstrated by Kong *et al.*, and could be integrated into 3D-printed objects by this hybrid approach.

To vastly expand the capabilities of 3D printing, new functional inks and multi-nozzle print heads and printing platforms must be designed for rapidly and accurately patterning materials over a broad range of compositions and ink-flow behaviour. As these advances are realized, it may be possible to print customized 3D electronic devices in a highly scalable manner. We are becoming increasingly reliant on electronics in our daily lives, and so successful outcomes should be of great benefit to society. ■

**Jennifer A. Lewis** *and* **Bok Y. Ahn** *are in the School of Engineering and Applied Sciences and the Wyss Institute for Biologically Inspired Engineering, Harvard University, Cambridge, Massachusetts 02138, USA.*
*e-mail: jalewis@seas.harvard.edu*

1. Kong, Y. L. *et al. Nano Lett.* **14,** 7017–7023 (2014).
2. Colvin, V. L., Schlamp, M. C. & Alivisatos, A. P. *Nature* **370,** 354–357 (1994).
3. Coe, S., Woo, W.-K., Bawendi, M. & Bulović, V. *Nature* **420,** 800–803 (2002).
4. Shirasaki, Y., Supran, G. J., Bawendi, M. G. & Bulović, V. *Nature Photonics* **7,** 13–23 (2012).
5. Smay, J. E., Cesarano, J. III & Lewis, J. A. *Langmuir* **18,** 5429–5437 (2002).
6. Lewis, J. A. *Adv. Funct. Mater.* **16,** 2193–2204 (2006).
7. Wood, V. *et al. Adv. Mater.* **21,** 2151–2155 (2009).
8. Dai, X. *et al. Nature* **515,** 96–99 (2014).
9. Hu, H. & Larson, R. G. *J. Phys. Chem. B* **110,** 7090–7094 (2006).
10. Ladd, C., So, J.-H., Muth, J. & Dickey, M. D. *Adv. Mater.* **25,** 5081–5085 (2013).
11. Ahn, B. Y. *et al. Science* **323,** 1590–1593 (2009).
12. Adams, J. J. *et al. Adv. Mater.* **23,** 1335–1340 (2011).
13. Sun, K. *et al. Adv. Mater.* **25,** 4539–4543 (2013).

**J.A.L. declares competing financial interests.** See go.nature.com/benofm for details.

ECOLOGY

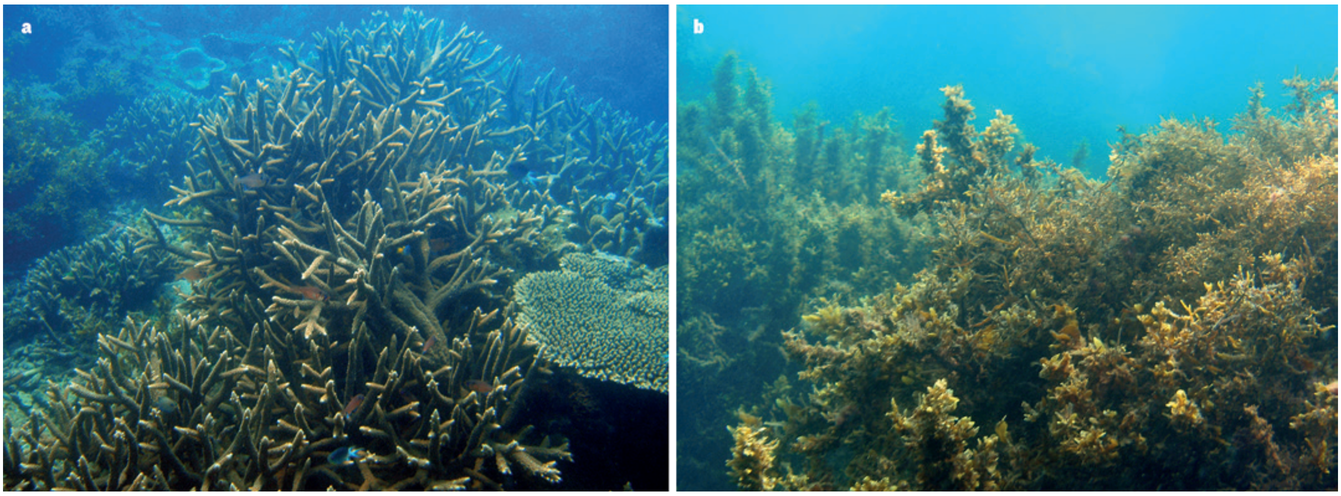
# Deep and complex ways to survive bleaching

**Mass coral bleaching events can drive reefs from being the domains of corals to becoming dominated by seaweed. But longitudinal data show that more than half of the reefs studied rebound to their former glory.** **SEE LETTER P.94**

JOHN M. PANDOLFI

A constant battle for space is fought every minute of every day on the hard substrates that provide the foundation for living coral reefs. In one corner are reef corals and the photosynthetic dinoflagellate microalgae that live in symbiosis inside them; in the other are fleshy macroalgae, better known as seaweed. On healthy reefs, corals are the clear winners and dominate reef substrates (Fig. 1a). But regime shifts to macroalgae (Fig. 1b) often occur in response to local anthropogenic drivers such as overfishing of herbivores[1] or increased nutrients[2] from pollution and land-use changes — two conditions more favourable for seaweed than for corals. On page 94 of this issue, Graham *et al.*[3] provide the first unequivocal evidence that regime shifts from corals to macroalgae also occur in response to coral bleaching, and they identify aspects of reef ecology that influence the likelihood of this occurring.

Coral bleaching occurs when the coral hosts expel their symbiotic dinoflagellates, which provide much of the vibrant coloration typical of coral reefs. Corals rely on the photosynthetic symbionts for their energy provision, and if bleached corals do not rapidly regain symbionts, they die. Mass bleaching events occur over broad spatial scales and affect a large component of the reef coral community. One such episode, in 1998, is often referred to as the largest mass bleaching event on record[4]; in the Seychelles, more than 90% of live coral cover was lost.




GEORGE ROFF

**Figure 1 | Changing reefs.** Graham *et al.*[3] show that mass coral bleaching events, such as the one that occurred in 1998, can drive reefs from being highly complex, coral-rich seascapes (**a**) to zones of dead coral dominated by macroalgae or seaweed (**b**). Such regime shifts had previously been known to occur only in response to local stressors such as overfishing or pollution.

Graham *et al.* tracked the response of coral and fish communities to this event across 21 inner Seychelles islands using a 17-year data set that started in 1994. They found that 9 of the 21 reefs underwent a regime shift to macroalgae, with the live coral cover decreasing from an average of 31% before the event to about 3% by 2011, and macroalgal cover increasing from 3% to 42% during the same period. Where these regime shifts occurred, the functional diversity of associated reef fishes shifted in concert with the changes in coral and macroalgal cover.

One of the key strengths of this study was its ability to test for predictors of ecosystem responses to the bleaching event. Graham and colleagues evaluated several potential factors: the three-dimensional structural complexity of the reef[5], water depth, abundance of juvenile corals, nutrient load, density of herbivorous fish and whether the reefs were part of 'no-take' marine reserves. The first three of these drivers turned out to be the most important. Indeed, combining structural complexity with water depth correctly predicted whether or not a regime shift would occur in 98% of cases — regime shifts occurred less frequently in more structurally complex and deeper-water habitats. These correlations bode well for our ability to predict the effects of future mass bleaching events, especially in tropical regions where conservation resources are limited, because these two variables can be quickly and easily measured on most reefs.

Coral reefs are often portrayed as one of the marine ecosystems that are most vulnerable to the threats of climate change, and global warming is commonly thought to be the principal underlying driver of mass bleaching events. Although Graham and colleagues' study is groundbreaking in its attribution of coral-to-algal regime shifts to a mass bleaching event, perhaps their most striking finding is that, in most cases (12 of 21 reefs), such regime shifts did not occur. The fact that more than half of the reefs fully recovered after the bleaching event is a promising outcome for the future of coral reefs. It is also consistent with studies showing that each mass bleaching leaves many sites unaffected, with almost complete recovery of corals from the 1998 event in many parts of the world[6], and that coral survivors of past bleaching events have a capacity to persist under subsequent bleaching events[7]. The findings also fit with experimental work suggesting that corals can quickly adapt to environmental change[8]. Put simply, many reef corals just might be capable of adapting fast enough to survive current rates of global environmental change[9,10].

A key challenge facing reef managers around the world is how to protect coral reefs from the 'big three' human threats: overfishing, pollution and climate change. A range of specific tools is available to tackle the first two of these, which are comparatively local stressors, but there is a paucity of appropriate climate-specific responses. Given the contribution of these local stressors to the global degradation of reefs, it is crucial that their management continues. However, Graham and colleagues' delineation of reef characteristics most closely associated with regime shifts caused by mass bleaching events means that we can now take concrete steps towards managing specifically for climate change as well. For example, the authors' findings suggest that structural complexity and water depth should be explicitly incorporated into the spatial design of marine reserves, with structurally complex and deep-water habitats targeted as high-value sites that will be more resistant to mass coral bleaching than shallower sites.

The authors' finding that the design of marine protected areas in the Seychelles had no bearing on the ability of reefs to rebound from the 1998 bleaching event is unsettling, and is a case in point of the need for new design approaches. But the Seychelles are not alone — many marine reserves only target areas that are important for sustaining fisheries. Perhaps we need to think about broadening the role of marine reserves to one that includes being a refuge from regime shifts, such that their success can be gauged not only by the number of fishes they contain, but also by the degree to which they protect explicit attributes of habitat diversity. To achieve this, Graham and colleagues' messages on how to manage reefs in the face of climate change will need to be placed in a global context, and further long-term studies from reefs in other regions will be needed if we are to fully understand the drivers of regime shifts on reefs. ■

**John M. Pandolfi** *is in the School of Biological Sciences and the Australian Research Council Centre of Excellence for Coral Reef Studies, University of Queensland, Brisbane, Queensland 4072, Australia.*
*e-mail: j.pandolfi@uq.edu.au*

1. Hughes, T. P. *Science* **265,** 1547–1551 (1994).
2. Smith, J. E., Hunter, C. L. & Smith, C. M. *Oecologia* **163,** 497–507 (2010).
3. Graham, N. A. J., Jennings, S., MacNeil, M. A., Mouillot, D. & Wilson, S. K. *Nature* **518,** 94–97 (2015).
4. Wilkinson, C. in *Status of Coral Reefs of the World: 1998* (ed. Wilkinson, C.) 15–38 (Australian Inst. Mar. Sci., 1998).
5. Graham, N. A. J. & Nash, K. L. *Coral Reefs* **32,** 315–326 (2013).
6. Baker, A. C., Glynn, P. W. & Riegl, B. *Estuar. Coast. Shelf Sci.* **80,** 435–471 (2008).
7. Thompson, D. M. & van Woesik, R. *Proc. R. Soc. B* **276,** 2893–2901 (2009).
8. Palumbi, S. R., Barshis, D. J., Traylor-Knowles, N. & Bay, R. A. *Science* **344,** 895–898 (2014).
9. Pandolfi, J. M., Connolly, S. R., Marshall, D. J. & Cohen, A. L. *Science* **333,** 418–422 (2011).
10. Munday, P. L., Warner, R. R., Monro, K., Pandolfi, J. M. & Marshall, D. J. *Ecol. Lett.* **16,** 1488–1500 (2013).

**This article was published online on 14 January 2015.**