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Operation Crayweed: Ecological and sociocultural aspects of restoring Sydney's underwater forests

By Adriana Vergés, Alexandra H. Campbell, Georgina Wood, Lana Kajlich, Aaron M. Eger, Derrick Cruz, Madelaine Langley, Damon Bolton, Melinda A. Coleman, Jennifer Turpin, Michaelie Crawford, Nigel Coombes, Adam Camilleri, Peter D. Steinberg and Ezequiel M. Marzinelli

Operation Crayweed focuses on the restoration of underwater forests that disappeared from the coastline of Sydney, Australia's largest city, 40 years previously. We show how a combination of science, hands-on restoration, community engagement and art has helped the project to reach its goals as well as raise awareness about the importance of underwater kelp forests that are experiencing global decline.

Key words: *art-meets-science, community engagement, ecological restoration, marine ecosystems, seaweeds.*

Adriana Vergés *is an Associate Professor;* ***Peter Steinberg*** *is a Professor;* ***Derrick Cruz, Madelaine Langley*** *and* ***Damon Bolton*** *are Research Assistants and* ***Georgina Wood, Lana Kajlich*** *and* ***Aaron Eger*** *are PhD candidates at the Centre for Marine Science & Innovation, in the School of Biological, Earth and Environmental Sciences, UNSW Sydney, NSW 2052, Australia.* ***Ziggy (E.M.) Marzinelli*** *is a Lecturer at The University of Sydney, School of Life and Environmental Sciences, Coastal and Marine Ecosystems, Sydney, NSW 2006, Australia. These authors are all associate scientists of the Sydney Institute of Marine Science, for which Peter Steinberg is Director.* ***Alexandra Campbell*** *is a Lecturer at the University of the Sunshine Coast, USC Seaweed Research Group, Sunshine Coast, QLD 4556, Australia.* ***Melinda Coleman*** *is a Principal Research Scientist within the Department of Primary Industries, New South Wales.* ***Jennifer Turpin*** *and* ***Michaelie Crawford*** *are public artists at Turpin Crawford Studio, 17 O'Connor Street, Chippendale NSW 2008.* ***Nigel Coombes*** *is a Senior Technical Officer at the ARC Research Hub for sustainable onshore lobster aquaculture at the Institute for Marine and Antarctic Studies, University of Tasmania.* ***Adam Camilleri*** *is a taskforce officer at the Australian Department of Agriculture, Water and the Environment..*

Figure 1. Community members from the Bold & Beautiful Swim Squad and the Friends of Cabbage Tree Bay help with the restoration of Crayweed at Cabbage Tree Bay Aquatic Reserve in Manly, Australia, in April 2019. Photo credit: Leah Woods.

Introduction

Although the beginning of the Anthropocene has been characterised by extensive human-driven destruction of the Earth's ecosystems, in the last few decades human activities have also intensely focused on reversing environmental degradation. Success stories of species and ecosystem recovery, either through improved environmental management (de los Santos *et al.* 2019) or

Box 1. Importance of underwater forests in the Great Southern Reef

Seaweeds (macroalgae) create vast underwater forests that are immensely important to coastal communities and marine food webs, providing food and shelter to a large number of species including fish, shellfish and many other invertebrates, and supporting coastal industries. Individual seaweeds are home to hundreds of mobile epifaunal species and the composition of these communities is often dependent upon the type of seaweed they call 'home' (Poore & Steinberg 1999). As well as creating habitat, seaweeds are directly consumed by herbivorous fish and invertebrates and support entire food webs (Steneck *et al.* 2002). After they senesce, detach and break down, seaweeds continue to contribute to food webs as detritus (Bishop *et al.* 2010). As primary producers, seaweeds also make a significant combined contribution to global oxygen production and carbon capture, and they can also act as living water filters, efficiently removing excess nutrients and other contaminants from the water column (Roberts *et al.* 2006; Yang *et al.* 2015).

Australia's Great Southern Reef (GSR) is a grand example of an extensive network of underwater forests that span 8000 km along the southern half of the continent (Bennett *et al.* 2016). A hotspot of biodiversity, the GSR provides habitat for some of Australia's most valuable fishery species as well as many endemic species, thereby contributing substantially to Australia's overall biodiversity as well as the nation's economy and the lifestyle of the 70% of Australia's population who live, work and play directly alongside it (Bennett *et al.* 2016).

In most places where seaweed forests exist, they are in decline (Wernberg *et al.* 2019). These declines are often linked to climate change and warming ocean waters, poor water quality, outbreaks of disease or the removal of predators at the top of food webs by overfishing (Steneck & Johnson 2014; Vergés *et al.* 2016; Wernberg *et al.* 2016).

through restoration at large spatial scales (DeAngelis *et al.* 2020), continue to emerge. These examples, where science successfully influences policy and leads to positive impacts, can inspire a sense of optimism that enhances community engagement in conservation and motivates further action (Krupnick & Knowlton 2017; Cvitanovic & Hobday 2018; McAfee *et al.* 2019b).

In this feature article, we describe the development, results to date and aspirations of 'Operation Crayweed', a collaborative project that combines basic discovery research, solution-focused science, large-scale restoration, community engagement and art to successfully restore lost seaweed forests along the Sydney Metropolitan coast (Fig. 1). Underwater forests dominated by seaweeds (macroalgae) such as kelp and fucoids contribute enormously to the world's biodiversity and to the provision of essential ecosystem services (Steneck *et al.* 2002; Smale *et al.* 2013; Coleman & Wernberg 2017; Box 1). Despite their importance, however, there is a relatively low level of public awareness about seaweed forests compared to ecosystems on land or coral reefs in tropical latitudes. Because these underwater forests are 'out of sight, out of mind', their value and disappearance has largely gone unnoticed by the public.

'Operation Crayweed' focuses on the restoration of the large fucoid *Phyllospora comosa* (Labillardier, C.Agardh; Fig. 2), a habitat-forming seaweed that disappeared from 70 km of Sydney's Metropolitan coastline around four decades ago (Box 2; Coleman *et al.* 2008). This species is

Figure 2. (a) Ziggy Marzinelli attaching Crayweed during the first restoration trials. (b) Close-up of Crayweed attachment points. To restore Crayweed, plastic meshes are attached to rocky substrate and Crayweed individuals are attached to the mesh using cable ties. A thin rubber tube is placed around the holdfast to avoid damaging the Crayweed. All plastic infrastructure is removed from the restoration trials after the adult Crayweed reproduces and once recruits settle onto nearby natural habitat and a self-sustaining population is established. (c) Crayweed recruit (also known as 'craybie') in the foreground in North Bondi, located about 25 cm away from a transplanted Crayweed adult (paler yellow) in the background. Photo credit (a, b): Adriana Vergés; (c) John Turnbull.

Box 2. Crayweed and its disappearance from the Sydney Metropolitan Region

Crayweed is a dominant canopy-forming perennial seaweed (also known as a macroalga) that grows on shallow rocky reefs along more than 2500 km of the south-east Australian coast, from mid NSW to Tasmania. It forms extensive underwater forests, providing habitat for a huge diversity of fish and invertebrates, including being a major contributor of habitat for two of the most valuable wild caught fisheries in Australia: the Rock Lobster (*Sagmariasus verreauxi*) and Abalone (*Haliotis* sp.). For example, Crayweed supports much higher abundances of abalone (7–10 times) than other seaweed species in the region (e.g. *Ecklonia radiata*) or barrens habitat (Marzinelli *et al.* 2014) and contributes uniquely to detrital food webs (Bishop *et al.* 2010), which support recreationally and commercially important fish species, including Bream and Mulloway. In addition, Crayweed has a specific diversity of epifauna and microbes on its surface, compared to other seaweed species (Campbell *et al.* 2015; Marzinelli *et al.* 2016; Fig. 4).

Disappearance of Crayweed from Sydney

Crayweed was once common along Sydney's coast, but disappeared around the 1980s. Despite this dramatic disappearance occurring along the most densely populated coastline in Australia, it was not noticed until 2008, when marine scientists observed it was dominant in the upper subtidal both north and south of Sydney, but absent from the metropolitan coastline (Coleman *et al.* 2008).

Although we do not know exactly why Crayweed disappeared from Sydney, embryos of this species are particularly susceptible to pollutants commonly found in sewage, to the extent that they are used as a test species in standard ecotoxicological assessments (Burridge *et al.* 1995; Burridge & Shir 1995). The timing of the disappearance overlaps with major sewage pollution problems in Sydney, which occurred until the construction of deep water outfalls and treatment upgrades. At the time, beaches were frequently closed due to public health concerns and locals knew to avoid certain surf breaks on a particular wind or tide, as sewage was dumped straight onto our shoreline. In 1990, new sewage outfall pipes for the major sewage flows in Sydney were finished, releasing sewage 3 km offshore at 80 m depth. Despite the resulting major improvements to the water quality around Sydney since the disappearance of Crayweed, the immense Crayweed forests that once thrived had not returned prior to our restoration programme.

Biology and recovery mechanisms

Crayweed can grow up to 3 m in length, although in NSW it is typically 1-2m long (Peters 2015). Crayweed is a dioecious species, that is with separate male and female individuals, which appear to live for more than two years (Coleman & Kelaher 2009) and are reproductive all-year round (Cumming *et al.* 2019). Crayweed has a diplontic life cycle (Womersley 1987), with spawned eggs remaining attached to the female blades until fertilised, and embryos being non-motile (Burridge 1990; Schoenwaelder & Clayton 1999). Adults are not capable of vegetative reproduction and so the species is dependent on sexual reproduction to recover after a disturbance event. Crayweed shows relatively high genetic connectivity throughout its range (Coleman et al., 2020; Wood, 2020; Coleman & Kelaher 2009). The thallus contains large and abundant gas-filled vesicles, and high dispersal and high connectivity is facilitated by floating fertile material that becomes removed from the seafloor during large storms (Coleman & Kelaher 2009). Although we lack data specific to Crayweed, propagules from floating fertile algal wrack are often viable for long periods following detachment (Macaya *et al.* 2005; Hernández-Carmona *et al.* 2006; Muhlin *et al.* 2008).

The recruitment of Crayweed and the persistence of this species as a dominant seaweed appears to be dependent on the presence of adult canopy (Campbell *et al.* 2014a). Therefore, if a pollution event prevents ongoing replacement of parents, a complete crash in the population can occur. Without reproductive material being readily available, the relatively short longevity of individuals and the fact that it is a dioecious species may severely limit recovery after a large pollution event. Recovery in reefs where adult Crayweed is completely absent would be dependent on the arrival of high-density fertile wrack material containing a mixture of male and female individuals.

also known as 'Crayweed' because 'crayfish' or rock lobster use it as habitat (Young *et al.* 2016). Starting from small scientific experiments through to trial reinstatement of Crayweed at large scale, our project has evolved through increasingly effective collaborations with local, state and federal government organisations as well as philanthropists and the broader community. Our story shows how ecological experimentation led to early engagement with stakeholders and how that engagement contributed important support, leading

Box 3. Examining the role of herbivores in Crayweed restoration

Herbivory is a critically important ecological process that shapes our coastlines, influencing the overall biomass of seaweeds, as well as what species are present (Poore *et al.* 2012). Herbivory can strongly limit the success of seaweed restoration trials, with consumers like sea urchins or fish often overgrazing newly established seaweed beds (Duggins *et al.* 2001; Carney *et al.* 2005; Yoon *et al.* 2014).

From the first Crayweed trials in Cape Banks, we identified herbivore pressure as a potential cause for restoration failure in the Sydney coastline, as our transplanted seaweeds had clear signs of physical damage consistent with fish bites (Campbell *et al.* 2014a). We subsequently tested the effect of consumers experimentally using herbivore exclusion cages (Fig. 5). To do this, we planted Crayweed mats using the same approach as in our trials, and experimentally controlled access to the seaweeds by large consumers. We set up 'open' plots that allowed free access to both urchins and fish, 'caged' plots that excluded all large herbivores, and 'partial-cage' plots to control for potential cage artefacts (Fig. 5b). After only 15 weeks, we found that herbivores had a dramatic impact on Crayweed, with uncaged seaweeds being three times shorter in length than caged Crayweed.

Urchins as consumers

In the Sydney region, the most dominant herbivore is the long-spined sea urchin *Centrostephanus rodgersii*, which has a major influence on the distribution and loss of seaweed populations, creating extensive barren systems when it reaches high densities (Underwood *et al.* 1991; Andrew & Underwood 1992; Ling 2008). Extant Crayweed populations and transplanted Crayweed are usually adjacent to patches of the golden kelp *Ecklonia radiata*. To understand how *Centrostephanus* interacts with these two dominant brown macroalgae, we conducted a series of feeding experiments where we offered individual urchins Crayweed and *Ecklonia*. *Centrostephanus* preferentially consumed fresh *Ecklonia*, rather than fresh Crayweed, both when offered at the same time (choice) or alone (Fig. 5c). These results suggest that urchin-driven herbivory pressure in the wild should be higher in *Ecklonia* patches, compared to Crayweed. Thus, although urchins can still negatively impact Crayweed restoration, particularly where they occur in large numbers and where *Ecklonia* is absent, other herbivores such as fish may have a much stronger and rapid impact (Campbell *et al.* 2014b).

us to a point where a commitment to restore Crayweed forests along suitable reefs within the 70-km stretch of coastline off Metropolitan Sydney is now feasible. This engagement has ultimately led to not only restoration of Crayweed forests, but is also playing an important role in increasing the 'visibility' and community appreciation of underwater forests.

Initial restoration trials that started in 2011 were inspired by the success of other restoration projects (Dobson *et al.* 1997; Benayas *et al.* 2009). The initial purpose was to identify whether conditions along the urbanised coast of Sydney were suitable for adult Crayweed to survive. However, once initial trials proved feasible, the value of communicating this good-news environmental story also became apparent. The purpose thus evolved to the multiple goals of large-scale restoration, increasing community engagement about the programme through a multi-faceted science communication programme, and increasing awareness about the general importance of seaweed forests to our marine ecosystems.

Ecological Elements of Operation Crayweed

Is restoration of Crayweed possible ecologically?

Globally, relatively few seaweed restoration attempts have been made (Benayas *et al.* 2009), and of these efforts, most have failed (Eger *et al.* 2020). The causes of these failures are to yet be formally analysed, but anecdotally factors related to insufficient propagule supply, overgrazing, storms and water pollution have hampered past restoration projects (North 1968; Turner *et al.* 1969; Hawkins *et al.* 1999; Hernández-Carmona *et al.* 2000; Carney *et al.* 2005; Borras-Chavez *et al.* 2012). Some of these factors can be mitigated by project maintenance but others can only be offset by additional restoration efforts to replace lost habitats, or, in the case of pollution, by significant engineering programmes to mitigate for example sewage outflows or stormwater. However, one overriding message from these project failures is the importance of maintaining an extended tenure over a restoration site.

Initial trials

The first Crayweed restoration trial was conducted in 2011 (Fig. 2a). We transplanted fertile adult Crayweed from two nearby donor populations into two rocky reefs in the Sydney Metropolitan region known to previously support Crayweed (Coleman & Kelaher 2009). A random mix of male and female reproductive adults was transplanted into each site, along with appropriate transplantation controls (Campbell *et al.* 2014a). Crayweed individuals (at approximately natural densities) were secured with cable ties to plastic meshes that had been bolted to the long-deforested rock areas (Fig. 2b; see Campbell *et al.* 2014a for method details). A second trial was conducted in late winter/ spring – using the same methodology but a higher number of adults, ensuring each receiving site had transplants from both donor sites, and this time monitoring recruits.

Formal monitoring of each individual showed that survival of transplanted individuals was high (~70%) overall but varied spatially. At one site, there were signs of herbivores overgrazing the transplants (Box 3), while at the other site survival was similar to undisturbed controls in natural populations at additional, independent 'reference' sites that we were also monitoring. After approximately six months, the transplanted Crayweed reproduced. At one site, the number of Crayweed offspring (recruits, so-called 'craybies'; Fig. 2c) after almost 18 months was about ten times higher than in natural populations (Campbell *et al.* 2014a).

These positive results motivated a second, larger trial in 2012, with the assistance of volunteers from Sydney's Underwater Research Group (https://www.urgdiveclub.org.au/). We planted over 20 m^2 of bare reef at two sites as described above. Similarly to the first trial, we observed large numbers of offspring approximately 6 months after transplantation. By late 2015, few of the originally transplanted, fertile adults remained (through natural loss and mortality). However, many of the 'craybies' produced by our transplants remained firmly attached to the rock and have now become reproductive adults in their own right. We now find dozens of these new plants at our sites, where populations have expanded across shallow sublittoral reefs over several hundred metres from the original restoration patch, at a range of depths and over multiple generations, with no ongoing maintenance and no addition of new, fertile adults form donor populations required.

These results indicated that conditions along the Sydney coast could support Crayweed survival and recruitment. Yet Crayweed had not re-established naturally onto Sydney reefs over the 15 years between the improvement of environmental conditions off Sydney's coast and our initial observations (Coleman *et al.* 2008; Box 2). This suggests, firstly, that the proximity of adults is necessary to ensure availability of Crayweed eggs, sperm and the other reproductive stages. Secondly, the presence of adults might also protect craybies from exposure to too much light, too much herbivory, or provide a space away from competitors (e.g. other seaweeds or sessile invertebrates; Anderson *et al.* 1997; Choi & Norton 2005; Layton *et al.* 2019). These observations, in combination with our initial restoration trials demonstrated the potential for conducting larger scale restoration activities to return Crayweed back onto reefs within its former range, with a small initial input of intervention, despite the fact that it has been missing for decades.

Incorporating genetics into restoration of Crayweed

Genetic diversity can enhance restoration success (Reynolds *et al.* 2012). As part of our programme, we characterised neutral and functional genetic diversity of Crayweed throughout its distribution to inform the choice of

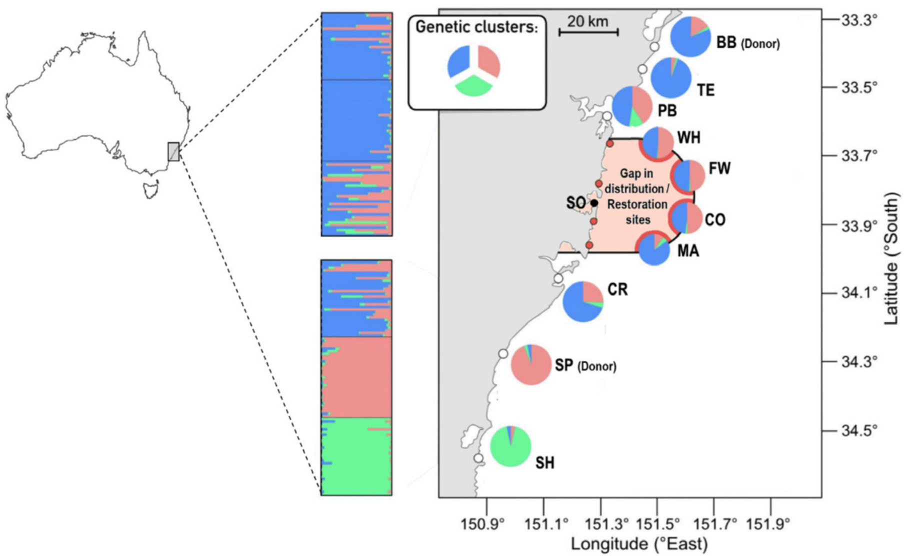

Figure 3. Genetics of extant and restored Crayweed populations, modified from Wood (2020). Left: location of Crayweed's disappearance (70 km coastline; not to scale) in Australia. Centre: genetic structure plot showing individuals from extant populations surrounding Sydney assigned to three inferred genetic clusters. Each column represents an individual; different colours within columns indicate maximum likelihood probability of belonging to different genetic clusters. Right: map of extant and restored sites coloured according to average probability of belonging to each genetic cluster. Sites from top to bottom are as follows: BB: Bateau Bay, TE: Terrigal, PB: Palm Beach, WH: Whale Beach, FW: Freshwater, SO: South Head, CO: Coogee, MA: Maroubra, CR: Cronulla, SP: Shark Park and SH: Shell Harbour. The three pie charts on either side of the black semicircle represent sampled extant populations and four smaller pie charts on the line represent recruits at four restored sites where genetics were sampled.

donor sites and mimic existing genetic structure (Wood, 2020; Coleman & Kelaher 2009; Coleman *et al.* 2011; Fig. 3). Relatively high connectivity among Crayweed populations meant that individuals could be sourced from within 60 km north and south of the gap in Crayweed's distribution for restoration. We subsequently genotyped the first generation of 'craybies', which exhibited patterns of genetic diversity and structure similar to donor plants and natural populations, indicating that we appropriately replicated the natural genetic seascape (Fig. 3).

Trying other methods

Since the initial restoration trials of 2011 and 2012, we have undertaken several additional trials to reduce the use of plastic materials deployed temporarily on the seafloor and to minimise the overall time spent underwater by divers during restoration. In particular, we have trialed substituting plastic mesh mats with coconut natural fibre matts and compostable plastic. Unfortunately, because Crayweed grows in high-energy environments with very high wave action, these alternative materials did not survive these harsh environments, instead breaking down within 2–8 weeks, well under what we require for effective restoration and recruitment of new generations had taken place (6–12 months). Alternatives such as these could nevertheless be considered in restoration trials involving other seaweed species that thrive in lower energy environments.

At two sites (southern Long Bay and Mona Vale), an alternative method was trialed to 'seed' Crayweed onto the seafloor, based on the premise that free-floating seaweeds remain reproductively viable for considerable time periods (Deysher & Norton 1981; Watanabe *et al.* 2009). Instead of attaching individual reproductive adults to the seafloor using matts, we contained groups of 10 reproductive Crayweed individuals in mesh-net bags, which were attached to the substratum using five eye-bolts. These Crayweed bags floated above the seafloor because of the buoyancy of the air vesicles in the Crayweed. This alternative system required much less infrastructure to be installed prior to transplanting. Unfortunately, this transplanting method was not successful as all bags were lost due to storm events, and no Crayweed recruits were recorded at either site.

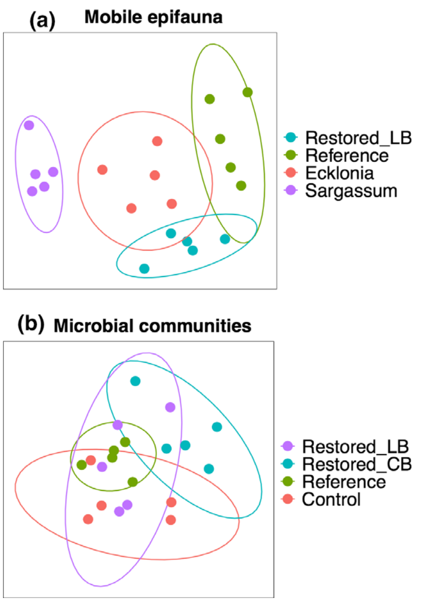

Figure 4. Communities of (a) mobile epifauna and (b) microorganisms associated with Crayweed (*Phyllospora comosa*) or other co-occurring seaweeds (*Ecklonia radiata* and *Sargassum* spp.) in restored locations in Sydney (Long Bay, 'LB', and Cape Banks, 'CB'), or in reference, extant populations surrounding Sydney. nMDS ordinations based on Bray–Curtis similarities on square-root transformed relative abundances of (a) mobile epifauna standardized per wet weight of alga 12 months after restoration (modified from Marzinelli *et al.* 2016) and (b) surface-associated bacteria and archaea obtained through DNA fingerprinting 5 months after restoration (modified from Campbell *et al.* 2015). Each point represents a sample; ellipses are 90% normal confidence levels. 'Control' in (b) are Crayweed moved to another extant Crayweed location surrounding Sydney.

Does re-establishing Crayweed enhance biodiversity?

Crayweed supports a unique subset of biodiversity compared to other, co-occurring species (Marzinelli *et al.* 2014; Marzinelli *et al.* 2016); thus, its disappearance from the Sydney Metropolitan coastline may have affected regional biodiversity. The capacity to restore both Crayweed and its closely associated biodiversity is therefore an important rationale for Crayweed restoration. In fact, two of the most economically important species in Australian fisheries, crayfish (rock lobster) and abalone, are strongly associated with Crayweed forests (Andrew 1999; Marzinelli *et al.* 2014; Young *et al.* 2016). Hence, one of the original motivations of our project was to enhance opportunities for recreational fishers, and monitoring of these species is ongoing.

Early indications demonstrate that restored Crayweed supports a different epifaunal assemblage to the two other dominant seaweeds in the region, which co-occur at our original restoration site in Long Bay: *Ecklonia radiata* (48 and 58% dissimilar for community structure and composition, respectively) and *Sargassum* spp. (72% dissimilar for community structure and composition; Fig. 4a). However, assemblages of mobile epifauna and, to some extent, of surface-associated microorganisms (Fig. 4b) on restored Crayweed did not fully resemble those from reference Crayweed populations, even after 18 months in their new habitat, suggesting that restoration of associated organisms is a more complex and potentially a long-term process (>18 months) than anticipated (Campbell *et al.* 2015; Marzinelli *et al.* 2016). We continue to monitor associated biodiversity in restored sites, as well as in multiple reference, extant Crayweed populations surrounding Sydney and in control, unrestored sites in Sydney, to determine effects of our Crayweed re-establishment on associated flora and fauna.

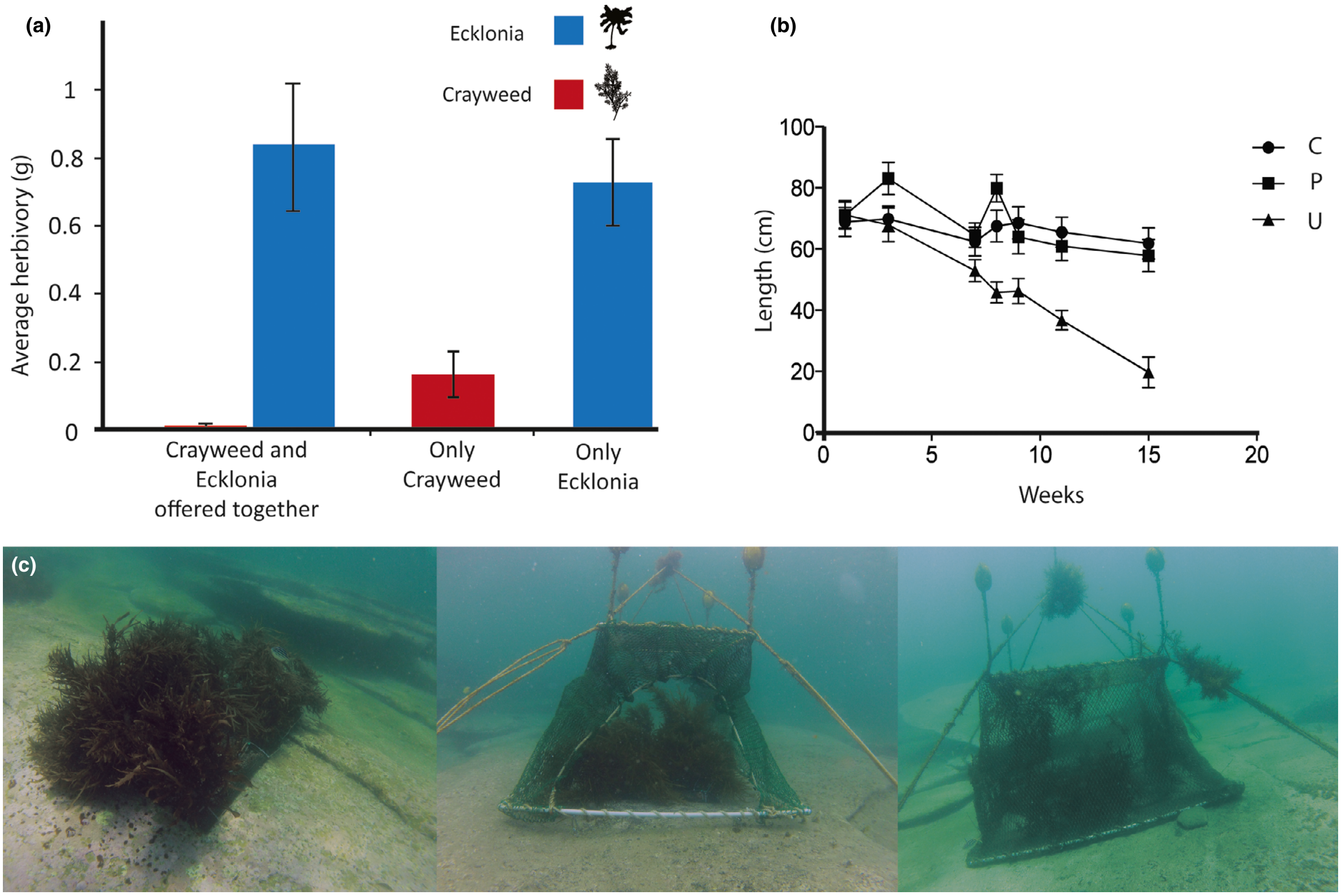

Figure 5. Experiments to test susceptibility of Crayweed to herbivores. (a) Centrostephanus urchins were given the choice between fragments of Crayweed and golden kelp (Ecklonia), the other dominant kelp in the region, in either choice (right) or no-choice assays (middle and left). Urchins consumed significantly more Ecklonia than Crayweed in both choice and no-choice assays ($P < 0.01$); sample size for each assay was n = 12 urchins. (b) Changes in Crayweed length (n = 10) of transplanted patches in the presence/absence of herbivores, measured at 2–4 week intervals. Four replicate plots of each experimental treatment were randomly allocated to haphazardly chosen flat sandstone surfaces in the shallow subtidal zone in 3–4 m depth. After 15 weeks, the length of Crayweed in uncaged plots 'U' was significantly shorter than in closed 'C' and partially open 'P' cages ($P < 0.01$). Reduction in Crayweed length is indicative of herbivory pressure. The lack of herbivory in partially caged Crayweed plots, despite the fact that these had openings and herbivores were theoretically able to access the Crayweed inside, was most likely due to the movement of the floating cages in the dynamic marine environment, which may have deterred both fish and urchins despite the openings. (c) Crayweed individuals were transplanted into uncaged plots (left), partially open cages (middle), and closed cages (left).

Cultural Engagement in Operation Crayweed

Bringing communities with us – a key to marine restoration

Operation Crayweed is not just about science and restoring one species of seaweed, it is also about the story of a coastline along Australia's largest city, Sydney, over the years and the value of looking after our own backyard. Nature can deeply influence our sense of self (Manzo 2003). Within the marine context, researchers are increasingly recognising that sustainable management of our coastlines requires a better understanding and appreciation of the emotional bond that people have with marine systems (van Putten *et al.* 2018).

We chose to connect people to the science of Operation Crayweed and the story of our coasts through a science communication and crowdfunding campaign that celebrated our success in reversing local extinction and re-establishing a long-lost species to the Sydney coastline. The literature has shown how good-news stories such as this one can be particularly effective in generating interest and inspiring positive conservation action (Cvitanovic & Hobday 2018; McAfee *et al.* 2019b). We further collaborated with artists to give interested communities the opportunity to interact and engage with the project in a variety of ways (Fig. 6, Box 4). By combining science with opportunities for our audience to engage in a way that resonated with them, our research on Crayweed disappearance and restoration has become a stronger, more compelling story.

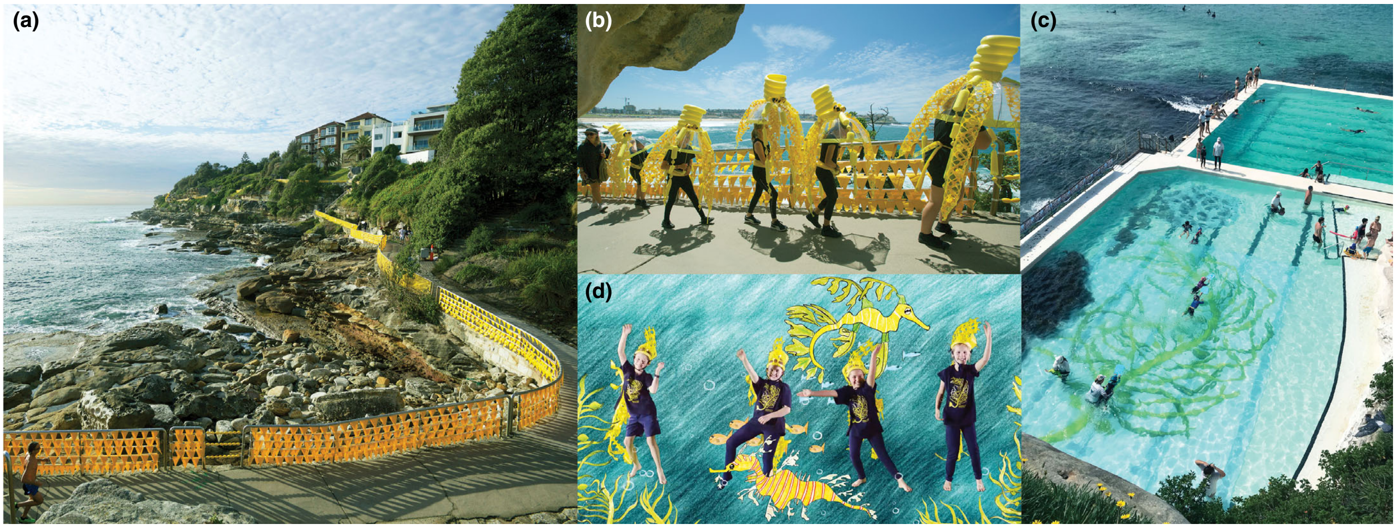

Figure 6. Art meets Science collaborations to raise awareness about the importance of our underwater forests and to engage local communities with Crayweed restoration. (a) Bright yellow fence wraps Bondi Bay to highlight where the underwater Crayweed is planted during Sculpture By the Sea 2016. (b) Children in octopus costumes activate the yellow fence in a parade for Sculpture by the Sea 2016. (c) A giant drawing of a Crayweed plant animates the bottom of the Icebergs Pool Bondi for Ocean Lovers Festival 2019. (d) A still from the film 'Operation Crayweed With Balgowlah North Public School' 2019 where children dance in weedy sea dragon costumes while their animated drawings swim behind them. Photo credits: (a and b) Ian Hobbs, (c) Jennifer Turpin.

Engagement through crowdfunding, art and storytelling

From the start of the project, we realised that this good-news story about reversing the local extinction of a seaweed species could become an important tool to engage local communities and boost public awareness about the local marine environment in Sydney (Cvitanovic & Hobday 2018; McAfee *et al.* 2019b). To do this, we created an identity for the project ('Operation Crayweed'), and we built a website, joined various social platforms and commissioned a short film about the story of our restoration project and our initial success. To maximise the effectiveness of our outreach, we used storytelling to communicate our restoration efforts in a personalised way and we developed a consistent branding style (Bik *et al.* 2015). We managed to elicit very positive engagement with the public through a crowdfunding campaign conducted in December 2015, designed to raise funds to scale up our restoration efforts. The campaign used the tagline 'plant an underwater tree for Christmas', which was catchy enough to feature on national and international news on TV (Channel 9, ABC), print and radio. Within four days we had met the initial funding target ($20 000), and by the end of the campaign 60 days later, we had doubled our initial target. The positive public response became part of the story, increasing its resonance and effectiveness. This crowdfunding was subsequently followed by much greater funding investments through an Australian Research Council grant and through substantial donations from individual philanthropists.

The scientists within our team were subsequently invited to participate in a major outdoor art exhibition in Sydney, Sculptures by the Sea, via a collaboration with public artists Jennifer Turpin and Michaelie Crawford (Box 4). The outcome was a participatory art event that made the underwater restoration happening in Bondi visible to all (Box 4). We used the opportunity of tapping into the large audience of Sculptures by the Sea (half a million visitors), to experimentally test the efficiency of different modes of science communication, and to find out more about what Sydneysiders know and feel about their local marine environment. To do this, we offered visitors to the exhibition the opportunity to either listen to a 3-min podcast or watch a 3-min film that brought the science behind the project to life. These media described the science behind our restoration project and explained the overall importance of seaweeds to the local marine environment. In some podcasts, the science was explained using narrative and storytelling, whereas in others it was communicated in a factual text-book style, and we then tested whether these different modes of communication impacted the understanding of science being communicated. We collected responses via surveys and assigned random participants to a control group, where we asked participants the same questions but without exposing them to our science communication. Eliciting stories from the public, we also asked participants for their connections to the temperate coastline and their responses to the restoration project.

Along that 500-m walkway at Bondi, over 600 participants took part in our

Box 4. Merging art and Crayweed

Connectedness with nature is not only linked to physical and psychological well-being, but is also a reliable predictor and motivation for environmentally responsible behaviour (Zylstra *et al.* 2014). Art can facilitate a closer connection between people and the natural world. It can heighten our relationship with nature and help us understand our inextricable interconnectedness to it – rekindling our relationships with plants and other animals. Art can give expression to the yearning for a closeness to nature, felt by many who are alienated from it, in contemporary urban environments like Sydney.

Our Crayweed restoration programme has incorporated a collaboration between scientists and public artists to develop participatory art-science projects for Operation Crayweed since 2016. The power of the arts in influencing positive environmental attitudes and inspiring restoration projects have long been recognised (Jacobson & Monroe 2007; Curtis 2009). The art projects have been run in local schools to harness the natural curiosity and open engagement of young students – and through them, to connect with the broader community of their families and social networks. The students, parents and teachers first participate in science workshops and field trips to learn about Crayweed and coastal ecosystems. They then explore and communicate what they have learnt about Crayweed through the creative and communal process of art-making in a variety of forms including drawing, sculpture, film making, song writing, recording and performance.

Operation Crayweed Art-Work-Site 2016, a multi-faceted environmental and community art project for *Sculpture by the Sea* (SxS) in Bondi, was our first collaboration. This artwork aimed to make visible the otherwise invisible underwater Crayweed restoration work in Bondi Bay, Sydney.

A 500-metre-long, land artwork snaked around the edge of south Bondi, activating the relationship between land and sea (Fig. 6a). The bright yellow 'art fence' was made of everyday worksite fencing to denote the underwater rehabilitation work of the scientists. A large floating yellow buoy, clearly visible from land, and adorned with marine biodiversity messages for passing swimmers, marked the site of the restoration. Local ocean swimmers joined the project with a synchronised performance around the buoy, helping to draw attention to the planting site beneath them. Three more marine buoys were repurposed as 'view-scopes' on the headland above the bay for passers-by to locate the underwater reforestation sites. The buoys displayed the names of the sea creatures that inhabit Crayweed, to draw the connection between the marine flora and fauna that flourish in a healthy ecosystem.

In the months leading up to the SxS installation, local primary and secondary school children participated in art workshops to make wearable marine creature sculptures of the fauna that inhabit Crayweed (Fig. 6b). The artists designed a series of wearable sculpture 'templates' for the students to make themselves. They were asked to consider the look and physical attributes of the marine creature they would make, focusing on how the animal propelled itself in water. The same worksite materials as the yellow 'Art-Work-Site' fence in Bondi Bay were used to make their wearable artworks. The children were encouraged to imagine 'being' their marine creature, so as to think and feel beyond the human frame – and see themselves inhabiting an underwater world.

The project aimed to heighten connections between humans and nature for participants and audiences alike. The scientific learning, creative engagement and environmental art installation culminated in a project launch with a musical performance and parade with the schoolchildren wearing their marine creature sculptures, including weedy sea dragons, octopuses and sea urchins, alongside the 'Art-Work-Site' fence around Bondi Bay (Fig. 6b).

Operation Crayweed Art-Work-Site prompted participants and audience to reflect on our role in protecting the marine environment and helped to develop awareness and understanding of the Crayweed restoration project. More than one hundred children participated in the art project that was experienced by over 450 000 visitors.

In early 2019, Turpin Crawford Studio created another artwork for Bondi with a giant Crayweed 'drawing' that lined the base of the Icebergs pool for *Ocean Lovers Festival 2019* (Fig. 6c). The artwork was designed to be experienced from the street above and within the pool itself. Flanked by clumps of living Crayweed, swimmers could float over the huge image or snorkel through the real seaweed with the Operation Crayweed scientists. The artwork image has become a visual icon for the project and is now printed on tee-shirts to further promote the project.

Operation Crayweed With Balgowlah North Public School, 2019, is the latest project in the ongoing art-meets-science collaboration (Fig. 6d). To accompany the reforesting of Cabbage Tree Bay Aquatic Reserve in Manly, Turpin Crawford Studio, in conjunction with digital studio Lightwell, made a short film with a group of enthusiastic year four students from Balgowlah North Public School. The film tells the story of Operation Crayweed. Over a period of several months, the children were involved in science and art workshops and creatively contributed to the film-making process.

Their roles included the following: narrating the film, both on and off camera; creating hundreds of drawings for the film's animation sequences; writing and recording the film's theme song with musician Ben Fink; devising and performing the choreography for the inspirational song-and-dance sequence that completes the film. The film was launched at the Manly

Box 4 (continued)

Museum and Art Gallery by Zali Steggall MP. Six of the students, wearing scientist laboratory coats or the Operation Crayweed marine creature costumes, from the earlier 2016 SxS project worn in the song-and-dance sequence, performed a lively Q&A session to explain the film to their audience (Fig. 6d).

One of the aims of this film project was for students to present the restoration project to other children using their own voice. It is intended that the film will be widely disseminated and used as an educational tool within classrooms and beyond. It is hoped the Balgowlah students will become ambassadors for their film in the northern beaches region.

Through the various 'Operation Crayweed' art-science collaborations, thousands of people have experienced a project that links our terrestrial lives with life under the water. We are reminded of nature's beauty and powerful energy, but also its fragility. The art-science project highlights the exciting potential to restore the marine environment. Through extensive educational and creative engagement, the collaboration aims to foster both knowledge and empathy, awareness and care – and to develop a committed 'Crayweed community' of custodians to support and protect this ongoing marine environmental recovery.

study. We found that while all styles of communication (podcasts and film, narrative and factual) improved comprehension about the problematic aspects of seaweed degradation, the narrative style significantly improved comprehension for questions relating to the drivers of success of the restoration trials (Kajlich *et al.* 2020, unpublished data). From our control group, we also uncovered two unexpected public misconceptions about the local temperate marine environment. First, a large proportion of visitors were not aware of the major improvements in water quality that have taken place in the last few decades. About 60% of the participants from the control group (i.e. not exposed to any media) thought water quality in Sydney has worsened in the last three decades, when it has in fact been markedly improving largely as a consequence of major changes in sewage outfalls (Scanes & Philip 1995).

Secondly, about 30% of participants from the control group thought the dominant habitat-formers in Sydney are *corals* (rather than seaweeds), even though major coral reefs are more than 1000 km away. These misconceptions showed that successful management actions (such as improving water quality) are not being communicated effectively to the public. They also pointed to a need to raise awareness about the importance of seaweed forests as the key foundation species supporting ecological communities in temperate coastlines.

Combining the Ecological and Cultural Elements to 'Scale Up'

Our initial efforts to restore Crayweed to Sydney reefs are very encouraging. In Long Bay, adult reproductive Crayweed have become established in about 4000 m^2 of reef along ~500 m of coastline in 6 years. This outcome was achieved because of a high level of recruitment, several hundred metres away from the initial transplant area (24 m^2) and demonstrated that scaling up restoration on Sydney's coast is ecologically possible. Large-scale success could be achieved through the transplantation of Crayweed to strategic locations where new forest nodes can act as propagule sources for subsequent natural establishment of Crayweed in potential habitats. This 'applied nucleation' strategy is not uncommon in restoration programmes in terrestrial sites (Benayas *et al.* 2008; Corbin & Holl 2012; Corbin *et al.* 2016; Holl *et al.* 2017).

The trials also showed that the methodology used is relatively cost effective. We have estimated our Crayweed 'revegetation' costs at US $46 250 per hectare (2018 year of evaluation). This figure includes materials, transport and personnel, but excludes project management and monitoring, and also excludes the initial and ongoing scientific research done to develop and optimise the restoration methods (Layton *et al.* 2020). This estimate sits well towards the lower end of coral reef restoration programmes (which vary between US $6000 and US$4M per hectare; Bayraktarov *et al.* 2016) and could likely be reduced through continued method development and optimisation.

Operation Crayweed has now expanded to 12 sites in total, six of which have had successful recruitment (i.e. establishment of craybies), with another six in the process of being reseeded and with two additional new sites planned for 2020. The feasibility and success of restoration of Crayweed at larger scales will, however, depend on continued financial investment and our capacity to maintain project logistics (Eger *et al.* In review). This in turn depends upon government and community appreciation of the benefits of Crayweed to fisheries and marine recreational activities in order to offset the cost of restoration. We therefore argue that a strategy for upscaling Operation Crayweed to the entire Sydney Metropolitan region is likely to be most successful if it continues to be accompanied by activities that raise awareness about the importance of underwater forests and actively engage local communities. Indeed, evaluations from successful large-scale coastal restoration projects have highlighted that providing resources to build public support prior to significant investments into ecological restoration is a particularly important element that facilitates success (McAfee *et al.* 2019a).

Bondi Beach was the first in a series of Crayweed reforestation sites engaging the public through a combination of art and science, and this was followed by comparable activities in Cabbage Tree Bay in Manly which helped raise awareness (Box 4). As the scientists move up and down the coast restoring Crayweed, the aim is to continue to raise awareness within local communities and funds to collaborate with artists and local communities in the creative work of reconnecting people with their coastal environments.

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