Institution: University of Southampton		
Unit of Assessment: 07 Earth Systems and Environmental Sciences		
Title of case study: 07-03 Translating coral reef science into new commercial products, inspiring education programmes and greater public awareness of the need to protect marine ecosystems		
Period when the underpinning research was undertaken: 2012 – 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Jörg Wiedenmann Cecilia D'Angelo	**Role(s) (e.g. job title):** Professor Lecturer	**Period(s) employed by submitting HEI:** September 2007 – present November 2012 – present
Period when the claimed impact occurred: August 2013 – December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

University of Southampton's Coral Reef Laboratory (CRL) has used its research to increase understanding and awareness of the importance of coral reefs, their critical status and opportunities to halt their decline, at a local, national and global level among stakeholders and public audiences. The team focussed on: **(A) Knowledge transfer**, working with industry to commercialise new products in the aquaculture and medical research sectors, and with policymakers to change environmental policy in the Middle East for the protection of coastal ecosystems. **(B) Educational programmes and public events**, engaging >4 million people from 128 countries, including schoolchildren, teachers, families, lifelong learners and policymakers, in coral reef science and inspiring them to take action, through online courses, face-to-face presentations and award-winning interactive exhibitions. **(C) Increasing public awareness**, engaging millions of people in >24 countries in their research via print, online and broadcast media and contributions to high-profile documentaries.

2. Underpinning research

Research undertaken at the Coral Reef Laboratory (CRL) has advanced the understanding of symbiotic reef corals. These organisms form the three-dimensional framework of coral reefs – unique habitats that sustain the livelihoods of half a billion people and about a third of all marine biodiversity. Natural and anthropogenic disturbances impair the functioning of the coral symbiosis and threaten coral reef survival. Understanding how corals respond to interacting stressors is therefore a crucial component of knowledge-based management and conservation programmes.

Research at the CRL has made significant contributions to the understanding of the roles of the coral host, the microalgal symbiont and the physico-chemical environment in shaping the response of reef corals to stress. In addition, it has yielded advanced fluorescent marker proteins from coral reef organisms for biomedical research applications. The research was led by Wiedenmann and D'Angelo and was delivered together with Postdoctoral Research Fellows (Rosset and Hume), PhD students (Smith, Bollati), ten undergraduates and collaborators from the global scientific community.

Since 2012, the team has:

i) Created a genetically enhanced variant of a red fluorescent marker protein derived from the coral reef-dwelling anemone *Entacmaea quadricolor* for imaging purposes in biomedical research [**3.1**].

ii) Established the mechanism that explains how disturbances of the nutrient environment reduces the tolerance of symbiotic corals to stress-induced bleaching [**3.2**]. These findings are critical to regional coral reef management.

iii) Discovered and described a new species of symbiont alga that is key to the survival of corals in the world's hottest reef waters, and in the adaptation of corals to historic climate change [**3.3-3.4**]. These studies sparked great interest as they reveal mechanisms that corals can utilise to adjust to rising seawater temperatures in a warming world.

iv) Elucidated the role of fluorescent pigments produced by the coral host in modulating the internal light availability for the benefit of its algal symbiont, specifically during coral bleaching [**3.5-3.6**].

v) Generated widespread interest in coral reefs by using the fascinating phenomenon of coral fluorescence [**3.5**] to highlight the application of fluorescent pigments in medical research [**3.1**] and as a gauge for the survival capacity of corals after bleaching episodes [**3.6**].

3. References to the research

3.1 Lam, A., St-Pierre F., Gong Y., Marshall J., Cranfill P., Baird M., McKeown M., Wiedenmann J., Davidson M., Schnitzer M., Tsien, R., Lin M. 2012. Improving FRET dynamic range with bright green and red fluorescent proteins. Nature Methods 9, 1005-1012. https://doi/org/10.1038/nmeth.2171

3.2 Wiedenmann J., D'Angelo C., Smith E., Hunt A., Legiret F., Postle A., Achterberg E. 2013. Nutrient enrichment can increase the susceptibility of reef corals to bleaching. Nature Climate Change 3, 160-164. https://doi.org/10.1038/nclimate1661

3.3 Hume B., D'Angelo C., Smith E., Stevens J., Burt J., Wiedenmann J. 2015. *Symbiodinium thermophilum* sp. nov., a thermotolerant symbiotic alga prevalent in corals of the world's hottest sea, the Persian/Arabian Gulf. Nature Scientific Reports 5, 8562. https://doi.org/10.1038/srep08562

3.4 Hume B., Voolstra C., Arif C., D'Angelo C., Burt J., Eyal G., Loya Y., Wiedenmann J. 2016. Ancestral symbiont diversity has enabled rapid adaptation of reef corals to climate change. Proceedings of the National Academy of Sciences USA, 113, 4416-4421. https://doi.org/10.1073/pnas.1601910113

3.5 Smith E., D'Angelo C., Sharon Y., Tchernov D., Wiedenmann J. 2017. Acclimatization of symbiotic corals to mesophotic light environments through wavelength transformation by fluorescent protein pigments. Proceedings of the Royal Society B: Biological Sciences 284 https://doi.org/10.1098/rspb.2017.0320

3.6 Bollati E., D'Angelo C., Alderdice R., Pratchett M., Ziegler M., Wiedenmann J. 2020. Optical feedback loop involving dinoflagellate symbiont and scleractinian host drives colorful coral bleaching. Current Biology 30, 2433-2445. https://doi.org/10.1016/j.cub.2020.04.055

Directly associated grants & funding of impact activities: ERC Starting Grant "Influence of nutrient starvation on corals' susceptibility to bleaching" **£1.1 million** (2012-17, Wiedenmann: PI, D'Angelo: main researcher); NERC NE/K00641X/1 "Understanding the exceptional heat tolerance of reef corals from the Persian/Arabian Gulf" **£471k** (2012-16, Wiedenmann: PI), included funding of "Pathways to Impact".

4. Details of the impact

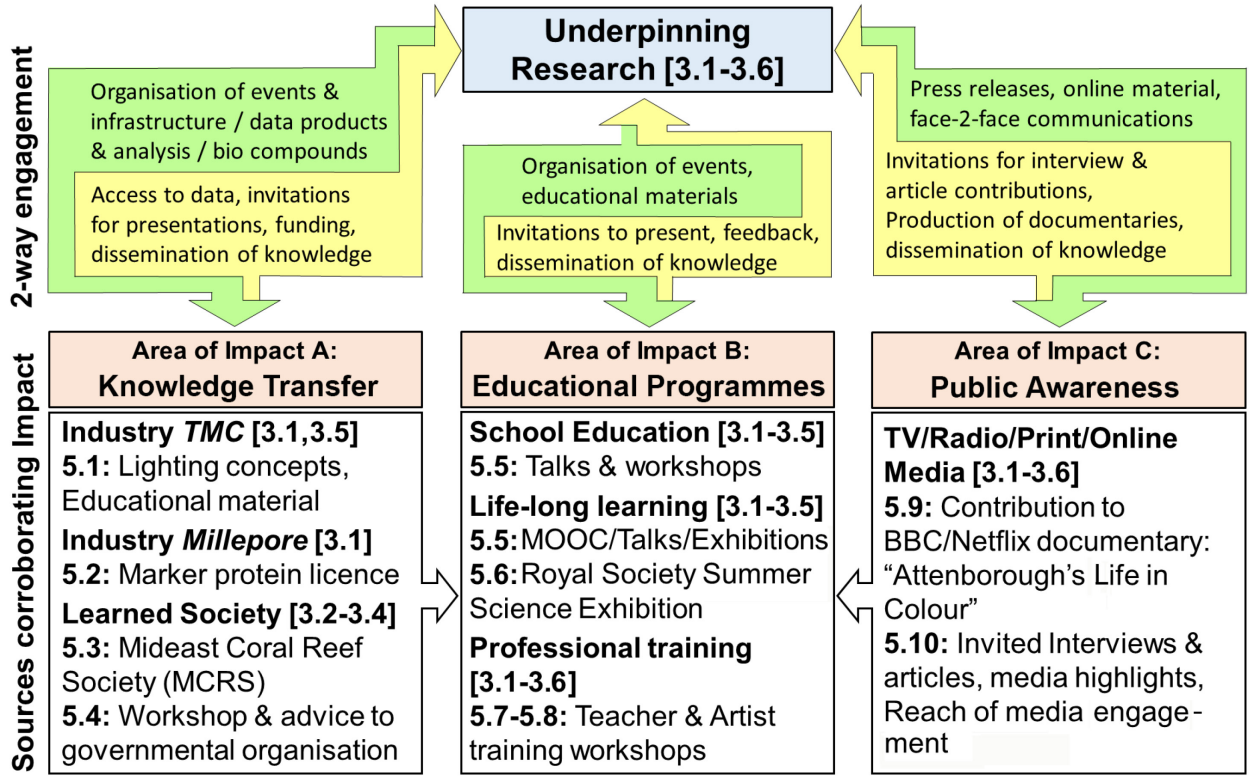

Figure 1: Relationship of underpinning research [3.1-3.6], two-way engagement in the three impact areas [A,B,C] and the sources corroborating impact [5.1-10].

The CRL team used their research findings to generate impact in three key areas: **(A) Knowledge transfer:** They translated their research on fluorescent coral pigments [**3.1, 3.5**] and coral stress physiology [**3.2**-**3.5**] into new commercial products for the life science and aquaculture sectors [**5.1**-**5.2**], and policy action and knowledge exchange in the Middle East to protect coastal ecosystems [**5.3**-**5.4**]. **(B) Educational initiatives:** Building on the visual power of coral fluorescence [**3.5**-**3.6**] and the colourful narrative of its medical research applications [**3.1**], the team inspired both young people and lifelong learners to treasure coral reefs and to engage in action against the global coral reef crisis [**5.5**-**5.8**]. **(C) Public Awareness:** Through sustained engagement with broadcast, online and traditional media, CRL researchers have increased public understanding and awareness of the wonders of, and the perils facing, coral reefs highlighting the urgent need for new policy responses to protect them [**3.1**-**3.6**] [**5.9**-**5.10**].

A) Knowledge transfer through industry collaboration and a new knowledge exchange forum

(i) Tropical Marine Centre London (TMC): In collaboration with TMC, the UK's leading supplier of innovative aquatic equipment, CRL research on the function of coral host pigments in optimising the internal light availability for their symbionts [**3.1**, **3.5**] was translated into the development of an advanced near-UV LED-based aquarium lighting system. The collaboration came in response to comments from TMC customers that the company's LED lighting systems, designed as sustainable alternatives to commonly used metal halide lamps, were causing their corals to lose colour [**5.1**]. Findings in [**3.5**] demonstrated that a near-UV LED system would promote the natural fluorescence of corals, thereby enhancing enjoyment for coral enthusiasts and the sustainability of coral aquaculture. TMC was the first to launch this product in 2014, and since then over 2,185 units with a cumulative market value of approximately £200,000 were sold [**5.1**]. As a result, the lighting concept was widely adopted across the industry.

The Head of Technical Development at TMC wrote that the CRL research was "*key to aid the rapid and successful transition to reduced carbon footprint LED lighting solutions in the marine aquaculture sector*" [**5.1**].

(ii) EMD Millipore Corporation: CRL outreach on fluorescent host pigments [**3.5, 3.6**] attracted the interest of EMD Millipore Corporation (now Merck Millipore) and led to knowledge exchange on applications of fluorescent proteins as molecular markers. A red fluorescent protein was licensed in May 2018 to the company for integration in their life science products for research purposes [**5.2**].

(iii) The Mideast Coral Reef Society: CRL conducted research in the Middle East to understand how corals tolerate high levels of environmental stress [**3.3**-**3.4**]. Wiedenmann recognised that the lack of a learned society for coral reef science in the region was limiting effective communication of scientific findings. Consequently, he initiated the founding of the *Mideast Coral Reef Society (MCRS)* in 2015 as a platform to communicate evidence to stakeholders and has since acted as one of its two chairs. More than 280 representatives of academic and governmental organisations, NGOs and private sector companies are MCRS members. In 2019, the MCRS achieved recognition as a regional chapter of the International Coral Reef Society (ICRS).

The ICRS stated: "*The formation of the MCRS filled a significant gap in promoting communication of coral reef science across and within a region that is proving key to understanding the response of the world's coral reefs to climate change and human impac*t" [**5.3**].

Interactions within MCRS resulted in Wiedenmann and D'Angelo collaborating with the Environment Agency Abu Dhabi (EAD), which advises UAE governments. They were granted access to environmental monitoring data, which they analysed in light of their findings from [**3.2**-**3.4**]. The outcomes were communicated at a workshop for senior members of governments from UAE and Kuwait in October 2017 [**5.4**]. This led to CRL being invited to recommend evidence-based changes to government monitoring programmes. The EAD implemented CRL recommendations to apply more sensitive analytical techniques to assess the quality of coastal waters, including coral reef stations; these continue to be widely used [**5.4**].

The EAD wrote: "*The link between disturbances of the nutrient environment and coral mortality became a key argument in support of our efforts to completely reduce the introduction of municipal wastewater from Abu Dhabi in the sea to protect the coastal ecosystems and we expect that this goal will be achieved by 2022*" [**5.4**].

B) Educational Initiatives:

(i) Coral reef-themed interactive presentations and workshops at schools: CRL has engaged schoolchildren in its research to inspire them to pursue STEM careers and to be ambassadors of sustainable lifestyles that support coral reef survival [**5.5**]. The researchers brought living corals, yellow filter goggles and blue light torches to classrooms for pupils to engage hands-on with coral fluorescence. Events were attended by >1000 students at *four secondary schools*. A teacher at Marlborough College writes: "*You gave them such a fascinating exploration into coral reefs which will make us all think about them differently*". After an event attended by ~300 14-18-year-old pupils at Downe House School, **100% of the responders confirm that they have learned something new** and **87% reported that they will change their behaviour in response to what they have learned**. A representative student response: *"I plan to try to be more eco-friendly and reduce my plastic waste, and also cut down on red meat consumption*" [**5.5**].

(ii) Permanent Exhibitions: Three permanent live fluorescent coral displays were set up at major visitor attractions [**5.5**]. The CRL team advised the (a) *Sea Life Centre at Chessington World of Adventures* and the (b) *Horniman Museum London* on aquarium set-up, lighting and suitable tank inhabitants. As part of these displays, two tanks were shown side-by-side in a darkened room in each of the venues, one with daylight illumination showing the 'natural' colour, one with a near-UV lighting system that shows only the coral fluorescence. The displays at both venues were accompanied by display boards that featured the research into functions and applications of coral fluorescence [**3.1**]. Venues contributed funding for these projects. Displays were visited by ~4.2 million people (Chessington Sea Life Centre, August 2013-2020) and ~120,000 people (Horniman Museum, August 2013-2016). The aquarium curator at the Horniman said: "*Visitors were always fascinated by the glow of the corals and the research and wanted to learn more about the science behind this phenomenon during guided tours*" [**5.5**]. CRL also introduced an interactive live coral display as a new teaching and outreach tool in the reception area of the (c) *National Oceanography Centre Southampton* (NOCS). Visitors can change the illumination of the tank to explore coral fluorescence. The tank, funded by NERC and sponsored by TMC, has become a central educational feature (~70,000 visitors over August 2013-2020), in particular during NOCS open days [**5.1**].

(iii) Temporary Exhibitions: CRL staged four coral fluorescence-themed exhibitions featuring interactive displays in which visitors gained hands-on experience of exploring the potential of coral fluorescence for reef monitoring purposes and biomedical research [**3.1, 3.5**]. This phenomenon was used to communicate how climate change and regional water quality affect reef survival [**3.2**] [**5.5-5.6**]. Exhibits were presented at the (a) *Marine stand* of the *Southampton Boat Show 2015* (~27,300 visitors; **rated 2nd most popular stand**), (b) *Southampton Science and Engineering Festival 2017* (~700 actively engaged visitors; **exhibit won the 'Wow-factor' award**) and the (c) *Royal Society Summer Science Exhibition 4th-9th July 2017*. In the school student survey conducted by the Royal Society, **51% of students chose CRL's *#GlowingCorals* as 'best exhibit on show'** [**5.6**]. #GlowingCorals was seen by an estimated >13,000 visitors and it received 100% positive comments from 233 survey participants. A representative comment reads: "*Who wouldn't want to be a scientist after seeing the glowing coral exhibition?*". A video on the research featured in our exhibit was published on the Royal Society's YouTube channel (>3000 views). A fluorescent coral exhibit and information stall featuring research on coral fluorescence and the effect of nutrient pollution on reef survival [**3.2**, **3.5**] was displayed at the (d) *Commonwealth Marine Science Event* held in April 2018 at NOCS as part of the *Commonwealth Heads of Government Meeting London 2018*. At the event, The Rt Hon Thérèse Coffey MP, UK Environment Minister praised our "*ground-breaking work"*, and announced that the UK was joining the Coral Reef Life Declaration, a global commitment to safeguard coral reefs [**5.5**].

(iv) Massive Open Online Course (MOOC): CRL translated its findings [**3.1-3.5**] into three chapters of a new version of the UoS MOOC "Exploring our Oceans". The MOOC ran four times from 2019-2020, actively engaging **6,980 participants from 128 countries** spanning the high-, middle- and low-income categories. Evaluations asked participants: Which of the six marine ecosystems featured in the course would you like to explore further? **Coral reefs came either first or second** across all the evaluations. **99.5% of the participants answered that they had gained new knowledge or skills**. Out of the responding participants, **62% have applied what they had learnt and 78% shared**

what they had learnt with other people. A representative comment on the coral reef section reads: *"Incredible. It makes me determined to do that little bit more to protect the oceans"* [**5.5**].

(v) Teacher Training: Teacher training based on the research in [**3.1**-**3.3**] was delivered by the *XL Catlin Ocean Academy*. Workshops included theoretical and practical components and were delivered in 2014 and 2015 for 35 teachers. An external evaluation demonstrated changes in perception and impact on practice. One teacher said: "*Research was made accessible to a level that I am now able to deliver it myself as a Geography teacher of 11–16-year-olds - who one day I hope to see continuing the critically important work Jörg and his team carry out today"* [**5.7**].

(vi) Training Workshop for Artists. CRL collaborated with artist Glenn Morris to deliver an educational workshop for UK professional artists. The aim was to initiate the production of artwork inspired by the colour changes of stressed corals [**3.2**, **3.5**, **3.6**] in order to communicate the impact of local water quality and global climate change on coral reef survival [**3.2**]. As an outcome of the workshop, the exhibition "BLEACHED" was set up together with 12 artists as an integrated and interactive science and art exhibition designed to explore the scientific messages from [**3.2**, **3.5**, **3.6**] in creative and innovative ways [**5.8**]. The exhibition was scheduled for March-April 2020 at God's House Tower Southampton, the flagship venue of the Arts Council organisation *A Space Arts*; it was postponed due to the Covid-19 pandemic and will run once permitted [**5.8**].

C) Public Awareness

Proactive media engagement significantly broadened the reach of CRL research. The key scientific messages of [**3.2**-**3.6**] were covered by 450 print, online and broadcast media items with a multi-million reach in >24 countries, including coverage by major news channels (*CNN*, *ABC, CBC), The Economist*, *The New York Times, National Geographic*, *The Times*, *The Independent*, *Daily Mail*, and *Nature***.** The impact of these activities is demonstrated by two-way engagement with the media:

(i) Documentaries: In addition to international radio broadcasts and online podcasts, research in [**3.1**] and [**3.2**] was featured twice on BBC Radio 4's *Inside Science* in 2015 [**5.10**]. The research in [**3.6**] is a key component of a new three-part series for BBC and Netflix called *Life in Colour* with Sir David Attenborough. It was made in 2020 (i.e., during the REF2021 period) and will be shown at prime time in April 2021 [**5.9**]. The producer wrote: '*We have an engaging, concise and stunning looking sequence which will bring to the public both the terrible implications of coral bleaching, and a novel mechanism how coral use fluorescence to protect themselves against stress*. *From our experience, this type of narrative will be most effective to inspire a large number of viewers to engage actively with the subject*' [**5.9**-**5.10**].

(ii) Invited interviews on broadcast media and invited outreach articles: Journalists responded to the CRL public engagement, resulting in broadcasting of 22 interviews specifically related to the underpinning research [**3.1-3.3**, **3.5-3.6**]. Highlights include interviews with *The New York Times* (2017, 2020), *IFLScience, Scientific American, The Independent*, *The Times* [**3.6**], *ABC News Australia* (2017), and 2x *Naked Scientist* (2017) [**3.5**]. An interview in the *"Living on Earth" program with Steve Curwood* was distributed to 250 public radio stations in the USA (2015) [**3.3**] [**5.10**]. In addition, CRL researchers were invited to write about their research [**3.2, 3.4, 3.6**] by the editors of *The Conversation, Ocean Challenge, Science Breaker, COSUST* and *Coral.* The article in *The Conversation* on the research in **3.6** was republished by 15 outlets (>89,000 confirmed reads) and shared by 10,600 Facebook users and 141 times on Twitter [**5.10**].

5. Sources to corroborate the impact

5.1 Corroborating statement from the Head of Technical Development, Tropical Marine Centre.
5.2 Marker protein licence issued to EMD Millipore via a 'Tangible Materials License Agreement'.
5.3 Corroborating statement from the Secretary of the International Coral Reef Society.
5.4 Corroborating statement from the Environment Agency Abu Dhabi.
5.5 Impact evaluation report for CRL's educational programmes and public events.
5.6 Impact evaluation report for the *Royal Society Summer Science* Exhibition, July 2017.
5.7 Impact evaluation report for the XL Catlin Ocean Academy Teacher training.
5.8 Details of the training workshop for artists, further artistic collaboration and resulting exhibition.
5.9 Corroborating statement from the producer of Attenborough's Life in Colour (BBC/Netflix).
5.10 Summary report of invited interviews, articles & reach of media engagement.