Institution: University of Exeter		
Unit of Assessment: UoA 14 Geography and Environmental Studies		
Title of case study: *ReefBudget*: a new global coral reef monitoring tool to support reef conservation and management.		
Period when the underpinning research was undertaken: 2008 onwards		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g., job title):**	**Period(s) employed by submitting HEI:**
Professor Chris Perry	Professor in Tropical Coastal Geoscience	Since Sept 2011
Period when the claimed impact occurred: 2014 to 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

The carbonate budget of a coral reef (defined as the balance between calcium carbonate production and erosion) is now recognised as a critical metric for quantifying the physical resilience of reef structures. This is important because reef structural resilience and growth potential determines reef capacity to sustain all key ecosystem functions (e.g., coastal protection, fisheries productivity). The global-scale application of carbonate budgets to guide management and conservation interventions has, however, been limited by a lack of standardized approaches.

ReefBudget is an open access tool, developed by Prof Chris Perry to address this challenge, and is the **only operational tool supporting budget quantification** in a way **that directly integrates with existing ecological monitoring programmes**. Since 2014, *ReefBudget* has had global impact through its **adoption by multiple national conservation and management organisations**, whose monitoring encompasses sites across four of the six global marine biogeographical realms in which reefs occur.

Adoption of the method has **changed operational practice in the monitoring programmes of major reef conservation agencies** globally and is supporting the management and conservation of 'at-risk' natural environments worldwide.

2. Underpinning research

A central aim of coral reef conservation and management is to implement strategies to sustain habitat diversity and ecosystem service provisioning. Past reef monitoring methods which focused on species cover and diversity, although relevant for assessing reef health, do not deliver data that can underpin assessments of reef structural resilience and growth potential, metrics critical for predicting how reefs, and the ecosystem services they provide, will be affected by global change. To address this, standardised methodologies for measuring reef carbonate budgets states in a way that can be integrated with existing ecological monitoring approaches were needed, a vision that guided the development of *ReefBudget*.

2.1 2008-2013: Conceptual development of *ReefBudget* and initial applications

The underpinning research on reef carbonate budgets has taken place since 2008. Both conceptual and empirical in nature, this included work setting out a framework within which to view the changing dynamics of reef carbonate budgets associated with changing environmental and climatic conditions. This work underpinned a 2009 *Leverhulme Trust International Network* grant led by Perry at MMU which he continued after arriving at Exeter. It had the specific aim of developing a new, open access methodology to support standardized ways of quantifying reef carbonate budget states [**3.1**], but which could be readily integrated with established ecological monitoring methodologies. With an initial focus on the Caribbean region, field testing and workshops supported the development of the resultant census-based methodology *ReefBudget* [**3.2**]. Associated field campaigns then employed this method at sites across the Caribbean, leading to highly cited work that

quantified the impacts of sustained ecological decline on coral reef growth, and changes in rates of coral carbonate production [**3.3**].

2.2 2013-2016: Expanding the geographic scope of *ReefBudget*

Following the development of these methods in the Caribbean, and with the aim of extending the methodology to the more ecologically diverse Indo-Pacific region, a revised version of *ReefBudget* was developed through funding under the *ESPA-SPACES* programme (2014-2017). With initial applications at sites in East Africa and the Seychelles, the methodology was then used to quantify the severe impacts of the 2016 coral-bleaching event in the Maldives. Perry was awarded a 2015 *Leverhulme Research Fellowship* to develop comparable census-based methodologies to quantify reef sediment production rates, and to apply these to questions around the resilience of low-lying reef islands. This research led to several methodological papers, as well as novel reef system scale studies that showed the critical importance of parrotfish to reef sediment generation in the Maldives [**3.4**].

2.3 2016-present: Applications of *ReefBudget* to spatial and temporal monitoring

Most recently this carbonate budget research has focused on two main areas. In the Caribbean, through the *Newton Fund* (2016 Newton Advanced Fellowship) new collaborative research between Lorenzo Alvarez-Filip (National Autonomous University of Mexico) and Perry facilitated a programme of budget assessments at sites along the length of the Mesoamerican Reef. This has been accompanied by work to revise and update the Caribbean *ReefBudget* methodology, and a regional workshop (June 2019) to provide training to local NGOs and marine park managers in the use of the methodology. Associated work in the Netherlands Antilles demonstrated the strong local negative impacts of anthropogenic influences on reef budget states and growth potential, and identified areas of enhanced coastal vulnerability to sea-level rise [**3.5**]. At the same time, work in the British Indian Ocean Territory of Chagos (under a *Bertarelli Programme in Marine Sciences* grant, 2017-2020) is using the methodology to monitor changes post the 2016 coral-bleaching event. Data from this collective body of research has most recently been used to assess global-scale trends in reef growth potential [**3.6**], which showed that water depths are likely to significantly increase above most reefs by 2100, thus increasing coastal wave energy exposure.

3. References to the research

3.1. **Perry C.T**., Edinger E.N., Kench P.S., Mumby P.J., Murphy G, Steneck, R.S., Smithers S.G. (2012). Estimating rates of biologically driven coral reef framework production and erosion: a new census-based carbonate budget methodology and applications to the reefs of Bonaire. *Coral Reefs,* 31: 853-868. https://doi.org/10.1007/s00338-012-0901-4.

3.2. The open access *ReefBudget* methodology developed by **Perry C.T**., is found here: https://geography.exeter.ac.uk/reefbudget/ - the resource contains copies of the field survey sheets and links to the relevant Excel data entry spreadsheets required to calculate rates of carbonate production and erosion.

3.3. **Perry C.T.**, Murphy G.N., Kench P.S., Smithers S.G., Edinger E.N., Steneck R.S., Mumby P.J. (2013). Caribbean-wide decline in carbonate production threatens coral reef growth. *Nature Communications,* 4: 1402. https://doi.org/10.1038/ncomms2409.

3.4. **Perry C.T.**, Kench P.S, O'Leary M.J., Morgan K.M., Januchowski-Hartley F (2015). Linking reef ecology to island-building: Parrotfish identified as major producers of island-building sediment in the Maldives. *Geology,* 43: 503-506. https://doi.org/10.1130/G36623.1.

3.5. de Bakker D.M., van Duyl F.C., **Perry C.T.**, Meesters E.H. (2019). Extreme spatial heterogeneity in carbonate accretion potential on a Caribbean fringing reef linked to local human disturbance gradients. *Global Change Biology,* 25(12) 4092-4104. https://doi.org/10.1111/gcb.14800.

3.6. Perry C.T., Alvarez-Filip L, Graham N.A.J., Mumby P.J., Wilson S.K., Kench P.S., Manzello P.D., Morgan K.M., & 19 others (2018). Loss of coral reef growth capacity to track future increases in sea-level. *Nature,* 558: 396-400. https://doi.org/10.1038/s41586-018-0194-z .

4. Details of the impact

Reef carbonate budget states have recently been identified as a key metric for predicting reef biodiversity responses to climate change, and for identifying thresholds at which reef structures shift to states of net erosion (Mace et al. 2014 *Global Env Change* 28:289-297), views strongly informed by the empirical research summarised in Section 2. The open access *ReefBudget* methodology developed by Perry was designed specifically to support assessments of these reef budget states, and the primary impact of this research has been the integration of *ReefBudget* into the monitoring programmes of major reef conservation agencies globally (Fig. 1).

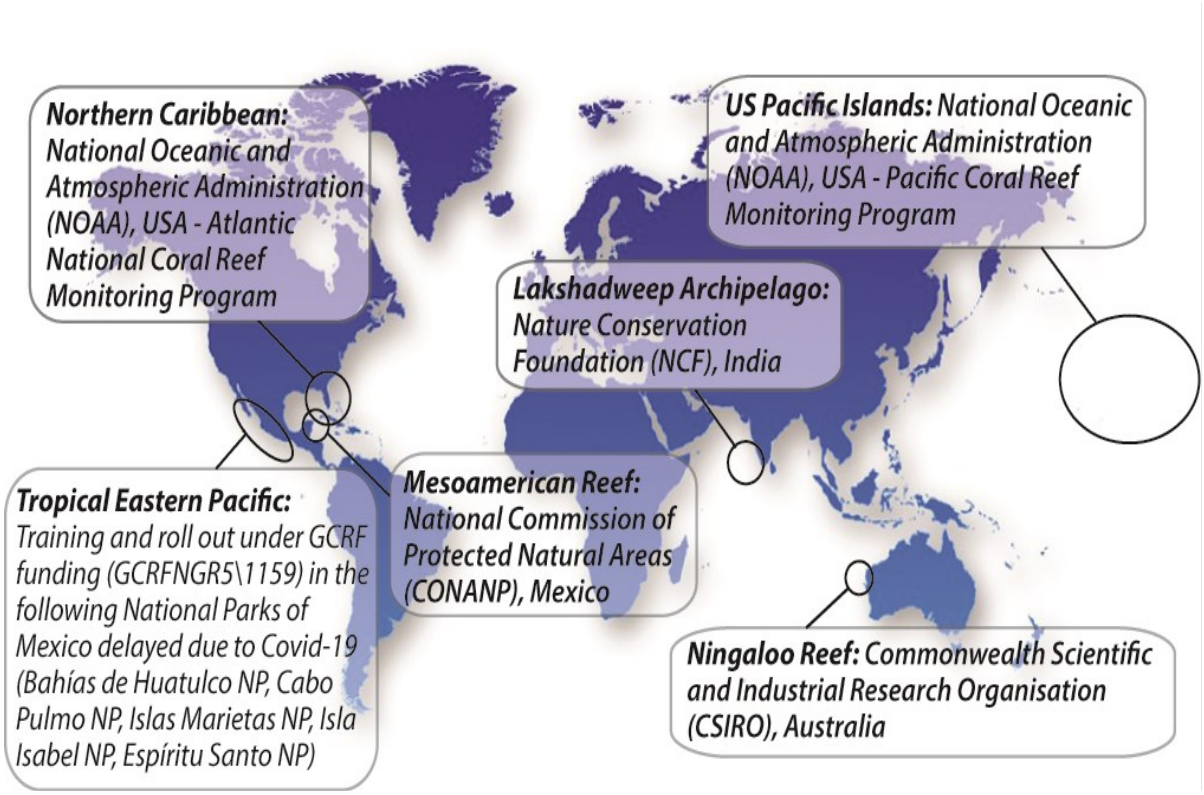

Fig. 1. Global distribution of conservation and management organisations using the ReefBudget methodology.

4.1 Changed operational practice in the monitoring programmes of major reef conservation agencies globally

Since 2014, Perry has engaged directly with these agencies, providing advice and training to support the adoption and integration of *ReefBudget* into their annual and post-disturbance monitoring protocols. This advice has been provided via dedicated in-person training workshops e.g., for Mexican Marine park managers in 2019 [**5.1**], as well as through virtual discussions following approaches from interested agencies [**5.2**] *ReefBudget* is now being used by regional reef management agencies and NGOs working at sites spanning four of the six global biogeographic realms in which coral reefs grow (Fig. 1).

The research outlined in Section 2 and the engagement outlined above has thus led to a change in operational practice by these management and conservation organisations. These organisations have modified their field protocols to integrate the methodology enabling the

acquisition of new data on the physical resilience of reefs under their jurisdiction, and the reefs' response to both local and climate stressors.

The following examples illustrate take up of the method by organisations worldwide:

Tropical Atlantic
Northern Caribbean (Florida, Puerto Rico, US Virgin Islands) through the US National Oceanic and Atmospheric Administration (NOAA) "… *your research has had a very significant impact on how we now assess reef health within our monitoring program. The ReefBudget census-based approach to carbonate budget modelling is vital to our goal of measuring the subtle impacts of ocean acidification relative to more acute stressors like coral bleaching or storm impacts*." (Team Leader for NOAA's Atlantic National Coral Reef Monitoring Program, July 2019) [**5.3**].

Mexican Caribbean through the National Commission of Protected Natural Areas (CONANP) who took the decision in 2020 to use *ReefBudget* "*as an important complementary tool that will support and expand our on-going reef monitoring in the region."* (Director, CONANP, Sept 2020) [**5.4**]. Moreover, the decision was taken because they recognised that with quantitative metrics provided by ReefBudget they would be able measure the success and value of coral restoration efforts at key local protected sites.

Western Indian Ocean
Lakshadweep Archipelago (India) through the Nature Conservation Foundation (NCF), where the methodology is being used within their reef monitoring programme and thus having "*a direct impact upon the reef health and status assessments we make across the Lakshadweep"*. (Programme Head, NCF Oceans & Coasts Programme, Feb 2019) [**5.5**].

Eastern Indo-Pacific
Across the NOAA long-term Pacific Island monitoring sites (main and Northwestern Hawaiian Islands, American Samoa, Marianas Archipelago, Guam, and the Pacific Remote Islands), where *ReefBudget* will now be part of their routine monitoring in the Pacific under the Coral Reef Conservation Program: "*ReefBudget data will make important contributions to addressing many of our regional management needs. Specifically, our federal, state, and jurisdictional management partners from the National Marine Sanctuary of American Sāmoa, Pacific Remote Islands Marine National Monument, Papahānaumokuākea Marine National Monument, the State of Hawai`i Department of Aquatic Resources, and the Saipan Division of Coastal Resources Management have expressed strong support for the collection of these data and interest in including the results in their future management planning."* (Ocean and Climate Change Team, NOAA's Pacific National Coral Reef Monitoring Program) [5.6**].**

4.2 Supporting the management and conservation of 'at-risk' natural environments worldwide

The following examples show how the resultant datasets are now being used by these agencies in formal reef status reporting protocols, directly supporting the management and conservation of these "at risk" environments in the following ways:

Guiding management planning
The Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia noted that within their major programme of reef site assessments at over 70 locations within the world heritage-listed Ningaloo Reef: *"the online ReefBudget methodology provides us with an invaluable tool to start linking ecological state and state change data to the physical functionality of reefs, and thus to feed such metrics into local management action plans. It is of immense value to us as a tool for advancing coastal vulnerability and planning actions"* (Lead Scientist Ningaloo Outlook Shallow Reefs Programme, CSIRO, March 2017) [**5.7**].

Identifying specific management interventions to enhance reef growth potential
NOAA, USA *"… [ReefBudget results] are incorporated into a Report Card presented to the United States Congress every four years on the status and trends of US coral reef health"* (Team Leader for NOAA's Atlantic National Coral Reef Monitoring Program, July 2019) [**5.3**]. Specifically, the latest (2020) NOAA status reports now include assessments of reef growth potential based directly on *ReefBudget* data, and which have graded this metric at their permanent monitoring sites as: Flower Garden Banks "very good", Florida Keys "critical", Puerto Rico "critical", and US Virgin Islands "impaired" [**5.8**]. Mitigation of pollution and fishing pressures are resultant recommended interventions in the US Virgin Islands, but urgent restoration action is recommended at the "critical" Florida Keys and Puerto Rico sites to restore reef growth potential.

Providing a methodology to assess the effectiveness of reef restoration efforts
Adoption of the ReefBudget tool is noted by the Director, CONANP Mexico as a way of providing them "*with quantitative metrics by which we can measure the success and value of coral restoration efforts in which we have participated at key local protected sites*" [**5.4**]. Using *ReefBudget* metrics is seen to enable managers to make informed decisions around, for example, reef restoration expansion programmes and which stakeholders may access sensitive sites: "W*e consider that these are critical for various Marine Protected Areas to evaluate and replicate the benefits of expanding current restoration efforts and protecting existing restoration schemes from the entry of tourists to these sites*." [**5.4**].

The *ReefBudget* methodology has been integrated into the monitoring programmes of major reef conservation agencies at sites across the world. This change in operational practice – supported by direct engagement, advice and training in using the *ReefBudget* methodology – is guiding management planning, informing intervention recommendations to enhance reef growth potential, and underpinning assessments of reef restoration efforts.

5. Sources to corroborate the impact

5.1. Copies of training workshop feedback from Mexican Marine Park Managers, 4-7 June 2019.

5.2. Copies of email exchange on *ReefBudget* use and adoption between Prof. Perry and Trustee and Programme Head, Oceans and Coasts Programme, Nature Conservation Foundation, India. July 2018.

5.3. Letter from the Team Leader, Acidification, Climate, and Coral Reef Ecosystems Team (ACCRETE), Atlantic Oceanographic and Meteorological Laboratory, US National Oceanic and Atmospheric Administration (NOAA). Caribbean, USA. 8 July 2019.

5.4. Letter from the Director the Mexican federal agency Comisión Nacional de Áreas Naturales Protegidas (CONANP, National Commission of Protected Natural Areas), Mexico. [Spanish language]. 28 September 2020.

5.5. Letter from Trustee and Programme Head, Oceans and Coasts Programme, Nature Conservation Foundation, India. 25 February 2019.

5.6. Letter from Coral Reef Ecosystem Oceanographer, Ocean and Climate Change Team Lead, US National Oceanic and Atmospheric Administration (NOAA), Pacific Islands Fisheries Science Center, USA. 20 July 2020.

5.7. Letter from Lead Scientist, Ningaloo Outlook Shallow Reefs Programme, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia

5.8. US National Coral Reef Monitoring Program – 2020 Status Report. Formal status reports downloadable from here: https://www.coris.noaa.gov/monitoring/status_report/