ACTIVE CORAL RESTORATION

Techniques for a Changing Planet

Edited by David E. Vaughan, PhD

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Thank you to Lisa Carne, Executive Director and Founder of Fragments of Hope, Ltd., for the photos on the front cover. The top photo is from October 2011 and shows degraded reef rubble with the first coral outplants of *Acropora palmata*, elkhorn coral, at sub-site #13 in Laughing Caye National Park, Belize. The bottom photo is of the same site in May 2016. Through active coral restoration, conducted by Fragments of Hope, this reef was successfully restored to a functional reef teeming with fish and invertebrates in just six years. Our gratitude to Lisa and her colleagues for sharing these photos, for telling their story in Chapter 11 of this book, and for their continued dedication to coral reef restoration.

Direct all inquiries to J. Ross Publishing, Inc., 151 N. Nob Hill Rd., Suite 476, Plantation, FL 33324.

Phone: (954) 727-9333
Fax: (561) 892-0700
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In memory of Dr. Ruth Gates, whose energy, enthusiasm, and dedication to the study and conservation of coral reefs has been a true inspiration—one that will lead us forward well into the future.

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FOREWORD

Philippe Cousteau Jr.

"If there is a *Garden of Eden* on earth . . . this must be it," I thought to myself as I stared in awe at the spectacle in front of me. It was a bright summer's day and I was floating in crystal clear water some 40 feet below the surface in front of a coral reef called Shab Rumi, a few hours boat ride off the coast of Sudan in the Red Sea. Every color imaginable could be seen stretching out along the contours of the reef. Fish of every shape and size, from gobies no larger than the head of a pencil to enormous groupers and shimmering reef sharks, darted all around me while enormous sea fans and sponges dotted the landscape—it was one of the most awe-inspiring things I had ever seen.

Of course, growing up exploring the ocean, I had seen many coral reefs before, but this one was special. Tragically, in just a few short decades, most reefs around the world, from the Caribbean to the Great Barrier Reef, had become a shadow of their former selves. This reef was different, due to its remoteness and the advantage it had by having evolved in such a historically warm body of water—it was thriving. For me, it was the first time I had ever seen a reef that was not ravaged by the effects of climate change, pollution, ocean acidification, destructive fishing, or a combination of all four.

Whenever I think back to that day when I was diving on Shab Rumi more than ten years ago, I am reminded of what's at stake. Though most reefs in the Red Sea are still thriving, that is not the case throughout the rest of the world. Indeed, coral reefs today continue to decline around the world and the critical function they play in maintaining a healthy ocean ecosystem continues to falter. Coral reefs, which cover less than 1% of the world's ocean (an area about the size of the U.S. state of Nevada) support nearly 25% of all known marine species. Their role in protecting shorelines, providing food to hundreds of millions of people, and as a source of important medical breakthroughs is vital not only to the health of the ocean but to the health of humanity as well. Despite all this, we have lost more than 40% of the world's coral reefs and it is estimated that, at the current trajectory, we may lose 90% by the middle of this century.

But there is good news, too, and that is why this book is so important. In the same way that humans are responsible for the destruction of these precious ecosystems, we can also become their saviors. This excellent book, edited by my dear friend Dr. David Vaughan, features both his ground-breaking work, as well as a collection of insights by a *who's who* in the coral restoration world. Starting with the early developers such as Austin Bowden-Kerby in the Caribbean, Buki Rinkevich in the Red Sea, and Ken Nedimyer in Florida and the Caribbean, it also includes many new and upcoming scientists who have forged reputations in their own areas of expertise such as technological innovation, genetics research, and assisted evolution. This clearly and inspiringly laid-out manual is a practical guide for today's practitioner as well as a roadmap for the future.

But, in some ways it is more than an exploration about active coral reef restoration; it is a guide for humanity to remind us that through innovation and determination, we can play an active role in returning the ocean to abundance. I have known Dave for 20 years and I continue to marvel at his dedication, humility, and brilliance. This book is a must-read for anyone interested in the exciting world of active coral reef restoration. This work proves that these *Gardens of Eden* need not be lost and that there is always hope for the future.

ABOUT THE EDITOR

Photo credit: Ian Shive

Dr. David E. Vaughan has held positions in aquaculture research and development for over 30 years. He directed the Aquaculture Division at the Harbor Branch Oceanographic Institution (HBOI) for 17 years, including the design, build, and operation of the 60-acre HBOI Aquaculture Development Park—the world's only completely recirculating center for aquaculture training and demonstration. He is often cited with creating the R&D and scale-up of clam-farming technologies in Florida, and directing the training programs and operations of the nation's largest hatchery to produce clams that are used for the retraining of displaced fisherman. He founded and developed Oceans, Reefs, and Aquariums Inc. (ORA), a large marine ornamental production facility for producing thousands of reef fish as well as hard and soft corals for the aquarium trade. He also worked with Philippe Cousteau at Earth Echo International on international coral reef restoration initiatives.

As Executive Director of the Mote Marine Laboratory Elizabeth Moore Center for Coral Reef Research and Restoration in the Florida Keys for 15 years, he started the Coral Reef Restoration Program. Through this program, he was heralded with being the first to develop the new technology of coral *micro-fragmentation*. Through micro-fragmentation, massive corals grow very quickly to reproductive size, which dramatically improves the rate at which coral reefs can be restored. In 2017, he received the Chicago Field Museum Parker/Gentry Award as *Conservationist of the Year* for his work with coral restoration, and served as an adjunct scientist at the Field Museum of Chicago.

Dr. Vaughan is now Founder and President of Plant a Million Corals Foundation and is actively helping people around the world to use micro-fragmentation as a scalable tool for reef restoration and is designing and building transportable land-based coral nursery systems that can be shipped to locations around the world in order to train others in this *game-changer* technology for restoration. Dave plans to continue sharing his discovered technologies and passion for coral restoration with the aim of fulfilling his goal of planting a million corals before he retires.

CONTRIBUTING AUTHORS

Juan José Alvarado, Centro de Investigación en Ciencias del Mar y Limnología, Universidad de Costa Rica, San José, Costa Rica *and* Escuela de Biología, Universidad de Costa Rica, San José, Costa Rica

Juan Carlos Huitrón Baca, Ancla Marina S.A. de C.V., Cancun, Mexico

Erich Bartels, Mote Marine Laboratory, 24244 Overseas Highway, Summerland Key, FL 33042, USA

Austin Bowden-Kerby, Corals for Conservation, P.O. Box 4649 Samabula, Fiji Islands *and* Teitei Livelihoods Centre, Km 20 Sigatoka Valley Road, Fiji Islands

Daniel Burdeno, Coral Restoration Foundation, 89111 Overseas Hwy, Tavernier, FL 33037, USA

Lisa Carne, Fragments of Hope, Placencia Village, Stann Creek, Belize

Jane Carrick, Rosenstiel School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149, USA

Nathan Cook, Reef Ecologic Pty Ltd, 14 Cleveland Terrace, North Ward, Townsville, QLD Australia 4810

Jorge Cortés, Centro de Investigación en Ciencias del Mar y Limnología, Universidad de Costa Rica, San José, Costa Rica *and* Asociación Raising Coral Costa Rica, San José, Costa Rica

Craig Dahlgren, Perry Institute of Marine Science, 5356 Main St., P.O. Box 435, Rte. 100, Suite 1, Waitsfield, VT 05673, USA

Nicole D. Fogarty, University of North Carolina Wilmington, Center for Marine Science, 5600 Marvin K. Moss Ln., Wilmington, NC 28409, USA

Zac H. Forsman, Coral Conservation Genetics & Restoration, Hawai'i Institute of Marine Biology, University of Hawai'i, Mānoa, Coconut Island, Moku o Lo'e, 46-007 Lilipuna Road, Kāne'ohe, HI 96744, USA

Sarah Frias-Torres, Nature Seychelles, The Centre for Environment & Education, Roche Caiman, Mahe, Republic of Seychelles *and* Vulcan Inc., 505 5th Avenue South, Seattle, WA 98104, USA

Victor Manual Galvan, Fundacion Grupo Puntacana, Puntacana Resort & Club, Punta Cana 23302, Dominican Republic

Johnny Gaskell, Daydream Island Resort and Living Reef, Great Barrier Reef—Whitsundays, QLD 4802 Australia

David Gilliam, Halmos College of Natural Sciences and Oceanography, Nova Southeastern University, 8000 N Ocean Dr., Dania Beach, FL 33004, USA

Elizabeth A. Goergen, Halmos College of Natural Sciences and Oceanography, Nova Southeastern University, 8000 N Ocean Dr., Dania Beach, FL 33004, USA

Jaime González-Cano, National Institute of Fisheries and Aquaculture, Puerto Morelos, 77580, Mexico

Shannon Gore, Association of Reef Keepers, P.O. Box 3252, PMB 2106 Road Town, Tortola British Virgin Islands VG1110, UK

Sean P. Griffin, NOAA Restoration Center, 260 Guard Rd., Aguadilla, PR 00605, USA

Boze Hancock, The Nature Conservancy, C/O URI Graduate School of Oceanography, 215 South Ferry Rd Narragansett, RI 02882, USA

Edwin A. Hernández-Delgado, Sociedad Ambiente Marino, P.O. Box 22158, San Juan, PR 00931, USA

Dalton Hesley, Rosenstiel School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149, USA

Bridget Hickey, Reef Renewal Foundation International, Kaya Gob Nicholas Debrot #85, Kralendijk, Bonaire, Dutch Caribbean

Yael B. Horoszowski-Fridman, National Institute of Oceanography, Tel Shikmona, P.O. Box 8030, Haifa, Israel *and* Department of Evolutionary and Environmental Biology, Faculty of Natural Sciences, University of Haifa, Haifa 31905, Israel

Roberto Ibarra-Navarro, Costa Occidental de Isla Mujeres, Punta Cancún y Punta Nizuc-National Park, CONANP, Mexico

Noel Janetski, Mars, Inc., 6885 Elm St., McLean, VA 22101, USA

Jamal Jompa, Hasanuddin University, 90245 Makassar, Indonesia

Les Kaufman, Department of Biology, Boston University *and* Pardee Center for the Study of the Longer-Range Future, 67 Bay State Road, Boston, MA 02215, USA

Jake Kheel, Fundacion Grupo Puntacana, Puntacana Resort & Club, Punta Cana 23302, Dominican Republic

Taratau Kirata, MFMRD, Line Islands, P.O. T609, Ronton Town, Kiritimati Island, Republic of Kiribati

Joan A. Kleypas, Climate & Global Dynamics, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307-3000, USA *and* Asociación Raising Coral Costa Rica, San José, Costa Rica

Hanna R. Koch, The Elizabeth Moore International Center for Coral Reef Research and Restoration, Mote Marine Laboratory, 24244 Overseas Highway, Summerland Key, FL 33042, USA

Ilsa B. Kuffner, U.S. Geological Survey, St. Petersburg Coastal & Marine Science Center, St. Petersburg, FL 33701, USA

Jessica Levy, Coral Restoration Foundation, 89111 Overseas Hwy, Tavernier, FL 33037, USA

Kemit-Amon F. Lewis, Formerly of The Nature Conservancy, Post Office Box 531, Frederiksted, Virgin Islands 00841, USA

Diego Lirman, Rosenstiel School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149, USA

Shelby Luce, Mote Marine Laboratory, 24244 Overseas Highway, Summerland Key, FL 33042, USA

Caitlin Lustic, The Nature Conservancy, Florida Keys Office, 127 Industrial Rd., Ste D, Big Pine Key, FL 33043, USA

José Andrés Marín-Moraga, Asociación Raising Coral Costa Rica, San José, Costa Rica

Frank Mars, Mars, Inc., 6885 Elm St., McLean, VA 22101, USA

Kerry E. Maxwell, FWC FWRI, 2796 Overseas Highway, Marathon, FL 33050, USA

Alicia McArdle, Mars, Inc., 6885 Elm St., McLean, VA 22101, USA

Samantha Mercado, Grupo Puntacana Foundation, Punta Cana Resort & Club, Punta Cana, 23302, Dominican Republic

Margaret Miller, Secore International, 2103 Coral Way, 2nd Floor, Miami FL 33145, USA

Phanor Montoya-Maya, Nature Seychelles, The Centre for Environment & Education, Roche Caiman, Mahe, Republic of Seychelles *and* Corales de Paz, Calle 4 No. 35A-51, Cali, Colombia

Tom Moore, National Oceanic and Atmospheric Administration, Restoration Center, St. Petersburg, FL 33701, USA

Ken Nedimyer, Nedimyer Reef Consulting, LLC, 212 Silver Palm Ave, Tavernier, FL 33070, USA

Michael I. Nemeth, ERT Inc., 260 Guard Rd., Aguadilla, PR 00605, USA

Claudia Padilla-Souza, National Institute of Fisheries and Aquaculture, Puerto Morelos 77580, Mexico

Christopher Page, The Elizabeth Moore International Center for Coral Reef Research and Restoration, Mote Marine Laboratory, 24244 Overseas Highway, Summerland Key, FL 33042, USA

Saipul Rapi, Mars, Inc., 6885 Elm St., McLean, VA 22101, USA

Claude Reveret, Nature Seychelles, The Centre for Environment & Education, Roche Caiman, Mahe Republic of Seychelles *and* CREOCEAN, Zone Technocean, Chef de Baie, Rue Charles Tellier, 17000 La Rochelle, France

Buki Rinkevich, National Institute of Oceanography, Tel Shikmona, P.O. Box 8030, Haifa, Israel

Laurence Romeo, Just World Partnerships, 117 Randolph Avenue, London, W9 1DN, UK

Claudia P. Ruiz-Diaz, Sociedad Ambiente Marino, P.O. Box 22158, San Juan, PR 00931, USA

Stephanie Schopmeyer, Fish and Wildlife Research Institute, Florida Fish and Wildlife Conservation Commission, 100 8th Ave SE, St. Petersburg, FL 33701, USA

Nirmal J. Shah, Nature Seychelles, The Centre for Environment & Education, Roche Caiman, Mahe Republic of Seychelles

Adam Smith, Reef Ecologic Pty Ltd, 14 Cleveland Terrace, North Ward, Townsville, QLD 4810, Australia *and* 1 James Cook Drive, James Cook University, Townsville, QLD 4811, Australia

David J. Smith, Mars, Inc., 6885 Elm St., McLean, VA 22101, USA *and* Coral Reef Research Unit, School of Life Sciences, University of Essex, Colchester, Essex, CO3 4SQ, UK

Samuel E. Suleiman-Ramos, Sociedad Ambiente Marino, P.O. Box 22158, San Juan, PR 00931, USA

Álvaro Teran, Asociación Raising Coral Costa Rica, San José, Costa Rica

Carlos Toledo-Hernández, Sociedad Ambiente Marino, P.O. Box 22158, San Juan, PR 00931, USA

Maya A. Trotz, College of Engineering, Department of Civil and Environmental Engineering, University of South Florida, 4202 E Fowler Avenue, ENG 030, Tampa, FL 33620, USA

Jos van Oostrum, Mars, Inc., 6885 Elm St., McLean, VA 22101, USA

Tali Vardi, ECS for National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Office of Science & Technology, Silver Spring, MD 20910, USA

David E. Vaughan, Plant a Million Corals Foundation, 24215 Caribbean Drive, Summerland Key, FL 33042, USA

Tatiana Villalobos-Cubero, Asociación Raising Coral Costa Rica, San José, Costa Rica

Francesca Virdis, Reef Renewal Foundation International, Kaya Gob Nicholas Debrot #85, Kralendijk, Bonaire, Dutch Caribbean

Cory S. Walter, Mote Marine Laboratory, 24244 Overseas Highway, Summerland Key, FL 33042, USA

Dana E. Williams, University of Miami Rosenstiel School of Marine and Atmospheric Sciences, Cooperative Institute for Marine and Atmospheric Studies, 4600 Rickenbacker Causeway, Key Biscayne, FL 33149, USA

Susan Williams, Bodega Marine Laboratory and Department of Evolution and Ecology, University of California—Davis, P.O. Box 247, Bodega Bay, CA 94923-2047, USA

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We are living in an era where many have witnessed the rapid decline of coral reefs around the world. The before and after pictures of our favorite dive sites in the last few decades reveal startling photographic evidence that cannot be ignored. The realization that mankind has adversely impacted our oceans has led many to despair. Hope is not gone, however, because scientists and practitioners are continuing to move forward in addressing climate change and, at the same time, developing techniques and strategies to restore our coral reefs in what is now called *active coral restoration*. These practices will allow us to transition to large-scale culture coral production, using naturally resistant coral strains to restore the reefs. Scientists and practitioners have been working for years to get us to this point, and I am very pleased that many of them have contributed to this first comprehensive book on the subject. It is a valiant effort and there are many to thank. To the authors who have shared their experience and knowledge in chapters that will help the next level of coral restoration efforts take a *giant step* for mankind, you have my sincere gratitude. For those who shared their real-life experiences in case studies from around the world, I applaud you. I am humbled to be a part of this collection of *who's who* in active coral restoration, and I am thankful to all who generously gave their time to help bring this very important text to life. To my dedicated family, Donna and Dee Dee, who have joined me in this effort, I am forever grateful. Lastly, to Gwen Eyeington of J. Ross Publishing, who has been our guide to direct us along, I am indebted.

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Downloads for *Active Coral Restoration: Techniques for a Changing Planet* include data sheets from the book in Excel format for record keeping.

SECTION I

Overview

1

INTRODUCTION

David E. Vaughan

People around the world are becoming more aware of the decline in the quality and quantity of natural resources and the impact this has on local and global ecosystem function, public health, and portions of the economy. Most are aware that these declining conditions also plague our oceans and affect all sizes of marine life, from the dinoflagellate to the blue whale. In this book, our focus is on coral reefs because they are the building blocks for the marine life in our oceans. Unfortunately, many of our coral reef systems have been degraded to such a point that we only have photos to remind us of what once existed. These photos that show how beautiful and diverse the coral reefs once were, are a dramatic reminder that we need to be proactive, right now, to save our oceans, and in turn—ourselves.

Coral reefs and their inhabitants are beloved by many due to their sheer beauty, which has been made known to the public through early television shows like “The Undersea World of Jacques Cousteau,” published pieces in magazines like *National Geographic*, marine parks with spectacular aquariums, and current shows such as “Chasing Coral” on Netflix. Unfortunately, coral reefs have been in decline over the past few decades and are now a shadow of what they once were. Climate change from carbon emissions and other stressors such as habitat loss, overfishing (including dynamite fishing), nutrient runoff, plastics, and other pollution have caused disease, decline, and death in coral reefs around the world. These stressors are avoidable if mankind would refrain from the unrestrained consumption of natural resources and the excessive burning of fossil fuels. Losing half of the world’s coral cover since 1970 (Intergovernmental Panel on Climate Change 2018) is a stark reminder that we must address these stressors, but this will take time. In the interim, we need new technologies to actively restore corals right now.

Restoration efforts on land first focused on the protection of natural areas from threats and stressors and then allowed nature to make a slow comeback on its own—essentially an *unassisted recovery*. For restoration of forests (reforestation), active methods are regularly used to cultivate and plant trees in order to return the area to a fully functioning forest more quickly than would occur if unassisted. Today, terrestrial and aquatic ecosystems can be restored through hydrologic alteration, invasive species removal, replanting of native species, pollution control, and so forth. Early efforts in coral reef restoration focused on repair and restoration of reefs from ship groundings, anchor damage, and other anthropogenic impacts that can be traced to a responsible party who would then be required to pay fines to support the recovery of the damage (Precht 2005). In many cases, the project only stabilized the reef structure itself while leaving natural biological recovery to occur over time. Over the last two decades, scientists, conservationists, and decision-making authorities have opted for *active coral restoration* tools, where unassisted recovery has failed to achieve the targeted goals. What initially started as *coral gardening* projects (Chapter 3) are now scaled to production projects where cultured corals are outplanted back onto the reef (Chapters 4 and 5). My passion and dedication to the restoration of coral reefs intensified throughout my unique career history that was both circuitous, fortuitous, and at times seemed divinely guided.

In 1966, I was privileged to be part of a science expedition to the Virgin Islands to sample corals in the area for the future West Indies Marine Lab in St. Croix. My job was to use a hammer to break off pieces of beautiful live corals to send back in formalin jars to the main laboratory at Fairleigh Dickinson University in New Jersey. Today, this practice would never be allowed due to the global decline in coral. Little did I know then, that many years later, I would be growing coral reef species. First, for the aquarium trade that started from a research project at Harbor Branch Oceanographic Institute (HBOI), which evolved into a new program and company called ORA (Oceans, Reefs and Aquariums); later, for the reef itself at Mote Tropical Research Laboratory; and now through the Plant a Million Corals Foundation.

During my early career at HBOI and through my projects at ORA, I grew a diversity of marine species including: clams, oysters, fish, shrimp, and ornamental corals using new large-scale sustainable recirculating technologies. In the year 2000, the success of the ORA project demonstrated that it was possible to produce both thousands of clownfish and over a hundred thousand hard and soft corals for the aquarium trade (so they did not need to be taken from the wild, predominantly the Pacific Ocean). On one occasion, Philippe and Alexandra Cousteau (grandchildren of Jacques Cousteau) were touring the facilities and said, "Dave, why aren't you growing corals for the reef?" We agreed to work together in this direction and our first effort was to start a new program within the Philippe Cousteau Foundation called the "International Coral Restoration Initiative" (CRI). In addition to my volunteer work with the CRI, I accepted a position at the Mote Tropical Research Laboratory in the Florida Keys (what is now the Elizabeth Moore International Center for Coral Reef Restoration and Research) as the Executive Director of the lab and manager of the Coral Reef Restoration Program. My entry back into the world of corals and reef systems hit me like a rock. The annual updates from reef monitoring efforts showed substantially less coral cover each year, more frequent bleaching events and increases in disease occurrences, which collectively made me feel like there was very little hope for these creatures. This catalyzed me to think about how to tailor the large-scale aquaculture technologies that I had used in the past, to improve coral reefs. My work with aquaculture system designs and the scaling up of the production of marine organisms would give me quite an advantage for producing and scaling up the growth of corals for reef restoration efforts.

During my tenure at Mote, I also managed the Coral Reef Restoration Program where we were starting to grow some of the massive species of corals into culture and from sexual reproduction. While trying to transfer a fragile three-year-old Elkhorn colony, I accidently broke it into several small pieces. This Elkhorn colony was one of the first ever cultured from sexual reproduction (test tube corals) and raised in the laboratory. What started as an accident, however, turned out to be what the *New York Times* called my "Eureka Mistake" in an article they ran in 2014 (https://www.nytimes.com/2014/11/25/science/a-lifesaving-transplant-for-coral-reefs.html). The breaking of this coral into tiny pieces or *fragments* stimulated them to grow faster than normal and was the foundation of a game-changing technology now termed *micro-fragmentation* (Chapter 6). Micro-fragmentation is a fast way to produce large numbers of smaller coral colonies that are suitable for outplanting onto restoration sites more quickly than we ever thought possible for the massive *reef-building* species. Furthermore, when these fragments from the same colony (clones) reach the size that is appropriate to be outplanted and are then planted near each other, they fuse back together again (Chapter 7). This "Eureka Mistake" led to the technologies of micro-fragmentation and fusion (or *re-skinning*), which are now two incredibly valuable tools for active coral restoration because they dramatically reduce the time it takes to grow the corals while also increasing the numbers of corals grown for use in restoration efforts. In late 2018, I retired from the Mote Tropical Research Laboratory and started my own foundation, Plant a Million Corals. I vowed, as in the frequently viewed AARP video (https://youtu.be/_0F5cQfke64), that "I would not retire until I planted a million corals."

While micro-fragmentation allows us to grow corals faster than ever thought possible, they still need to survive the environmental stressors once they are outplanted. Consequently, we need to culture sufficient numbers of corals that can survive these stressors through both asexual and sexual reproduction (Chapter 8). The selection for diverse genotypes that can better withstand the increases in water temperature and ocean acidification that is caused by global warming is paramount (Chapters 9 and 10). Observations of all the parameters of survival, such as resistance and resiliency, for the whole biome community must be the science that drives restoration—as well as emerging technologies and engineering that can scale it to make economic sense (Chapters 22 and 23). There are numerous scientists and leaders in the field who have also made big contributions in their areas of expertise (Chapter 2)—and they all agreed that the time is now to bring all of the information together into the first comprehensive volume on active coral restoration. Our collective work, energy, and passion for the coral reefs of the world is what inspired me to move forward as editor of this book.

This volume is divided into four sections. Section I: *Overview*—provides important foundational information on the history and evolution of active coral reef restoration. Section II: *Biological Considerations and Methodologies*—is complete with five chapters that provide in-depth discussion of current methodologies for the development of land and field nurseries, sexual and asexual coral propagation in the laboratory setting, coral fusion, and genetic selection for resistance and resilience. Section III: *Case Studies from Around the World*—provides eleven case studies that illustrate what has been successful and lessons learned of what has not. Section IV: *The Future of Coral Reef Restoration*—discusses emerging technologies in the field of active coral restoration and what we should look forward to in the years to come. As the editor, it was my absolute pleasure to collaborate with the dedicated scientists and practitioners who worked tirelessly—many in remote areas—to develop the technologies and manage the restoration projects that are discussed in this book. My hope is that this volume will inspire generations to come to continue the practice of active coral restoration and hope well into the future.

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2

HISTORY OF REEF RESTORATION

Adam Smith, Boze Hancock, Nathan Cook, and David E. Vaughan

ABSTRACT

This chapter collates historical information about the people and organizations who have contributed to active reef restoration over the past 40 years. We include indigenous people, scientists, managers, communicators, educators, and businesses. We also present results from a global literature review of reef restoration that covers 52 countries, with the majority of projects conducted in the United States, the Philippines, Thailand, and Indonesia (together representing 40% of projects). Coral restoration case studies are dominated by short-term projects, with 58% of all projects reporting less than 18 months of monitoring of the restored sites. Overall, 75% of the coral restoration projects focused primarily on fast-growing branching corals, 28% involved the coral genus *Acropora*, while 9% of studies included a single species—*Acropora cervicornis*. Overall, direct transplantation studies reported an average of 51% survival, with 20% reporting >90% survival of transplanted corals.

It is difficult to measure the number of people and organizations that are interested and involved in active coral reef restoration. In this chapter we shine the light on 20 individuals who have pioneered and contributed to global reef restoration. We make three recommendations to improve the history of reef restoration: (1) develop and maintain a global database of reef restoration knowledge, people, and projects; (2) develop and deliver a global reef restoration training and education program to one million people by 2025; and (3) identify 100 global priority reef restoration demonstration locations.

INTRODUCTION

The history of reef restoration has rarely been written, with the exception of Singapore (Chin Soon et al. 2017) and Japan (Omori 2010). We have conducted global reviews of scientific literature and practitioners that highlight major developments in the science and methods of those involved in reef restoration. The purpose of this chapter is to share the collective knowledge of a community of scientists and restoration practitioners who have been working both independently and collaboratively to restore populations of corals throughout the world. By sharing lessons learned from the people, organizations, and projects over approximately 40 years of experience of coral propagation and coral transplantation, we want to increase the success of others' efforts and accelerate conservation and restoration on a global scale.

CORAL REEFS

A coral reef is an underwater ecosystem that is characterized by reef-building corals. Reefs are formed of colonies of coral polyps held together by calcium carbonate. When alive, corals are colonies of small animals called polyps, arranged in diverse shapes. Reef-building or hermatypic corals live only in the photic zone (above 50 m), the depth to which sufficient sunlight penetrates the water. It takes approximately 10 thousand years for coral polyps to form a reef, and between 100 thousand and 30 million years for a fully mature reef to form.

Coral reefs occupy a small percentage (less than 0.1%) of the world's oceans, but they contain a disproportionately high share of its biodiversity. Coral reefs are vital for food, tourism, coastal protection, and many other ecosystem services.

Coral reefs are fragile, partly because they are sensitive to water conditions. Coral can survive short-term disturbances, but if the conditions that lead to the expulsion of the symbiotic algae (zooxanthellae) persist, the coral can die within a period of one day to two or three weeks. Mass mortality of coral reefs has increased in frequency throughout the world due to global warming, coastal development, declining water quality, and destructive fishing.

CORAL RESTORATION

Coral restoration is a term that is commonly used by scientists. Coral restoration is closely allied with (and often used interchangeably with) reef restoration, rehabilitation, remediation, transplantation, recovery, and intervention. In the United States and Australia, the terms remediation and intervention are more commonly employed in industry, the development of public policy, and the civil services. Coral farming, gardening, and coral nursery are often used by practitioners, divers, and the tourism industry.

In this chapter the authors consider coral reef restoration in a broad sense and include both active manipulation of reef building corals as well as activities designed to raise the profile and awareness of restoration and generate the social license needed to conduct active restoration.

The history of coral restoration can be categorized into distinct phases, which can be described as the addition of species and habitats or the removal of species (Figure 2.1). Early scientific pilot scale projects in the 1970s and 80s focused on methodology. Projects in the 2000s began to focus on increasing densities of endangered Caribbean corals and fast-growing staghorn corals. In the 2010s the global decline in coral reef health from climate change, cyclones, and coastal development resulted in great prioritization, communication, and action of coral reef restoration throughout the Caribbean, Pacific, and Indian Oceans including methods to *scale-up* coral restoration. Coral restoration has primarily focused on ecological aims such as coral growth and survivorship; however, more recently, social, economic, technological, and political outcomes have been seen as important factors.

Documenting the history of reef restoration is important because it allows us to understand our past and be more informed to take action in the future. We have approached this chapter by looking at key groups of active coral reef restorers: indigenous, scientists, managers, communicators, and educators. We have also provided our opinions on the leading individuals and organizations that have contributed to coral reef restoration (Table 2.1, Figure 2.2). The great men, women, and organizations in our history were innovators who were curious, responded

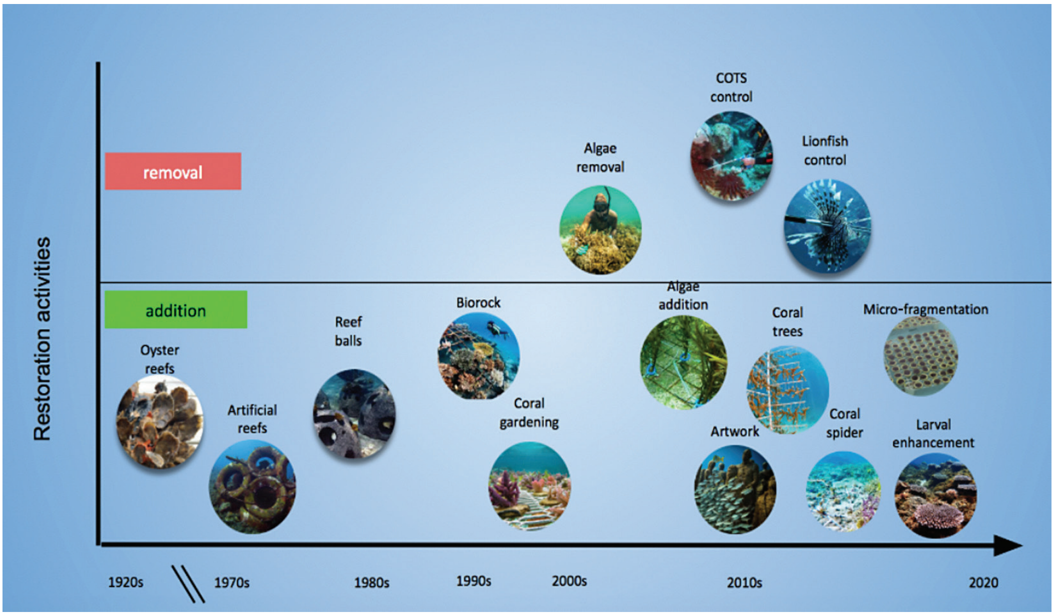

Figure 2.1 Chronology of the methods of reef restoration (Smith et al. 2018).

Table 2.1 Chronology of individuals and organizations and their contribution to coral reef restoration

Date	Name	Contribution
1979	Tom Goreau and Wolf Hilbertz	Biorock
1980s	Eduardo Gomez	Philippines coral and clam restoration
1984	National Oceanic Atmospheric Administration	Hawaii coral conservation lab
1987	Austin Bowden-Kerby	Coral farming
1988	Vicki Harriot and David Fisk	Coral transplantation—GBR
1990s	Chou Loke Ming	Coral restoration—Singapore
1993	Todd Barber	Reef Balls
1994	Baruch Rinkevich	Coral gardening—Red Sea
1997	David Lennon	Artificial reefs
2002	Ken Nedimyer	Coral Restoration Foundation
2003	Reef Resilience Network	Training
2006	Jason deCaires Taylor	Underwater sculptures
2006	Bill Precht	*Coral Reef Restoration Handbook*
2007	Mars Inc	Coral spiders—Indonesia
2009	ARRA Acropora coalition	NOAA, TNC, Mote, CRF
2010	Alasdair Edwards	*Reef Rehabilitation Manual*
2010	Margaret Miller	Sexual reproduction in coral

Continued

Date	Name	Contribution
2010	David Vaughan	Micro-fragmentation, Mote Marine Lab, FL
2011	Johnson et al.	Caribbean *Acropora* restoration guide: best practices for propagation and population enhancement
2011	Peter Harrison	Larval enhancement
2011	U.S. Navy	Restore reef after Port Royal ship grounding
2013	Lisa Carne	Fragments of Hope registered—Belize
2015	SECORE	Tetrapods—spawning coral restoration project
2016	Coral Restoration Consortium	Foster collaboration
2017	The Nature Conservancy	Caribbean Coral Hubs
2017	Great Barrier Reef Marine Park Authority	Reef Resilience Blueprint
2017	Australian Institute of Marine Science	Reef Restoration and Adaptation Program
2017	Ruth Gates	Assisted evolution of corals—Hawaii
2017	Mexican Government	Goal of 260,000 corals planted by 2022
2017	Reef Restoration Foundation	First coral nursery in the Great Barrier Reef
2018	Australian Government	Reef Restoration and Adaptation Program
2018	Reef Ecologic	Coral gardening—Great Barrier Reef
2018	Ken Nedimyer	Reef Renewal International—Bonair
2018	Plant a Million Corals Foundation	Assisting ten Caribbean projects and TNC
2018	Coral Restoration Consortium	NOAA assisted working groups
2020	National Environmental Science Programme	Global review of reef restoration

to crises, made mistakes, and shared their knowledge. We acknowledge that our chronology is based on published and unpublished information, but is biased towards English-speaking countries and individuals.

INDIGENOUS PEOPLE AND REEF RESTORATION

There is no published information on reef restoration by indigenous people. The earliest confirmed indigenous planting of coral was the 1940s at Turtle Bay, Cairns (personal communication, Gudjugudju).

SCIENTIFIC PIONEERS OF REEF RESTORATION

In the early 1900s, *hard hat* diving was available for a few individuals to observe the underwater world. The earliest published research on coral transplantation methods was from the 1928–29 Great Barrier Reef Expedition on Low Isles. The scientists used hard hat diving helmets and glass viewers to conduct coral growth experiments. They published a book called *A Year on the Great Barrier Reef 1928–29 the Yonge Expedition*. The invention of the self-contained underwater

Figure 2.2 The pioneers of coral reef restoration. Top row: Tom Goreau, Wolf Hilbertz, Eduardo Gomez, Austin Bowden-Kerby; second row: Vicki Harriot, David Fisk, Todd Barber, Baruch Rinkevich; third row: Ken Nedimyer, David Lennon, Chou Loke Ming, Nathan Cook; fourth row: Bill Precht, Alastair Edwards, David Vaughan, Jason deCaires Taylor; fifth row: Peter Harrison, Frank Mars, Kirstin Marhaver, Ruth Gates.

breathing apparatus (SCUBA) in 1942 and subsequent commercialization of equipment and training opened up access to coral reefs for more people and scientists.

It is challenging to find who was the first modern scientific reef restorer. There were several pioneers in the Caribbean, United States, and Pacific. These pioneers included Tom Goreau and Wolf Hilbertz who patented Biorock®, a method using mineral accretion technology and steel and electricity to increase the rate of calcium carbonate deposition. Tom said, "No one believes what we do is possible until they see it themselves. Growing bright coral reefs that are swarming with fish in a few years in places that were barren deserts is something everybody thinks can't be done—but has been done in nearly 30 countries with only small donations, mostly from local people who remember how their reef used to be and realize they must grow more corals now." The team of Goreau and Hilbertz continued on a path of research and development that spanned over three decades, but ended with the untimely death of Hilbertz in 2007. Further development of the Biorock method continues through the leadership of Goreau as acting president of the Global Coral Reef Alliance.

Dr. Austin Bowden-Kerby (Figure 2.3) is a true pioneer and possibly the most published scientist in reef restoration (Figure 2.4). In his own words, he began:

> *Plugging broken frags into dead corals in the 1980s as it is was a natural no-brainer* (he planted his first corals in the Pacific in Chuuk in 1987). *I was apparently the first person to work on the Caribbean* Acropora *corals—starting in 1993* (he developed and adapted various reef restoration methods including A-frame, steel and wire mesh, cookies, and rope strung between two tables). *As far as methods: plugging broken frags into dead corals I began in the 1980s and the A-frame I developed in 1994 in Puerto Rico for my thesis. The steel frame coral nursery table design I copied from the ICLARM giant clam culture tables of the Solomon Islands, where I traveled for a coral farming workshop in 1997 at Marau Sound. The wire mesh tray was my invention from 1997, tying the corals onto sea shells with fishing line and weaving them into the mesh. This was improved when I learned from Simon Gower, a Solomon Island marine ornamentals trader, that you could make and use concrete discs, but he used solid ones without any eyes and he had not figured out how to keep them from tipping over. He had also used super glue instead of a cable tie or fishing line, so we joined the two ideas and made the first perforated cookies in 1997. The cookies grew in size over the years with my work to accommodate much bigger fragments and to grow a much larger coral before outplanting—that was much the focus of the Fiji work from 2000–2007.* (These turned out to be ideal methods for palmata coral in the Caribbean and the corymobose, digitate, and table form corals of the Pacific). *The rope method—strung between two tables—I copied pretty much from the seaweed farmers of the Philippines. The micro-fragmenting of staghorn tips—I had never called it that, but I had been doing that for some time, since 2005 or so—with multiple very tiny tips from the same mother colony that would otherwise die in the environment being plugged into a wet cement ball. The pegged rope method of outplanting I developed in 2009 for the Belize work. The places presently using these methods are Belize, Dominican Republic, Kiribati, and Fiji, but I have shared the manual with those in Thailand, Malaysia, the Philippines, and Indonesia. The manual was published by Punta Cana Ecological Foundation in Dominican Republic and is from 2014.*

Dr. Baruch Rinkevich is the godfather of reef restoration in the Red Sea. He completed a Science degree between 1972–82 at Tel Aviv University in Israel and a post doctorate at Scripps Institute of Oceanography in California, USA.

In our communication he wrote: *"I am pleased to hear about the reef restoration symposium in Australia and to see the developments in this discipline, something that 2–3 decades ago, was just a dream. It is unfortunate that I'll not attend this meeting, to meet my colleagues from Australia that till 2–3 years ago, many displayed reservations about the option of combining the phrases 'coral reef restoration' and 'Great Barrier Reef (GBR), Australia.'"*

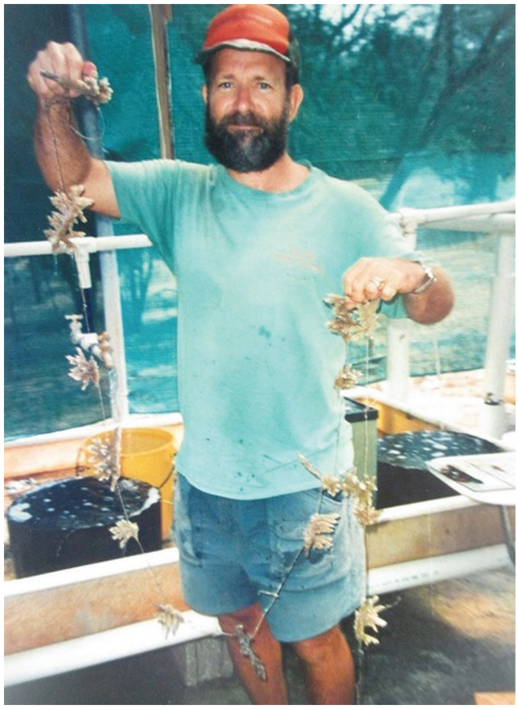

Figure 2.3 Austin Bowden-Kerby with one of his early coral restoration experiments.

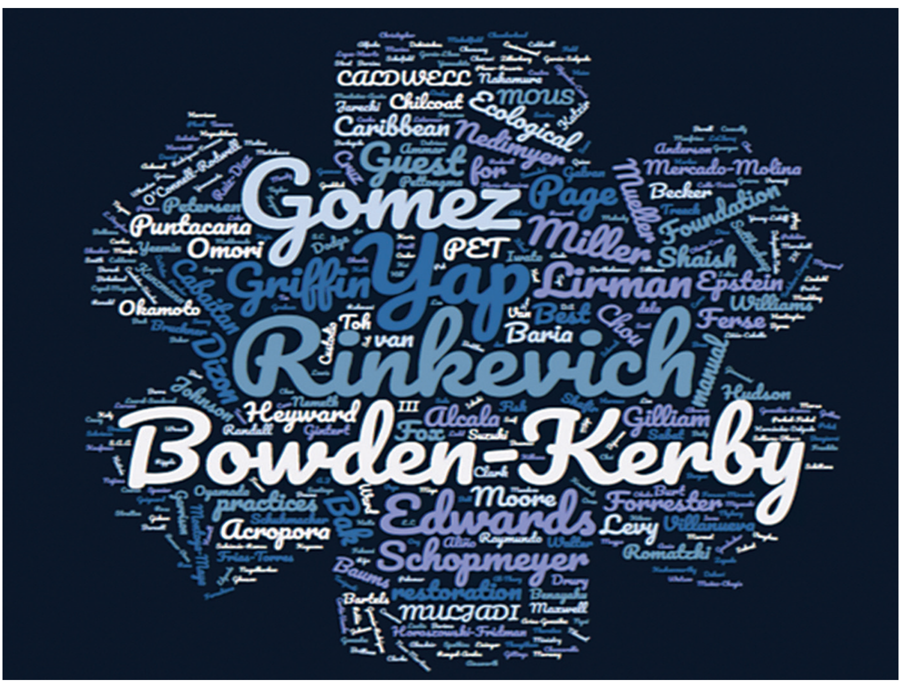

Figure 2.4 A word cloud of the scientists who have contributed to the academic literature on reef restoration (the larger the name the larger the contribution) (Smith et al. 2018).

According to Dr Rinkevich, coral reef restoration was guided by the notion of *gardening*, influenced by the silviculture discipline (forestation). The aims and methodologies were further distinguished between the two major phases in reef restoration: the nursery and the transplantation phases. Much of the literature has been devoted to develop and to support ideas and methodologies for both of these phases (Chapter 3). Dr. Rinkevich wrote:

During the last two decades, the 'gardening notion' as the cutting edge of coral restoration, and other approaches for reef restoration, have surmounted four major obstructions, all are currently satisfactorily deciphered:

(a) Developing the needed credentials for farming a wide variety of coral species (now >100 species) from worldwide-distributed reefs in different types of nurseries
(b) The ability to develop stocks of coral colonies: one of these methods is employing the use of coral 'nubbins' and another approach is growing coral colonies from larvae
(c) Documentation that nursery farmed coral colonies perform well in their 'new homes,' following transplantation
(d) Verification of the low-cost gardening approach (down to 0.17 and 0.19 US$/coral colony for farming and transplantation phases, respectively).

Now, this discipline is facing its fifth challenge—performing a large, ecologically profound, spatially relevant restoration act (hundreds of thousands to millions of coral colonies/site) to reveal the ecological impacts of large-scale transplantation acts. In the last five years we have been facing a new development: the employment of ecological engineering approaches and suggestions for genetic/molecular biology tools.

Ken Nedimyer (Figure 2.5) is the founder and former president of the Coral Restoration Foundation and Director of Reef Renewal International. By 1998, he saw that with climate change and ocean acidification, his Florida reefs were in serious trouble and he started to consider how to expand his live rock aquaculture into growing live coral reefs (Chapter 4). In 2002 he began an offshore coral garden in the Florida Keys. His years of experimentation involved developing better methods and improved coral nursery techniques, training volunteers, and developing effective ways to transplant the corals onto the nearby reefs.

Ken's persistence paid off and led to the formation of the nonprofit Coral Restoration Foundation in 2007 and the development of one of the world's largest offshore coral nurseries. In

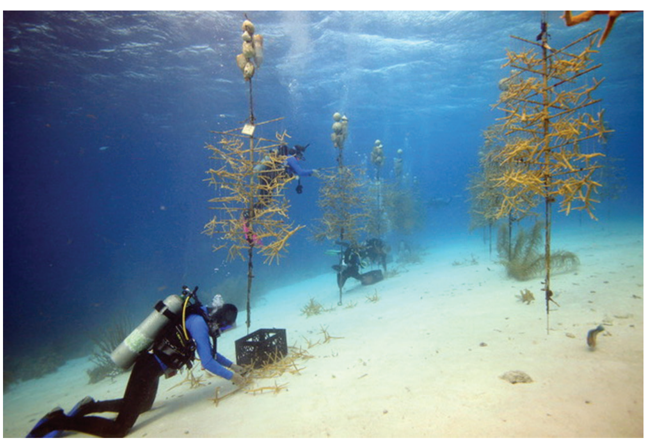

Figure 2.5 Ken Nedimyer working on coral trees in the Caribbean.

2012, Ken began nursery programs in Colombia, South America and Bonaire (Netherlands Antilles) (Chapter 20); those programs are now producing thousands of corals per year that are being transplanted onto their local reefs. In 2014, Ken helped start the Coral Restoration Foundation International, to work on developing coral nursery and restoration programs throughout the Caribbean over the next five years. Ken's story and the results of his work addressing ocean issues have resulted in him being given several prestigious awards, including being named as a 2012 CNN Hero for "Defending the Planet" and SCUBA Diving Magazine's "Sea Hero of the Year."

It is important to recognize that individuals are parts of teams and collaborations. Ken's work was strongly linked with the National Oceanic and Atmospheric Administration (NOAA) and The Nature Conservancy (TNC) through the 2005 TNC-NOAA Community-Based Restoration Program (CRP) Partnership project and the 2009 NOAA American Recovery and Reinvestment Act (ARRA), with funding as part of a coalition of eight restoration interests.

Professor Chou Loke Ming has tested many reef restoration strategies in Singapore's sedimented waters. It started in the 1990s with the Marine Conservation Group of the Nature Society (Singapore) mobilizing over 400 volunteers to shift coral colonies and reef invertebrates. However, the early efforts were largely unsuccessful. Less than 11% of the transplants survived due to the poor choice of recipient site (a shallow area easily overgrown with algae and constantly subjected to surge and heavy sedimentation) as well as improper securing methods (transplanted colonies were only wedged between boulders without the use of adhesives, and were thus easily dislodged by wave action) (Chou and Tun 1997). This episode led to improvements in coral relocation techniques and subsequent mitigation projects. These included the relocation of corals from Labrador Park (for the installation of new power and water cables; Kesava 2007a), Sultan Shoal (for the construction of a mega container terminal; Chew 2014), and Pulau Semakau (for the disposal of incinerated waste; Tan 2015). Transplant survival rates for coral relocation projects are currently an estimated 70–80% (Chew 2014).

Coral restoration in Singapore has necessitated the use of specialized techniques to circumvent the problems of heavy sedimentation and unstable substrates. These strategies include the deployment of artificial substrates known as *reef enhancement units* to increase opportunities for coral recruitment, rearing of coral fragments on nursery frames, and transplantation.

Reef restoration in Thailand has had a long history with a number of key players experimenting with innovative ideas and implementing new projects to progress the marine conservation agenda. Nowhere in Thailand was this testing more active than on the small island of Koh Tao in southern Thailand. In the late 1990s, Thai groups such as the Thai Royal Navy and Khun Jintana, known locally as Queen of the Giant Clams, worked with local businesses to disseminate important knowledge about coral reef ecology and marine conservation in general. Small coral restoration projects including artificial reefs, and the islands first biorock project were implemented in 2005 by local community groups lead by Devrim and Kean Zahir and supported by the local community through the Koh Tao Dive Operators Club.

Since 2006–2007, Chad Scott of New Heaven Reef Conservation Program and Nathan Cook of Eco Koh Tao have implemented and expanded the scale and scope of reef restoration projects, including artificial reefs, coral nurseries, coral gardening, and biorock. Chad Scott, with Dr. James True of Prince of Songkhla University, conducted one of the first larval enhancement experiments on Koh Tao in 2010 and has been continuing reef monitoring while expanding. Many of these projects were conducted in partnership with the Save Koh Tao Community group.

Dr. David Vaughan's history in his own words: *"My career was in aquaculture production research and development and included scaling up hatchery production of clams, oysters, fish,* *shrimp, and marine ornamentals such as the clownfish (Nemo). I scaled up Pacific corals for the aquarium trade as well, under the development of Oceans, Reefs and Aquariums as its founder and president. While showing the grandchildren of Jacques Y. Cousteau around, Philippe mentioned to me that I "missed the point" of culturing corals for the aquarium trade, when I could be growing corals for the reef. In 2000, he and I founded the International Coral Restoration Initiative to do just that. I worked at Mote Marine Lab in the Florida Keys for several years and developed methods for restoration of the massive corals including micro-fragmentation and re-skinning, and now propose to not retire until I plant a million corals through my foundation, Plant a Million Corals!"*

Professor Peter Harrison is the founding Director of the Marine Ecology Research Centre at Southern Cross University. He was one of a consortium of scientists who *discovered* mass coral spawning in the 1980s and is currently leading research into sexual reproduction and larval enhancement of coral reefs with field projects in Australia and the Philippines.

MANAGEMENT SUPPORT FOR CORAL REEF RESTORATION

Management actions for coral reefs may be either in the form of passive or indirect measures, or in the form of active or direct interventions. The former generally involve improving the management of anthropogenic activities that are impeding natural recovery processes, and include many potential tools including legislation, policy, plans, and guidelines. One of the most effective tools for coral reef health is a well-managed marine protected area. Active physical restoration and/or biological restoration interventions may involve coral nurseries, transplantation of corals, and other biota to degraded areas.

There were two historical rationales for management support of reef restoration. The first reason was replacing declining coral reefs in the Asia\Pacific and Red Sea. The second reason, led by the United States, focused on restoring the damage, including both structural damage and the services lost from impacts to coral reefs from events such as ship groundings. The early leader in management of reef restoration was NOAA, which developed legislation in 1973 to protect and restore habitats. The legislation required companies to restore the public resources injured by discrete environmental incidents such as chemical or oil spills, the release of pollutants from an identifiable catastrophic event, or from physical damage to the habitat such as dredging for port expansion or land reclamation (e.g., NOAA 1997). The initial legislation was described in the Comprehensive Environmental Response, Cleanup, and Liability Act (1980) and the Oil Pollution Act (1990). For each incident addressed under such legislation, the damage first needed to be quantified, prior to designing restoration, in order to make the community *whole*. The acts dictate that restoration is undertaken to compensate the public for losses or injuries to natural resources under public ownership and held in trust by government managers, and that restoration includes the services that those natural resources would have provided. This legislation continues to influence the quantification of ecosystem services from multiple habitats, including bivalve habitat, and is being expanded in the U.S. section of the Gulf of Mexico through the *Restore Act* (2012), legislating the response to the Deep Water Horizon oil spill.

In the United States, the U.S. Coral Reef Task Force, established by Presidential Executive Order in 1998, leads U.S. efforts to preserve and protect coral reef ecosystems. The National Coral Reef Action Strategy was developed in 2002 based on the U.S. National Action Plan to Conserve Coral Reefs.

The Australian pioneers of coral transplantation and the links to management were Vicki Harriot and David Fisk. They published *Coral Transplantation as a Reef Management Option* for the Great Barrier Reef Marine Park Authority in 1988.

Edwards & Gomez (2007) concluded that "*there is little that managers can do in the face of the large-scale 'natural' drivers of degradation such as climate-change-related mass bleaching, storms, tsunamis, and disease outbreaks*." Some scientists and manager have recently argued that this message may be overly pessimistic in relation to large-scale drivers such as ocean warming and that the climate resilience of corals may be augmented through assisted evolution (van Oppen et al. 2015). Such innovative management methods represent a major change to our thinking about and approach to coral reef restoration (i.e., a shifting paradigm) and would increase the probability of survival of corals used for restoring degraded reefs.

In 2017, as a response to unprecedented coral bleaching and mass mortality, the Great Barrier Reef Marine Park Authority (GBRMPA) held a summit and published the GBRMPA Reef Resilience Blueprint (2017). This document identified 10 key initiatives that focused on actions to deliver maximum benefits for reef resilience. One of the initiatives was the broadscale implementation of active, localized restoration. This priority initiative focuses on three activity areas: testing, improving, and scaling up local-scale reef restoration methods—based on the best available science—for potential application across the resilience network facilitating opportunities for community and industry participation in local-scale restoration, and researching and developing large-scale restoration methods.

To achieve these initiatives and protect the reef, GBRMPA is working toward:

- Developing a policy to provide guidance on restoration activities in the GBR Marine Park;
- Establishing restoration demonstration site(s), with supporting communication material, to test, improve, and where appropriate, scale-up restoration methods; and
- Developing guidance for community participation in restoration activities, including *reef restoration toolkits* to support localized restoration activities and support the establishment of a research program on large-scale restoration methods.

COMMUNICATION AND EDUCATION ON REEF RESTORATION

Reef restoration communicators are authors of books, manuals, and scientific papers, as well as photographs, films, TED talks, and underwater art. The notable people in this field include Margos (1974), Jaap (2000), Precht (2006), Edwards and Gomez (2007), Edwards (2010), and Johnson et al. (2011), along with David Vaughan (2021) who wrote manuals for practitioners and scientists.

Jason de Caires Taylor gained international notoriety in 2006 with the creation of the world's first underwater sculpture park, situated off the west coast of Grenada in the West Indies. Now listed as one of the Top 25 Wonders of the World by National Geographic, the park was instrumental in the government declaring the site a National Marine Protected Area. In 2009, he went on to co-found Museo Subacuático de Arte, a vast collection of over 500 of his sculptural works that are installed between Cancun and Isla Mujeres in Mexico. He has since installed the Coralarium in the Maldives and is working on a project for the GBR.

We rely heavily on handbooks and manuals to collate the knowledge on coral restoration and translate it into projects. There are several reef restoration/rehabilitation manuals written by various professionals including: Precht (2006), Edwards and Gomez (2007), Edwards (2010), and Johnson et al. (2011). *Active Coral Restoration*, the book you are now reading, was edited by David Vaughan. The *Reef Rehabilitation Manual* (Edwards 2010) provides detailed, hands-on advice regarding how to carry out coral reef rehabilitation in a responsible and cost-effective manner. The rehabilitation project cycle was split into five main stages by Edwards (2010) (Figure 2.6).

It was only recently that sociocultural and economic considerations have been regarded as essential components of coral restoration effectiveness (Hein et al. 2017). They proposed 10 indicators to measure reef restoration projects, including six ecological indicators and four sociocultural and economic indicators (Figure 2.7).

The importance of educating professionals in proper reef restoration techniques is essential. Globally funded training programs such as the European Commission project "Developing ubiquitous restoration practices for Indo-Pacific coral reefs" in 2004 (Chou 2011) and the IOC/WESTPAC (Intergovernment Oceanographic Commission for Western Pacific) Workshop on Coral Reef Restoration Techniques in the Western Pacific Region in 2012 (Chavanich et al. 2014) have played key roles in capacity building for Southeast Asian marine scientists. German Mendez Cozumel developed the Cozumel Coral Reef Restoration Program in 2013 to help with restoring coral reefs and to conduct training programs. The Reef Resilience Network and Conservation Training have developed a short online course—*Advanced Studies in Reef Resilience*—which has a module for Reef Restoration.

There are popular (over one million views) TED talks by scientists such as Kristen Marhaver and artist Jason deCaires Taylor. Dr. Kristen Marhaver's work combines classic scientific

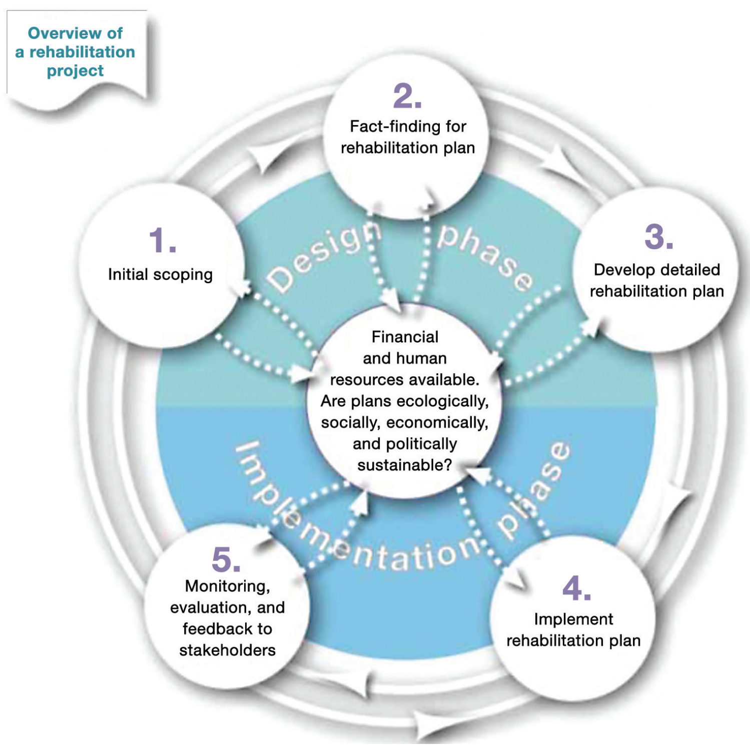

Figure 2.6 Five stages in a rehabilitation project, according to Edwards (2010).

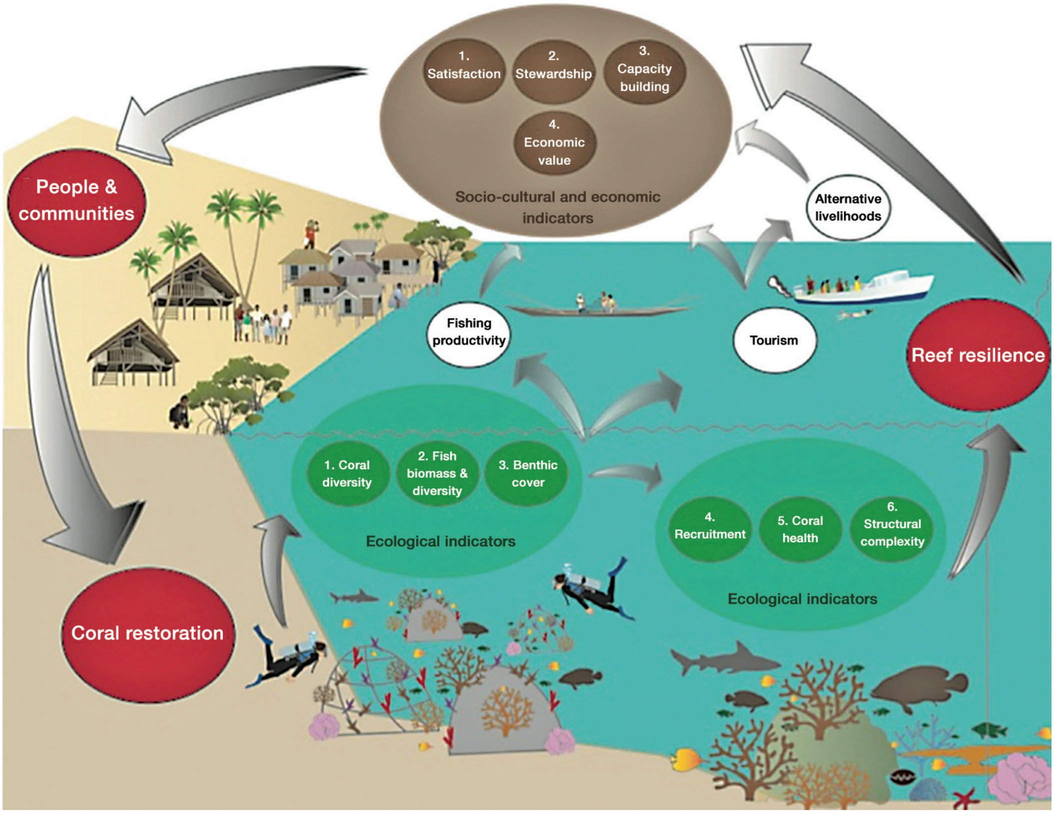

Figure 2.7 Illustration of the framework of positive interactions that link people and communities, coral restoration, and reef resilience. The six proposed ecological indicators are highlighted by green ovals; the four proposed sociocultural and economic indicators are highlighted by brown ovals (from Hein et al. 2017).

methods with new technologies to help threatened coral species survive their early life stages. She was the first person to rear juveniles of the endangered Caribbean Pillar Coral.

THE ROLE OF PRIVATE BUSINESS IN REEF RESTORATION

Private businesses and individuals have played an important part in the field of reef restoration. We describe a small number of businesses and people who have been important in the history of reef restoration.

Todd Barber's family had owned a dive store since 1979 and Todd naturally became an avid scuba diver with over 10,000 dives. After a high-flying career in computer and management consultancy, Todd returned to his first love, the *hobby and science* of marine reefs, in order to invent the Reef Ball and implement the concept in over 3,500 projects in 48 countries. A Reef Ball is a designed artificial reef that is used to restore ailing coral reefs and to create new fishing and scuba diving sites. Reef Balls are made of a special, marine-friendly concrete that is designed to mimic natural reef systems. They are used around the world to create habitats for fish and other marine and freshwater species. Reef Balls are made in many sizes in order to best match the natural reef type that is being mimicked. The most common sizes range from 0.1–1.8 m and 3–1,814 kg.

The business of reef restoration includes aquaculture, insurance, conservation, and tourism. The Nature Conservancy, Coral Restoration Foundation, Mars Foundation, Plant a Million Corals Foundation, Reef Renewal International, and SECORE are international leaders in coral restoration. In 2017, the Reef Restoration Foundation deployed Australia's first coral nursery using methodologies pioneered by the Coral Restoration Foundation (Nedimyer 2011).

David Lennon is an innovative businessman and has operated as a director of Reef Ball Australia since 1999. In 2008 he developed Sustainable Oceans International, and in 2012, Reef Arabia. He has designed ridge modules, seawall titles, and other interesting habitats and has been involved in industrial scale restoration activities in multiple countries.

A reef restoration project in North Sulawesi is one of David's favorite projects because the Newmont gold mine was closing, which meant their funding of hospitals, schools, and roads would end. Subsequently, they decided to fund construction of reefs that would replace reefs damaged by blast fishing and help boost the local commercial fishery. The positive result of this corporate, socially responsible investment is that this initial outlay contributes to producing fish for the locals indefinitely, even though the mine has closed. Newmont hired David to pick locations, design the reefs, and train the local fishermen in how to construct Reef Balls. The fishermen then went on to make over 3,000 units by hand; the coral growth proliferated and it is now a popular dive site.

Through his company Reef Arabia, David constructed a reef in Qatar from coral rubble that had been relocated from a shipping channel that was dredged for the new port. He planned the coral mitigation and offsets for the project and included relocation of 800 m^3 of coral rubble. People often overlook the value of the rubble, but it is wonderfully productive material and worth saving. As a resource, it is great to build with because it is already teeming with life.

David designed the prototypes of unique *ridge modules* specifically for the Arabian Gulf, but they are excellent for other areas and are about to be used in the United States. This concrete reef unit is designed to look more natural, provide substrate for attaching relocated or fragged corals, and has caves designed for local fish, such as grouper.

Off the coast of Indonesia, Mars Inc. has been working since 2007 to rebuild damaged sections of coral reef and to establish a marine protected area (Chapter 18). Frank Mars, one of the owners of the Mars Corporation, decided to implement a program to rehabilitate a coral reef in South Sualwesi. The villagers of Badi prepared *spiders* made from steel that were then coated in sand. The spiders are used as frames to place young coral in areas where the reef needs rehabilitating. Pieces of young coral are tied to the frame, which is then placed firmly on the sea floor. Each month the project will run for around three days, and each working day the Badi islanders will aim to place around 250 spiders around the edge of the island's reef flats. After a year, most places that have had spiders in place, show good coral regrowth. After two years the spiders are no longer visible, but covered by abundant new coral. This may be the world's largest coral reef restoration program with dimensions of over 8,000 sq. m and 8,645 spiders installed.

Not to be confused with the Mars Corporation, the Modular Artificial Reef Structure, a.k.a. MARS, was designed by Alex Goad in 2013 specifically to assist with the coral farming industry. Its ceramic surface is designed to house transplanted corals. Transplanted corals can be continually divided as they grow and eventually transplanted back to natural reefs.

Stewart Christie is the co-founder and CEO of the Reef Restoration Foundation, and in 2017 set up the first coral nursery at Fitzroy Island, Cairn, in the Great Barrier Reef Marine Park. Australia is stepping up efforts to help repair some of the damage the Great Barrier Reef has sustained, pledging over half a billion Australian dollars (around US$379 million) to an extensive recovery effort. Over $100 million of the funding is for reef restoration over a six-year period.

SECORE International is developing and testing techniques to raise and handle large amounts of coral offspring. SECORE and partners have designed small coral settlement substrates that self-attach to the reefs, enabling seeding coral recruits to join the reef in meaningful numbers. SECORE uses a multidisciplinary strategy combining research, active reef restoration, education, and outreach to help coral reefs. They work with a global network of scientists, public aquarium professionals, and local authorities, partners, and stakeholders.

GLOBAL LITERATURE REVIEW

To collate the latest knowledge of coral restoration, a global literature review was conducted (Boström-Einarsson et al. 2019; Boström-Einarsson et al. 2020) which assembled case studies and descriptions of coral restoration methods from four sources: (1) the primary literature (i.e. published peer-reviewed scientific literature), (2) grey literature (e.g., scientific reports and technical summaries from experts in the field), (3) online descriptions (e.g., blogs and online videos describing projects), and (4) an online survey targeting restoration practitioners (www.coralrestorationsurvey.com). We included only those case studies, which actively conducted coral restoration (i.e., at least one stage of scleractinian coral life-history was involved). The key dates from a historical perspective of scientific peer review literature are: in 1993, the substrate stabilization method was published; in 1996, substrate stabilization-electric was published; in 1997, coral gardening was published; and in 2002, larval enhancement was published (Figure 2.8). There was a massive spike in reef restoration studies in 2017 that was partially due to the survey methodology that included scientific and practitioner studies.

Coral transplantation is a commonly employed tool in reef restoration that involves securing whole colonies, fragments, or juveniles onto a degraded area with adhesives such as marine epoxy, concrete, and wires (reviewed by Rinkevich 2005; Edwards and Gomez 2007; Edwards 2010; Gomez et al. 2010; Omori 2010; Young et al. 2012). It hastens recovery processes of degraded reefs by increasing coral cover, biodiversity, and habitat complexity (Lindahl 2003). The coral *gardening* concept (Rinkevich 1995) involves corals reared in nurseries (on land or in water) to a suitable size before they are transplanted to degraded areas.

The earliest developed and most common method of coral restoration (used in 70% of reviewed projects, Boström-Einarsson et al. 2019) involves transplantation of coral fragments, which, in essence, could be seen as a simulation of asexual reproduction through fragmentation (Edwards and Gomez 2007). This technique is also called *asexual propagation* or *fragmentation*. Coral restoration involves many different approaches and technologies depending on the requirements of the situation. It can involve heavy equipment like cranes, graders, bulldozers, barges, or excavators, and also hand processes like the planting of corals. It can involve high-tech laboratory processes such as those applied in genetic engineering and micro-fragmentation.

In some situations, such as ship groundings, coral restorative work is handled entirely by professionals working with skilled operators and technicians. In others, ordinary local community members, divers, citizen scientists, and even tourists may do much of the work, acquiring skills as the project proceeds.

A total of 52 countries (Boström-Einarsson et al. 2019) (Figure 2.9(a)) were identified in which coral restoration projects have occurred, with the majority of projects conducted in the United States, the Philippines, Thailand, and Indonesia (together representing 40% of projects). We identified 329 case studies of coral restoration, of which 195 were from the scientific literature, 79 were sourced from the grey literature (i.e., reports and online descriptions), and 55 were responses to our survey for restoration practitioners (Boström-Einarsson et al. 2018; Figure 2.9(b) and (c)).

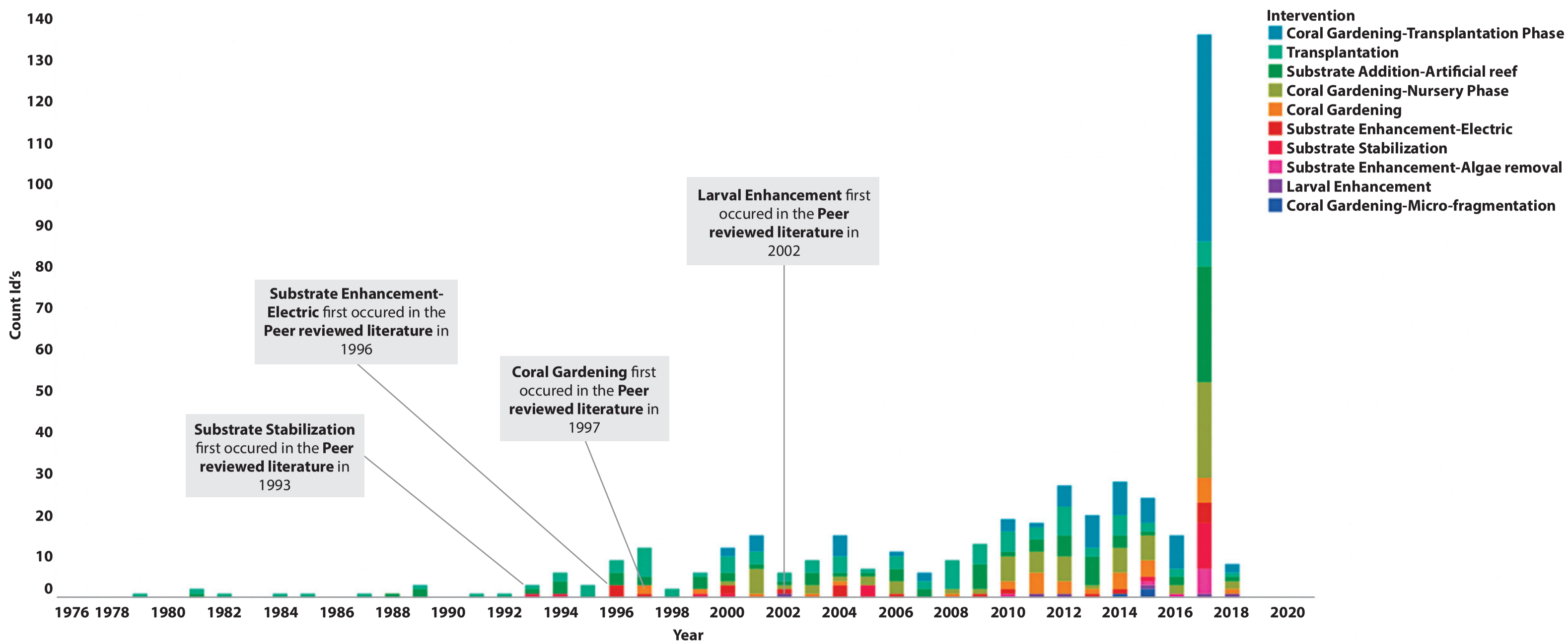

Figure 2.8 A chronology from the global literature review of the major developments in reef restoration and intervention. This included peer reviewed and practitioner surveys.

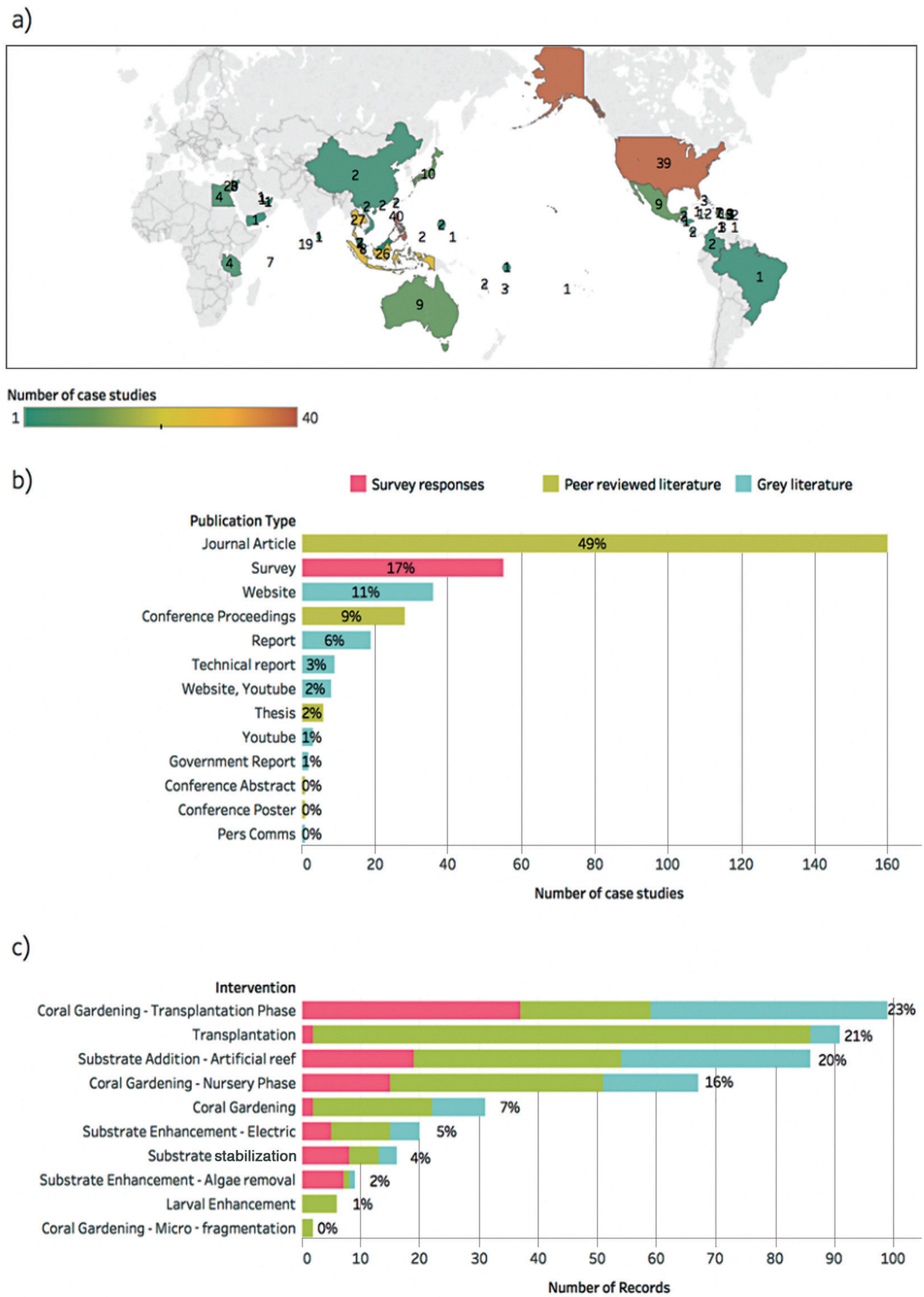

Figure 2.9 The (a) location, (b) source, and (c) type of intervention described in a global review of coral reef restoration methods (from Boström-Einarsson et al. 2018).

Coral restoration case studies are dominated by short-term projects, with 58% of all projects reporting less than 18 months of monitoring of the restored sites (Figure 2.10(a)). Overall, the median length of projects was 12 months. Similarly, most projects are relatively small in spatial scale, with a median size of restored areas of 440 m^2 (Figure 2.10(b)). The longest study monitored a transplantation project for 12 years (Garrison and Ward 2012), and studies that lasted 10 years or more (n = 5) tended to be monitoring programs on artificial reefs or restoration sites with transplanted corals; these also tended to be larger in spatial scale (>1,000 m^2) than the short-term studies.

Overall, coral restoration projects focused primarily on fast-growing branching corals, with 75% reporting using branching morphologies (Figure 2.11). Over a quarter of projects (28%)

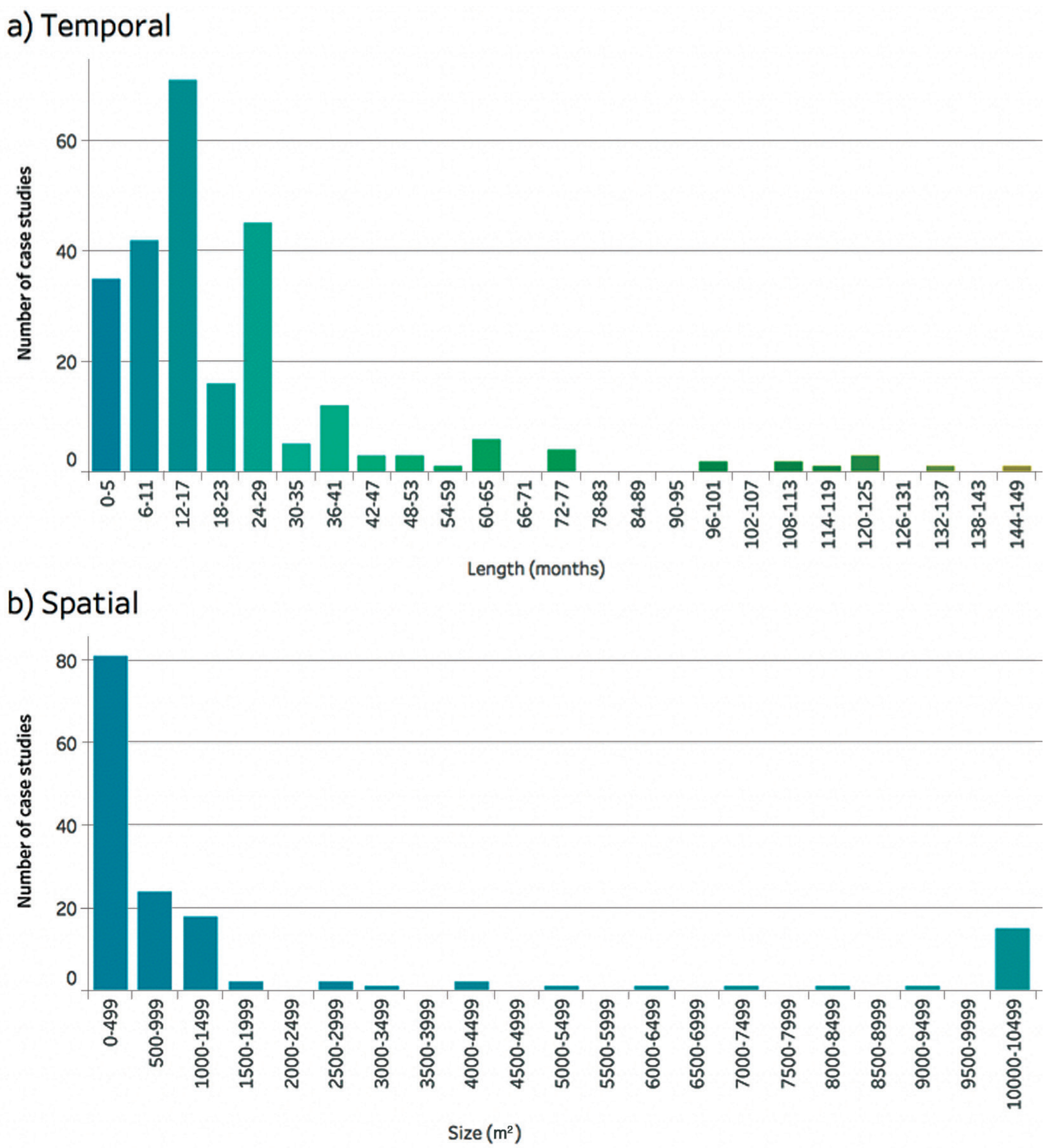

Figure 2.10 The (a) temporal and (b) spatial scale of coral restoration projects (from Boström-Einarsson et al. 2018).

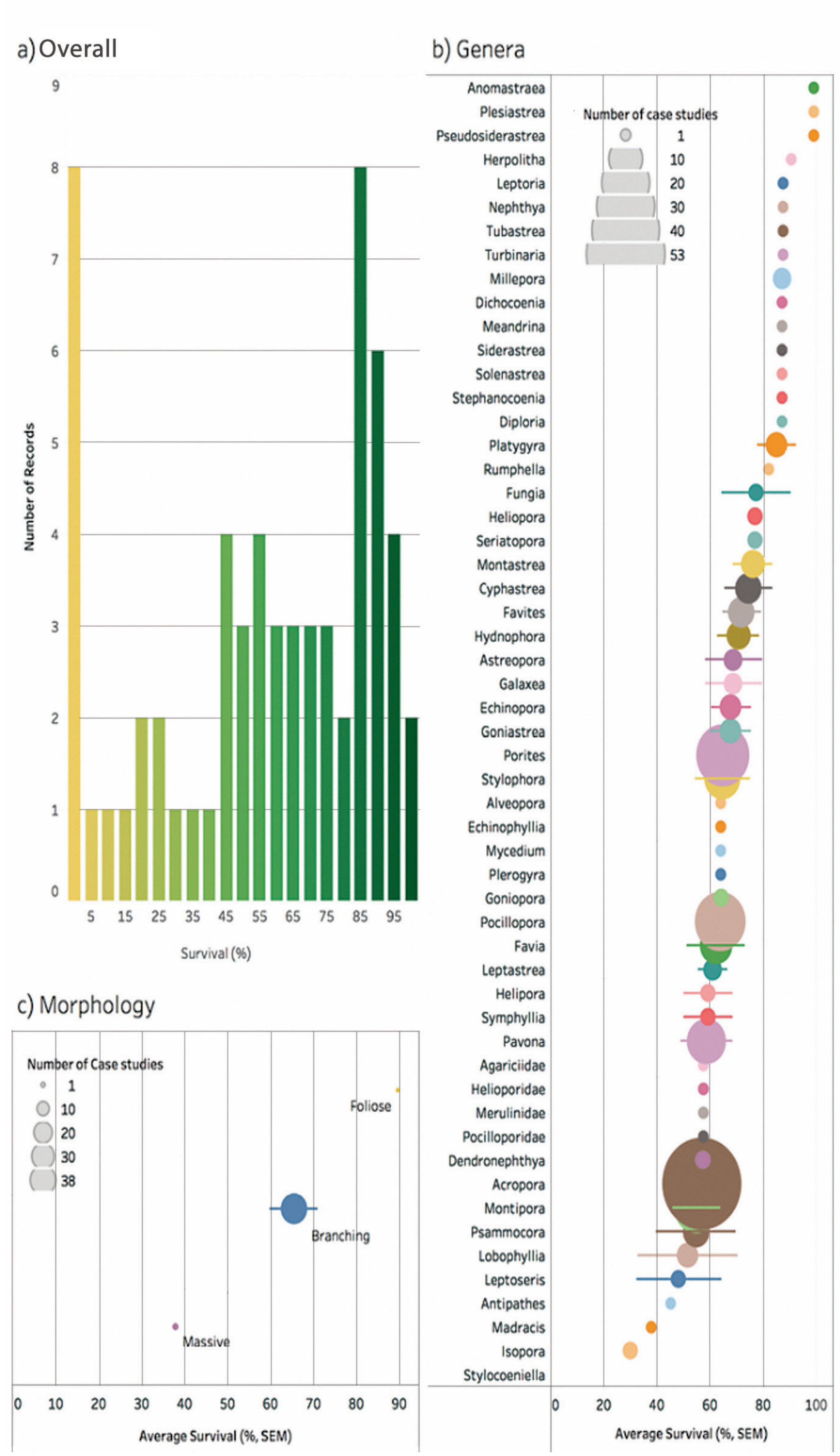

Figure 2.11 The average survival (a) overall, (b) by genera, and (c) by growth morphology of corals used in direct transplantation interventions. The size of each data point reflects the number of case studies supporting each calculation, the error bar represents standard error of the mean (SEM), and the different colors represent different species.

involved the coral genus *Acropora*, while 9% of studies included a single species—*Acropora cervicornis* (e.g., Bowden-Kerby 2008; Mercado-Molina et al. 2014; Schopmeyer et al. 2017). Among all the published documents, the top five species, represented in 22% of studies, were *Acropora cervicornis, Pocillopora damicornis, Stylophora pistillata, Porites cylindrica,* and *Acropora palmata*.

The success of direct transplantation depends on the size and health of the fragments, the method of transportation and attachment, and other extrinsic factors such as environmental conditions in the months following the transplantation, when coral fragments are stressed and vulnerable (van Woesik et al. 2017). Overall, direct transplantation studies reported an average of 51% survival, with 20% reporting >90% survival of transplanted corals.

DISCUSSION

Studying history is important because it allows us to understand our past, which in turn allows us to understand our present. If we want to know how and why our world is the way it is today, we have to look to history for answers. People often say that *history repeats itself*, but if we study the successes and failures of the past, we may, ideally, be able to learn from our mistakes and avoid repeating them in the future.

Modern reef restoration was pioneered by Tom Goreau and Wolf Hilbertz in 1979. The next wave of practitioners and scientists involved with reef restoration were Austin Bowden-Kerby, Vicki Harriot, David Fisk, Chou Loke Ming, and Baruck Rinkevich, who experimented with techniques for harvesting, growing, and transplanting coral. The drivers for their involvement with the new technique of reef restoration included concern for degradation to local coral reefs and the declining quality of scuba diving experiences as a result of cyclones, water quality, and coastal development.

Coral restoration involves many different approaches and technologies, depending on the requirements of the situation. It can involve heavy equipment such as cranes, graders, bulldozers, barges, or excavators, and also hand processes like the planting of corals. It can involve high-tech laboratory processes such as those applied in genetic engineering and micro-fragmentation.

Coral gardening is a simple and popular technique that is used in 70% of projects, and there is a major focus on fast-growing branching corals, with 75% of the projects showing the use of branching morphologies. The top five coral species being used in reef restoration were *Acropora cervicornis, Pocillopora damicornis, Stylophora pistillata, Porites cylindrica*, and *Acropora palmata*.

The global reviews of scientific literature and practitioners presented in this chapter identified 52 countries in which coral restoration projects have occurred, with the majority of projects conducted in the United States, the Philippines, Thailand, and Indonesia. Coral restoration case studies are dominated by short-term projects, with the median length of projects being 12 months. The longest study monitored a transplantation project for 12 years.

Reef restoration is about people and organizations who care about reefs. Non-governmental organizations such as The Nature Conservancy, Reef Resilience Network and Reef Restoration Foundation, Coral Restoration Foundation, Plant a Million Corals, and Reef Renewal International have been vital to partner with government and industry and involve the community on active projects. Scuba diving and consultancy businesses, such as Reef Balls, New Heaven Reef Conservation Program, Reef Arabia, and more recently, other businesses with a strong focus on sustainability, such as Mars Corporation and Reef Ecologic, have been involved in research, projects, training, and communication.

In the past five years, there has been an enormous increase in research and communication of reef restoration. Our global literature review documented an apparent 600% increase in published literature from 10–20 articles per year between 2000 and 2016 to over 120 articles in 2017.

It is difficult to measure the number of people and organizations interested and involved in reef restoration. An indicator of interest is the attendance of 300 people and multidisciplinary organizations at the Great Barrier Reef Restoration Symposium in June of 2018 that was held in Cairns, Australia, and the 450 people at the Reef Futures conference in Florida, USA, in December 2018. We recognize that the increased interest in reef restoration is linked to people who are willing to take action to help counter the global and local decline of coral reefs.

CONCLUSIONS

Coral reefs are under extreme pressure and it is necessary for people to share knowledge and take actions to reduce threats and improve reef health. The good news is that leading coral reef researchers, managers, tourism businesses, politicians, and stakeholders have recognized the challenge facing our coral reefs and are focusing on solutions. In 2018, reef restoration took another major step forward in terms of interest and funding when the Australian Government provided $6M to establish the Reef Restoration and Adaptation Program (RRAP). Over 18 months, RRAP conducted the world's most rigorous and comprehensive investigation into medium- and large-scale reef intervention, drawing on more than 150 experts from more than 20 organizations across the globe. The aim: to study the feasibility of intervening at scale on the Great Barrier Reef to help it adapt to, and recover from, the effects of climate change.

At the time of this writing, the consortium was embarking on a concerted, 10-year research and development program to rigorously risk-assess, test, develop, and if necessary, deploy a toolkit of novel interventions to help keep the reef resilient and sustain critical reef functions and values in the face of climate change (Figure 2.12).

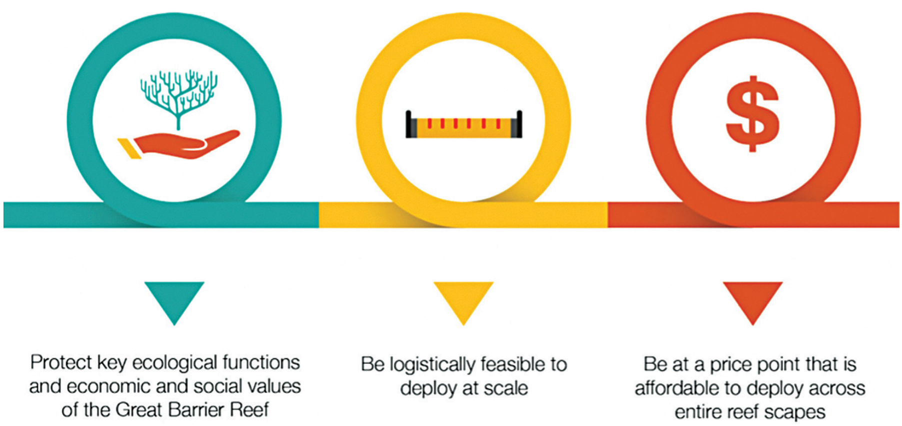

Figure 2.12 The ecological, social, logistical, and economic solutions sought by the RRAP (AIMS 2018).

RECOMMENDED FUTURE RESEARCH AND GOALS

We recommend a combination of environmental, social, and economic research projects and ongoing communication to share the history of reef restoration.

1. A global database of reef restoration knowledge, training, projects, practitioners, and funders to ensure that we work collaboratively, efficiently, and effectively.
2. A global training and education program for reef restoration. We estimate that there are approximately 1,000 self-taught people with demonstrated experience in active reef restoration and we recommend a target of one million trained people by 2025 in order to make a positive difference for coral reefs and communities. We recommend a global initiative where the people who rely on healthy reefs such as scuba divers, freedivers, snorkelers, tourists, and fishers participate in reef restoration training and donate at least one day a year or a small fee to a reef restoration project or foundation.
3. We recommend identification of 100 global priority reef restoration demonstration locations that implement best practice temporal goals of a 5–10-year project and spatial goals of 5,000–50,0000 m^2.

ACKNOWLEDGMENTS

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