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Chapter 11

Using Repertoires to Explore Changing Practices in Recent Coral Research

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Abstract: In the last three decades of the twentieth century, scientists working in coral reef biology documented unprecedented and extensive changes and degradation of reefs worldwide. This chapter investigates the evolution of coral reef biology research during this critical period, focusing on the emergence and use in the field of an "infection repertoire" which as we document was borrowed from biomedical research. Coral reef biology researchers borrowed and used this repertoire, recognizing and leveraging critical institutional factors such as strategies to align their research with national and global funding priorities, as well as managerial decisions concerning the set-up, infrastructures, and technologies to be prioritized for the production and circulation of data. These institutional and managerial characteristics were as crucial to emerging approaches in the field of coral reef biology as were the conceptual and methodological factors relating to the identification and investigation of the causes of the changes being observed. The fruitfulness of the disease-related explanation of reef damage was not a serendipitous outcome of the application of a theoretical framework, but rather a well-engineered and deliberate choice made by a coalition of marine researchers who actively decided to reproduce a certain way of organizing and conducting research. The field of coral reef research presents an intriguing domain to study to reflect on practices in marine biology, given its rapid evolution in recent years and because it has involved researchers from multiple disciplines working together, importing and adapting resources (including repertoires) from other fields in ways that significantly impacted ongoing research.

Keywords: coral reef research; repertoires; scientific practice; scientific change

Introduction

In the last three decades of the twentieth century, scientists working in coral reef biology documented unprecedented and extensive changes and degradation of reefs worldwide (Bryant and Burke 1998), including global declines in live cover, species richness, and the condition of reef-building corals. Researchers conducted numerous assessments in the late 1990s showing that these changes were likely due to a combination of several factors including global warming; ozone depletion;, hypertrophication (an excess of nutrients in the water); and anthropogenic influences including overfishing, habitat destruction, pollution runoff, and poor land use practices (for a review, see Richardson 1998). Beginning in the 1970s, researchers tended to describe many of these conditions based solely on their external characteristics, all of which involved changes in coloration and other patterns in the coral with distinct banding patterns and were observed to destroy corals at a rate of several millimeters per day (e.g., Antonius 1981). However, during the 1970s to the 1990s, most coral research was descriptive; efforts to identify any potential underlying pathogens were limited and there was even disagreement amongst researchers as to whether it was correct to think of these conditions as diseases.

The increasing amounts and extent of damage to coral reefs documented worldwide in the closing years of the twentieth century created clear imperatives for researchers to find ways to control and mitigate this type of damage. However, the global community of coral reef biology researchers faced considerable challenges in understanding the causes of the extensive changes that they were observing and documenting, and devising actionable solutions. One key challenge arose from the confluence of several potential and competing explanations for these phenomena, ranging from climate change and to related environmental disturbances, human interventions and their impacts on marine ecology, and the nature of the micro biota themselves. One explanation that emerged in the 1990s and took increasing hold in the 2000s among many coral researchers was that the destructive changes being observed were best understood as symptoms of underlying coral disease, rather than as resulting from external or environmental forces. This explanation was in many ways a simplification of a much more complex ecological phenomenon, and unavoidably involved downplaying the potential usefulness of differently focused ecological approaches. Nevertheless, as we document below, the disease-related view proved invaluable to many leading researchers in the field for rallying resources, deepening understanding of the changes being observed, and devising interventions.

This chapter investigates the evolution of coral reef biology research during this critical period at the cusp of the twenty-first century, focusing on the emergence and use in the field of a "repertoire" (Ankeny and Leonelli 2016; cf. Leonelli and Ankeny 2015) which as we document was borrowed from biomedical research and which we refer to as the "infection repertoire." As to be discussed in more detail below, a repertoire serves as a framework for research practices. The infection repertoire as we define it involves the ensemble of practices, strategies, tools, venues, and concepts used by biomedical researchers when they face the problem of local disease outbreaks potentially becoming global pandemics. Coral reef biology researchers borrowed and used this repertoire, which included recognizing and leveraging critical institutional factors such as strategies to align their research with various national and global funding priorities, as well as managerial decisions concerning the set-up, infrastructures, and technologies to be prioritized for the production and circulation of data. As we argue, these institutional and managerial characteristics were as crucial to emerging approaches in the field of coral reef biology as were the conceptual and methodological factors relating to the identification and investigation of the causes of the changes being observed.

In this chapter, we argue that the fruitfulness of the disease-related explanation of reef damage was not a serendipitous outcome of the application of a particular theoretical framework, but rather a well-engineered and deliberate choice made by a coalition of marine researchers who actively decided to reproduce a certain way of organizing and conducting research which had previously been utilized in biomedical research. We contend that the adoption of the infection repertoire in coral research was due as much to the practical know-how derived from imitating the structures of research, management, and intervention characterizing current reactions to global epidemics, and the potential benefits from these structures, as it was to the explanatory power of understanding many forms of reef damage as the result of infectious disease. The introduction of new concepts, such as dysbiosis, and an increased focus more generally on the role of microbes in health, did provide conceptual rationales that allowed application of this repertoire to both realms. Nevertheless, we contend that these factors do not suffice to explain the emergence of a novel approach to research in coral biology. To do so, we must analyze how comparability across insights, techniques, and data from these two communities was strategically construed and nurtured through a range of organizational, conceptual, institutional, and methodological innovations, in ways that that led to a sustained and fruitful research program in coral reef biology.

The field of coral reef research presents an intriguing domain to study in order to reflect on practices in marine biology, given its rapid evolution in recent years and because it has involved researchers from multiple disciplines working together, importing and adapting resources (including repertoires, as we discuss below) from other fields in ways that significantly impacted ongoing research. We contend that the use of the infection repertoire in coral reef research had a critical impact not only on the conceptualization of coral health but also on the tailoring of investigative methods towards specific forms of public health-style interventions. Our analysis builds on early historical work on related topics by Jan Sapp (1999), who has explored this field up to the late 1990s. Sapp emphasizes the importance of the institutional growth of coral reef environmental science and management, the growing political emphasis in this period on global environmental issues, and increasing awareness among coral researchers of the need for baseline data in order to distinguish human-induced changes from long-term natural processes, all of which are critical to our story. However, our account takes the analysis of research developments in this field through the 2000s, a period during which coral reef biology underwent significant changes, and thus draws out different elements of the history of this field as well as utilizing a distinct analytic framework in order to reflect on some of the scientific practices that characterize contemporary marine biology.

Studying Corals in the Mid to Late 20th Century

Roughly through the 1970s and early 1980s, researchers generally saw corals as highly stable, and thus the field tended to focus on documenting and explaining this stability by measuring distribution patterns and on exploring "biologically accommodating" ecological processes such as competition and predation (e.g., Endean 1977). Some went so far as to claim that the most unpredictable events in the lives of large corals might only include millennial-scale changes in sea level which would be exceedingly rare (Potts 1984). Infrequent storms were thought to be responsible for what were considered to be intense and localized mortality among large reef-building corals (Hughes and Jackson 1985). In the 1980s, evidence started to mount that reefs were not stable, including key episodes of major change such as the mass pathogen-induced die-off of the long-spined urchin *Diadema antillarum* (the dominant herbivore in the Caribbean), resulting in a rapid increase in algal biomass and a "phase-shift" from a coral-dominated to an algal-dominated system (Hughes 1994), which was described retrospectively by those in the field as a "complete surprise" (Mumby and Steneck 2008). During this period, coral researchers also began to suggest that negative changes had been anthropogenically induced or at least exacerbated rather than being a result of natural cyclical fluctuations (e.g., Richmond 1993; Wilkinson 1999).

During the 1980s and 1990s, there were a number of larger-scale studies by conservation organizations and various national governments that began to reveal the significant threats facing coral reefs (for a more detailed summary of this history in a relatively contemporaneous source, see Sapp 1999). For example, a survey conducted for the International Union for the Conservation of Nature (IUCN) in 1984–89 indicated that significant damage or destruction of reefs had occurred in ninety-three countries. Estimates suggested that approximately 10% of coral reefs globally were degraded beyond recovery, with an additional 30% likely to degrade over the next twenty years. However, questions still remained as to whether this damage should be classified as a form of "natural stress," along with storm damage, earthquakes, and wave action (ICRI 1998, 2), and also about the relative influences of human activities on reefs.

Reports of increased coral bleaching, including major bleaching events in the late 1990s and early 2000s and related increases in disease incidence and prevalence (Hoegh-Guldberg 1999), also accelerated attention to these types of issues. Coral bleaching occurs when corals expel the algae (zooxanthellae) living in their tissues, which causes the coral to turn completely white. Corals can survive a bleaching event and recover, as bleaching itself does not cause death, but bleached coral is under more stress and thus is subject to higher rates of disease and mortality. The causes of bleaching events are related to stresses caused by changes in conditions related to light, temperature, and/or nutrients. One of the key issues under debate in the late 1990s, particularly following the initial report of the United Nations' Intergovernmental Panel on Climate Change (IPCC) in 1990, related to the role of global warming and whether bleaching events were caused or merely accelerated by opportunistic infections. No one disputed that bleaching was in fact occurring and causing serious damage and destruction of coral reefs; however there were debates about the scope and, most importantly, the significance of these phenomena, particularly in relation to global warming, as well as about whether bleaching was an artifact of reporting and increased attention to coral reefs particularly as a result of the implementation of larger-scale monitoring programs (e.g., Glynn 1996).

Those in the field retrospectively note what they describe as a "major paradigm shift"[1] (Woodley et al. 2003, 11) during this period among scientists and environmental managers about the major causes of coral damage and decline, including disease as related in part to global climate change in addition to the factors that had traditionally been recognized (see also Knowlton and Rohwer 2003). In addition, there was growing recognition of the value of and need for monitoring research, which had been previously thought to be "mindless" and not adequately hypothesis-driven (Sapp 1999, 334).

Another supposed major shift in this period was associated with abandoning long-held assumptions about corals being spatially uniform and temporally stable on the scale of millennia due to mounting evidence of a number of emerging diseases (Mumby and Steneck 2008). Although by 2000 over thirty-five different coral diseases and syndromes had been reported globally, only a small number had been explored or addressed in the peer-reviewed scientific literature (Green and Bruckner 2000; Richardson 1998). Thus despite the rapid emergence of new diseases, disease etiologies remained uncertain and underexplored, as did the causative agents underlying them (Woodsley et al. 2003, 5). In addition, researchers in this period identified a number of gaps in key concepts relating to these new threats: for instance, previous models of bleaching had been primarily high level and phenomenological (e.g., induction of bleaching via light, heat, and other stimuli was the main focus, mostly occurring in laboratory settings) with limited attention to underlying cellular or molecular mechanisms; researchers also did not have the necessary tools to determine what causes bleaching in individual, natural reefs (Woodsley et al. 2003, 11ff.). Furthermore, there was limited understanding or baseline measurements that allowed disease to be distinguished

[1] Although we think it is important to maintain the wording preferred by the scientists whose work we are exploring, we do not believe that these changes in fact represent "paradigm shifts" in a Kuhnian sense, as they in fact did not reflect a complete overthrow of existing understandings of causes of the changes being observed in coral reefs. We discuss the difference between Kuhnian views and our own repertoires framework in more detail in the next section.

from natural variation, due to a lack of detailed investigations of coral physiology (Woodsley et al. 2003, 17).

A useful analysis of trends in coral reef management and research notes that while most work (58%) in the 1970s focused on patterns of diversity and habitat use, the majority of citations in the 1980s and into the 1990s focused on explanatory processes such as reproduction, recruitment, herbivory, and predation (Mumby and Steneck 2008). In the 1990s, disturbances and degradation of reefs (primarily due to disease and bleaching but also anthropogenic impacts) became key topics, resulting in 35% of the citations in that decade. Most notably, from 2000–2008, 85% of citations focused on these disturbances, with publications on disease and management steadily increasing. As the researchers put it: "clearly the scientific focus has shifted from small-scale, curiosity-driven basic research of a presumed stable system to larger-scale (even global) threats to coral reef ecosystems and how best to manage them" (Mumby and Steneck 2008, 557).

Borrowing the Infection Repertoire

At the turn of the century, driven partly by the increasing frequency with which major bleaching events and other forms of damage were occurring with increasingly devastating effects as detailed in the last section, coral biologists turned to other fields for inspiration about how to tackle such threats. Biomedicine, and particularly attempts to tackle the spread of human disease around the globe, was an attractive source of inspiration on several counts. Given its potential impact on public health and the perceived urgency of the threat, the battle against infectious diseases was highly visible to funding bodies and public policy organizations, and thus commanded immense human, financial, and technological resources. There is also a long biomedical tradition of attempting to monitor, study, and intervene with regard to pathogen spread, in order to limit the potential damage of highly contagious, fast-spreading agents. Building on the recognition that contagion is impossible to contain without international coordination, the history of framing and intervening on disease has increasingly involved an emphasis on global networking and the establishment of a rich infrastructure for the circulation and commodification of disease-related information (Hinchcliffe et al. 2016). Coral biologists noticed the parallels and started to collaborate with biomedical researchers to establish commonalities and identify lessons learnt from their approaches (e.g., see the overview of these efforts in Work et al. 2008).

In 2002, in response to the U.S. Coral Reef Task Force's National Action Plan to Conserve Coral Reefs, a network of field and laboratory scientists, coral reef managers, and federal agency representatives came together to found the collaborative Foundation of a Coral Disease and Health Consortium in order to consult a range of experts including those working in ecology, biology, and coral disease as well as environmental microbiology and human and veterinary medicine. From this consultation, a series of guidelines and suggestions for structuring future research on coral biology emerged, which were captured in a Report on Coral Reef Management published in 2003 by this group (Woodley et al. 2003, 1).[2] The report identifies four short-term objectives for coral biology: (1) the establishment of standard terminology, methodology, and protocols to enable effective communication among researchers; (2) the expansion of knowledge about pathogens and infection processes; (3) the establishment of model coral species on which basic research could be conducted to improve the understanding of disease mechanisms and infection processes; and (4) the development of centralized data/knowledge systems, websites, repositories, and core diagnostic facilities to facilitate comparisons of sites and systematic monitoring of reef damage around the globe. These objectives are presented in the Report as building on interdisciplinary expertise and

[2] It is important to emphasize that this report comes out of a group of researchers based primarily at US institutions and also clearly is a political document aimed at drawing attention to key issues and gaps in research in order to attract funding. We rely on it here because it provides an excellent contemporaneous overview of global coral research, and because it is subsequently frequently cited in the research literature in the field as an authoritative source.

insights to produce an integrated, effective, and systematic approach to coral reef management, and in turn a better way to monitor and prevent continued damage and mortality. Underpinning the implementation of these objectives was a series of assumptions and commitments to methods, conceptualizations, and ways of organizing and managing research, many of which were newly imported into coral biology as fundamental ingredients of what we call here the infection repertoire.

In order to understand our use of the repertoires framework to analyze these developments in the field, we must briefly outline its key components (for more details, see Ankeny and Leonelli 2016). A "repertoire" is a framework used to describe, analyze, and explain the conditions under which groups of researchers organize themselves and form relatively stable epistemic communities and systems of practice (see Chang 2012), particularly within large-scale, multidisciplinary projects such as the coral reef research analyzed in this chapter. A critical component of any repertoire is the assemblages of the skills, behaviors, and material, social, and epistemic components that groups use to practice and manage certain kinds of science and train newcomers, and whose enactment affects the methods and results of research. For our framework, we exploit the complementary character of two typical definitions of "repertoire."[3] On the one hand, scientific repertoires include material and conceptual elements, such as specific technologies, methods, and theories. Indeed, the adoption and use of instruments and concepts is a crucial step within the establishment of a repertoire, which is why many twentieth century philosophers have identified these elements as core components of research programs (e.g., Bachelard 1985 [1934]; Lakatos 1970; Laudan 1977). On the other hand, a repertoire only emerges when scientists establish what they perceive to be reliable and effective *ways to work* with these ideas and materials within and across groups, which typically means developing appropriate

[3] For instance, the *Oxford English Dictionary* currently defines a "repertoire" in two main ways: as the "body of items that are regularly performed" and as the "stock of skills or types of behaviour that a person habitually uses."

social structures and know-how (ways of distributing labor, norms, skills, and behaviors). Most importantly, the development of a repertoire involves the elaboration of strategies for coordinating and managing these conceptual, material, and social components, so that when they are combined, they produce the intended performance.

Repertoires are clearly distinct from Thomas Kuhn's notion of "paradigms." The two notions are both aiming to identify activities that are simultaneously conceptual, social, and material and that are constitutive of research communities. Kuhn (1962) points to "revolutionary" paradigmatic shifts as ways to identify and circumscribe such activities into coherent and stable assemblages.[4] This intertwining of conceptual, social, and material factors in research is a core idea that serves as a starting point for our own approach. However, Kuhn conceptualizes paradigms as static and inflexible entities in which change only occurs in dramatic fashion and on rare occasions, where as much of science is in fact everyday and mundane, or what Kuhn terms "normal." As many commentators have observed, this makes paradigms into unhelpful framing concepts for the analysis of fast-moving, dynamic and interdisciplinary science, like much of recent and contemporary research in the life and environmental sciences. Furthermore, Kuhn's account and his choice of case studies gives undue primacy to theoretical knowledge as primary output of science; because of this framing assumption, and despite his deep awareness of the significance of material and social aspects of research, the idea of a "paradigm" does not provide guidance for those who wish to investigate and analyze the critical roles of shifts in technologies, social and institutional resources and infrastructures, and procedures and norms specifically aimed at stimulating institutional and financial support for science, as we wish to do in our

[4] Here we provide a brief overview of Kuhn's key ideas and point the reader to the voluminous literature on his work including various interpretations and criticisms, notably Toulmin 1970, Hoyningen-Huene 1993, and de Langhe 2018.

analysis.[5] This rather narrow focus encourages an excessively internalistic view of scientific practice, in which strategies and activities aimed at attracting and retaining material, human, economic, and political resources tend to be viewed as external to the processes of scientific research, and are typically only acknowledged as significant when they directly shape the content of the propositional knowledge derived from these processes.[6]

To return to practices in coral biology, during this period, DNA, RNA, and protein data became essential as the evidence base for inferences about the mechanisms and potential spread of disease (for discussion, see Woodley et al. 2003). Thus, expensive technologies for the rapid and automated production, analysis, and comparison of molecular data, such as high-throughput sequencing tools and related data repositories, as well as collaborators skilled in use of these technologies, became crucial to research advancement and funding applications in the field. A sequencing program also was proposed of the genome of a representative coral species and their symbiotic dinoflagellate algae to permit researchers to interpret gene function in healthy and diseased colonies (Woodley et al. 2003).[7] Such information was incorporated, systematized, and aligned with environmental and climate data through international and national online databases.[8] These databases were geared as much to raising alerts about new or emerging crises in coral reefs as to providing evidence for ongoing and future studies; hence they simultaneously had management and research implications, as would be expected based on the repertoires framework. The same was the case for techniques and tools that would facilitate rapid identification of bacteria, monitoring

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[5] Imre Lakatos's views on research programmes (1970), though much less inflexible concerning the degree change happening within any given programme, are susceptible to similar critiques.
[6] This interpretation is one that Kuhn himself would likely endorse (see Kuhn 2000, 287). On Kuhn's internalism, see especially Wray 2010.
[7] The first coral genome to be completed sequenced was a staghorn coral in 2011 (see CoE CRS 2011).
[8] These include ReefBase (the Global Information System for Coral Reefs, http://reefbase.org/about.aspx), CoRIS (Coral Reef Information System, https://www.coris.noaa.gov/), and more recently the International Coral Reef Initiative (ICRI, https://www.icriforum.org/).

of the symptomatology of affected species, and faster diagnosis and an advance warning system for emerging infections. Again, we see the intertwining of managerial, organizational, and more traditional scientific aspects of the research in the choices of techniques and tools to adopt.

Furthermore, specific histological techniques and standard approaches to sampling (e.g., of cells and other diagnostic indicators) as used in clinical research were to be associated with easily applicable criteria to determine what counts as normal variation versus disease or deviation in reef structure and ecology (Woodley 2003, 18). Again, mirroring standardized clinical terminology for health and disease, the report on coral reef management also advocated improvements in existing methods of taking case histories and reporting field and laboratory observations, so that the resulting data could be comparable across affected locations around the world (Woodley et al. 2003, 26). Such heavy-handed standardization efforts were accompanied by extensive work on implementing and enforcing related guidelines, and the establishment of international venues and conferences to promote and strengthen international collaboration and coordination among those using related infrastructures and experimental systems. Importing these elements had obvious implications in terms of training new generations of coral researchers. Existing skills had to be complemented with specialized training in pathology, histology, and disease etiologies as well as the data science skills necessary for scientists to work with large data collections.

To obtain such resources and implement training programs on a large scale, the very rhetoric underpinning funding applications, public engagement, and policy programs associated with coral conservation shifted towards a discourse that mimicked the “fight against disease” typical of global health initiatives geared towards identifying and preventing the spread of potential pandemics. Within this repertoire, disease is typically conceptualized in relation to environmental stressors acting as triggers on particular biological mechanisms (Hinchcliffe et al. 2016; Reiss and Ankeny 2016). The conceptual foundations and key theoretical commitments underpinning research on corals were strongly affected by this repertoire. Coral biology moved to a similar conception of disease grounded in knowledge of how coral respond to different pathogens under varying environmental conditions. This conception of disease prompted researchers to place increasing emphasis on the study of particular pathogen-host interactions, so as to understand the biological causes and processes underpinning host susceptibility to particular pathogens, the ways in which the presence or absence of given micro-organisms may affect corals. Furthermore, the conceptualization of what constitutes the relevant environment for the study of pathogen-host interactions became associated to the idea of microbiomes (the collective genomes of the microorganisms residing in an environmental niche or the microorganisms themselves) that could be identified and analyzed through emerging 'omics' technologies. Experimental research on the biological characteristics of specific model systems and the ever-changing microbiome to which they are exposed thus became central to coral biology.[9]

This approach was in contrast with more traditional observational studies of biodiversity and stable ecological relations within the reefs that previously had dominated the field. As outlined in the previous section, while much of twentieth century biological thinking around coral environments had focused on their stability and resilience against external stressors, the emphasis now shifted to the extent to which corals were responsive to and interdependent on the marine environment, and specifically with its microbiome (Garren et al. 2009; Bourne, Morrow, and Webster 2016). Several review papers published in the early 2000s focus on possible explanations for seemingly disrupted responses in coral to what was previously assumed to be a relatively stable environment. Explanatory options provided by researchers include: (1) the presence of undiscovered new pathogens; (2) internal coral

[9] Note that this focus on microbiomes and the role of specific pathogens is not necessarily reductive or mechanistic in nature, and in fact parallels the emphasis on complex systems and related disruptions that emerges in this so-called postgenomic period – as well as its reliance on next generation sequencing and related molecular approaches to the study of microbial environments (Richardson and Stevens 2015; Guttinger and Dupré 2018).

malfunction; and (3) sudden shifts in the relation between host and the environment (e.g. Knowlton and Rohwer 2003; Work et al. 2008; Bourne et al. 2009).

The first two of these options became strongly associated with the use of “omics” technologies to investigate molecular mechanisms that can trigger disease within corals or as a result of the interaction between corals and specific components of the microbiome. Indeed, it is in this period that coral biologists adopted the notion of “holobionts,” which they use particularly in reference to hard corals as a way to indicate the extent to which they are dynamic, multi-domain assemblages (Knowlton and Rohwer 2003). Corals themselves come to be increasingly referred to as “metaorganisms,” that is, as multicellular organisms consisting of a macroscopic host and multiple microorganisms that interact synergistically to shape the ecology and evolution of the entire association (Bosch and McFall-Ngai 2011). Increasing amounts of research also began to be focused on the susceptibility of coral hosts to bacteria.

The third explanatory option, sudden shifts in the relation between host and the environment, was explored through the adoption of the notion of “dysbiosis,” which is often meant to indicate a disturbance or shift in the microbiome of an organism resulting in chronic disease (or more generally, as discussed in Hooks and O’Malley 2017, the interdependence between microbiota patterns and disease states). The term emerged in the late 20th century in relation to the biomedical study of intestinal diseases in humans (e.g., Tamboli et al. 2004), as a counterpoint to the notion of symbiosis and as an innovative way to conceptualize disease and therapeutic interventions in biomedicine. The concept of dysbiosis has recently become a pillar for a broad biological understanding of disease caused by environmental imbalances rather than single etiological agents, not just in corals but more broadly in marine ecosystems (see Table 1 in Egan and Gardiner 2016).

This terminology of dysbiosis and associated concepts acquired increasing prominence given their coherence with the material, technological, and institutional elements of the repertoire that we outlined earlier in this section. Later research continued to build on this approach and became ever more focused on the idea that using biomedical concepts and approaches coming both from human and veterinary medicine was crucial to tackling bleaching and other threats to coral reefs and their "health." Last but not least in our inventory of elements central to the infection repertoire is the central role played by reliable and efficient diagnostic procedures as investigative tools for researchers working in the infection repertoire. As noted also by Cheryl Woodley et al.: "diagnostics are biological tests used to define boundaries of disease, and to define the state of health. It is a process by which potential causes are eliminated. The steps involved include: a) collecting comprehensive case histories; b) recording gross observations; c) developing a flowchart of steps used to identify patterns; d) implementing diagnostic tools; and e) deriving a final diagnosis from total body information" (Woodley, et al. 2003, 23). This process occurs at two levels, that of communities and of individuals, mirroring human diagnostic efforts in public health and infectious disease. Community-level approaches provide historical information typically after an outbreak or deaths have occurred, whereas analysis of individual organisms focuses on the identification of causative agents and characterization of mechanisms of disease and transmission patterns to identify probable causes and suggest preventative strategies or treatments.

Table 1 summarizes the core elements of the infection repertoire borrowed from biomedicine that we have identified in coral biology at the turn of the twenty first century.[10]

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[10] Arguably there have been and continue to be a number of different repertoires at work in this field, including the genome sequencing repertoire (as documented in historical detail by Hilgartner 2017) and the model organism repertoire of the 1990s (Ankeny and Leonelli 2011, Leonelli and Ankeny 2015), the microbiome repertoire emerging in the 2000s (Ankeny and Leonelli 2016), the repertoire associated with the "one health" movement (which seeks to improve health and well-being at the interface between humans, non-human animals, and their various environments), and a repertoire relating to the investigation of climate change (which arguably developed within climate and environmental science in parallel to discussions within oceanography and marine conservation). However space limits prevent us from exploring each of these in detail in the context of this chapter.

The extent to which these components consistently align with each other as a specific approach to research was noted by several commentators writing in the late 2000s. A review paper by David G. Bourne and colleagues published in 2009, for instance, starts with a statement in which the authors pinpoint precisely which elements of strategy, vision, and method are being imported from human/veterinary research into coral biology:

> we review our current understanding of the role of microorganisms in coral health and disease, and highlight the pressing interdisciplinary research priorities required to elucidate the mechanisms of disease. We advocate an approach that applies knowledge gained from experiences in human and veterinary medicine, integrated into multidisciplinary studies that investigate the interactions between host, agent and environment of a given coral disease. These approaches include robust and precise disease diagnosis, standardized ecological methods and application of rapidly developing DNA, RNA and protein technologies, alongside established histological, microbial ecology and ecological expertise. Such approaches will allow a better understanding of the causes of coral mortality and coral reef declines and help assess potential management options to mitigate their effects in the longer term. (Bourne et al. 2009, 554)

Table 1. Elements of the infection repertoire

Type of element	*Elements in the repertoire that moved from biomedicine to marine biology*
Methodological	Microbiome toolkit and ways of producing, analyzing, and comparing data Identification of bacteria

	Focus on symptomatology and fast diagnosis/warning Role of histology and sampling Criteria for what counts as normal variation versus disease or deviation Establishment of standardized clinical terminology for health and disease, improved methods for taking case histories and for reporting field and laboratory information to produce comparable data across worldwide sites Set-up of data collections and repositories as systems of monitoring, geared to raising alerts and to providing evidence for ongoing and future studies
Managerial	Implementation and enforcement guidelines/practices for standards (terminology, composition of case histories, and data collection) Development of platforms and venues for international collaboration Coordination of data collections and infrastructures Coordination of adoption and handling of model organism of reference
Financial and institutional	Focus on interdisciplinary and specialized training in pathology, histology, and disease etiologies Resourcing involves the acquisition of instruments for microbiome sequencing and genetic (re-)classification, as well as infrastructural elements as above Framing of social relevance of research as ‘fight against disease’
Conceptual	Fundamental assumptions around stability of environment get overthrown Adoption of the term ‘dysbiosis’

	Awareness of host susceptibility to bacteria Criteria for defining what counts as a disease View of animals as 'metaorganisms' Adoption of term 'holobiont' to indicate that corals are dynamic, multi-domain assemblages

Conclusions: Scientific Change, Repertoires, and Coral Research

Recent changes in scientific practices associated with coral research have been claimed by those involved to have required dramatic shifts about the way in which various key concepts are understood: "[t]he paradigm of widespread healthy, stable coral reef ecosystems has evolved to one that views them as patchy, unstable and fragile" (Mumby and Steneck 2008, 562).[11] Many also contend that the field has been deeply impacted due to revised understandings of the roles of climate change and other anthropogenic impacts on coral, as discussed above. Our account allows a more nuanced view on this critical period in coral research by using the repertoires framework as a way to understand scientific change, which also permits us to make better sense of a range of factors which have contributed to this change without requiring defense of any radical notions of discontinuity, paradigm shifts or otherwise.

Over the last decade, the infection repertoire has acquired increasing prominence within coral research, most substantially by intersecting with research on the crucial role of microbial colonies in reef health and resistance. Technological innovations in microscopy, such as the ability to use high-speed confocal microscopy on live coral, are providing new

[11] Again here, we contend that this use of "paradigm" is very loose, as is often the case in scientific research, and the researchers are not intending to make any deep claims about their practices in relation to Kuhn's theories of scientific change.

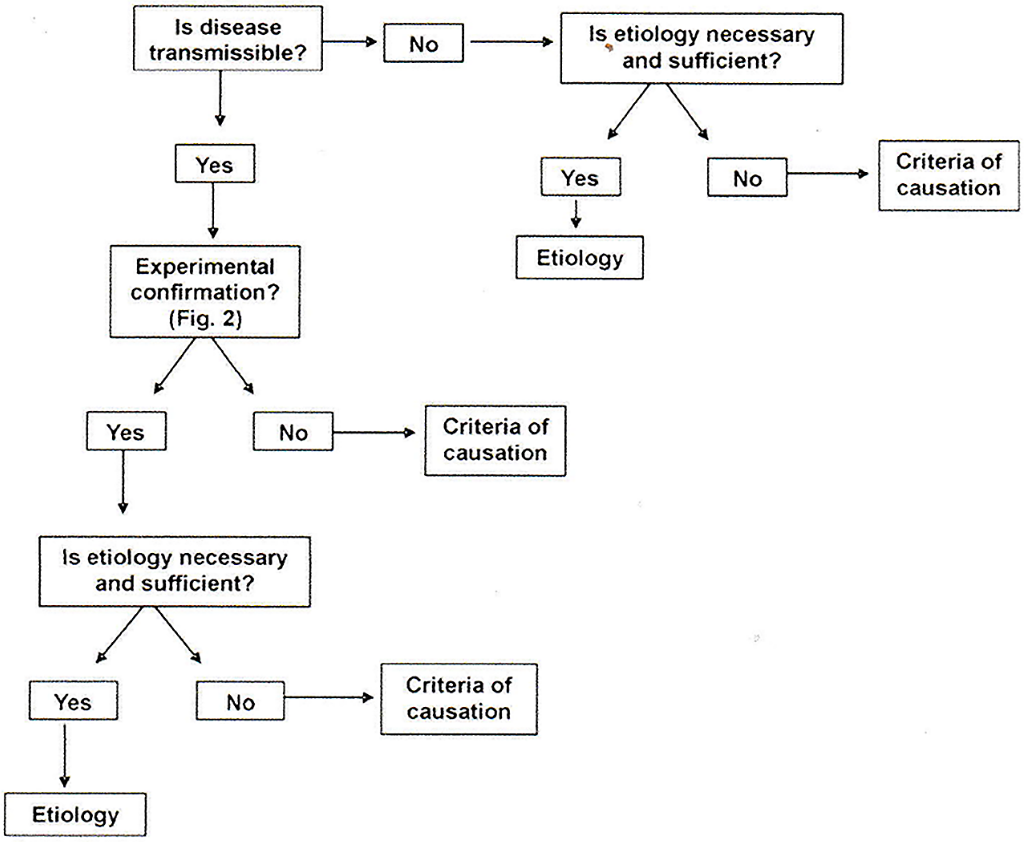
evidence for the role of microbiome regulation (through actions such as shedding bacteria) in coral health and disease (Garren and Azam 2012). The conceptual and methodological implications of this move are a reframing of the ideas around ecology and environment in marine research, and a resulting shift away from studies of wider environmental diversity and observational approaches together with adoption of a more mechanistic focus on specific model systems and related microbiomes.

It is crucial to emphasize the extent to which this shift has opened up opportunities for new kinds of experimental interventions on coral, and for the formulation and testing of preventative, diagnostic, and therapeutic measures based on the manipulation of the microbiome (Glasl, Webster, and Bourne 2017). As in the case of pandemics, and particularly given the recent catastrophic, rapid, widespread, and seemingly accelerating nature of reef destruction, the timeliness of such measures is of the essence. Researchers working on coral reefs are not necessarily rejecting, or even explicitly critiquing, observation-based modes of research focused on macro-ecological factors and the effects of human intervention on reef ecology. In fact, these elements are noted in many narratives within reef research and remain equally plausible ways to investigate and explain the phenomena currently.

In other words, what has occurred in coral research as documented here was not a conceptual and methodological change that could be simply explained as a “paradigm shift” in a Kuhnian fashion, requiring a radical change in the theory central to the field in question. Not only were there no obvious crises in explanatory resources within coral biology, but many conceptual elements present for decades actually persisted throughout the 1980s, 1990s, and even 2000s. Our analysis presents a case that it is more plausible to understand emerging developments in coral biology as a response to a biological crisis, requiring a complex apparatus and strategy which coral biology research did not possess, including the intersection of specific conceptual apparatuses with techniques and tools (including databases, sequencing of microbial species, identification of species in microbiota, and microbiome analysis). This requirement is the main reason why the infection repertoire was adopted: it provided a set of easily applicable tools and strategies that helped researchers to confront the current emergency in the short term, and in ways that could be internationally coordinated and funded.

Indeed, as in biomedicine, the infection repertoire has proven useful for facilitating translational research, in the sense that it helps researchers to couple their evolving understandings of coral biology with sophisticated forms of intervention in marine ecosystems (for a characterization of translational research that fits this account, see Leonelli 2013; Rajan and Leonelli 2013). Figure 1, which was adapted and published by reef biologists, indicates precisely how traditional steps based on Koch's postulates that are used in biomedicine to generate human disease diagnoses and interventions may be reframed to fit coral disease and health. This demonstrates the strength of this motivation for reef biologists and the extent to which such translational efforts explicitly underpin and frame their choices of conceptual tools.

Figure 1: What is termed a "conceptual road map," redrawn from a review paper intended to demonstrate to marine researchers what can be learned from biomedical notions of disease and related interventions (Work et al. 2008)



This translational motivation, and its underlying goal of putting research at the service of what researchers perceived as a global emergency threatening the very existence of their research objects, is a key historical and epistemic factor. The notion of repertoires as relatively stable arrangements of well-aligned and reproducible elements of research, including institutional and material components, helps us not only to identify this factor, but also to analyze in detail how it accounts for the choices of instruments, concepts, and collaborations to be pursued by researchers, and the extent to which these choices affect previously existing commitments and ways of practicing coral biology. For example, a critical advantage brought to coral biology by the infection repertoire is that this approach to research permits more systematic alignment of "omic" data, observations, and more traditional phenotypic descriptions of damage or lesions (together with symptomatology and possible underlying causes), thus making it possible at least in principle to gather them in databases that are globally accessible. Given the crises faced by coral reefs, ready availability of data and the opportunity to combine many different types of data in pursuing research on these phenomena is crucial. These efforts allow expanded scale and scope of comparisons of various types of host-pathogen interactions, as well as prompt identification of microbiota and their microbiological components.

As we have shown, the repertoires framework helps to reveal the complexities often present during episodes of science change, including the continued use of some key concepts and approaches side-by-side with novel ones that may on the surface appear to be incompatible. For instance, in coral research it rapidly became clear that the notion of assumed stability in fact underestimated the possibility of major changes such as those due to climate change. Subsequently researchers changed their views to understand such conditions of relative stability and uniformity as potentially negative, as they in fact make corals more vulnerable and very sensitive to physical and chemical changes, and hence open to mass effects (Woodsley et al. 2003, 35).

The repertoire framework also helps us to understand recent exchanges between biomedical and marine researchers, and the formation of a common set of allegiances and tools that facilitate the circulation of knowledge between these two communities. It could be argued that thanks to the common ground provided by the infection repertoire, there are now representational claims being transferred not only from biomedical research to coral research but also from coral research back to research on human subjects, as some of the conceptual and methodological work on coral disease has recently become used in biomedical work on dysbiosis in relation to gut disease (Bosch and Miller 2016; Ferrer et al. 2017). Hence our analysis demonstrates how the adoption of a common repertoire can facilitate interdisciplinary interactions and conceptual transfers across historically-distant and distinct research traditions. It also provides an example of how the repertoires framework can be utilized by historians seeking to track the evolution of scientific practices at the community level over longer periods of time, particularly in cases where both change and continuity are simultaneously at issue.

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