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The changing dynamics of coral reef science in Arabia

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ABSTRACT

Six percent of the world's coral reefs occur around the Arabian Peninsula, providing a valuable ecological, economic and scientific resource for the nations bordering its shores. We provide the first region-wide assessment of the current status and historical trends in coral reef research, focusing on research in the Red Sea, Arabian Sea, and Arabian Gulf. In total, 633 regional reef publications have been produced since the 1930s, covering a wide variety of themes and taxa. Our results show a great deal of commonality in regional reef research, but also highlight important differences in research among the various seas as well as knowledge gaps that represent opportunities for future research. A regionally-integrated approach to future research is essential. There is a growing need for large-scale research to guide management of reefs and their stressors, as these operate at much larger scales than the national borders within which most research currently occurs.

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1. Introduction

The Arabian region contains approximately 6% of global coral reefs (Burke et al., 2011). These represent the most diverse ecosystem in the region, and are particularly important in Arabia given the low diversity of the surrounding arid terrestrial environment (Burt, 2014; Sheppard et al., 1992). They are also home to a variety of endemic coral and fish species (Coles, 2003; Ormond and Edwards, 1987; Riegl et al., 2012a; Sheppard and Sheppard, 1991), and in some areas these can make up a substantial proportion of the total community (Roberts et al., 1992; Sheppard et al., 1992). In addition to their ecological value, reefs are also important for supporting a multi-million ton fishing industry and hundreds of thousands of jobs by providing food, shelter, and nursery habitat to a variety of commercially important species (FAO, 2015; Grandcourt, 2012).

Coral reefs in the Arabian region are of particular interest to science due to the wide variety of environmental conditions in which reefs occur, and the unique biogeographic patterns that occur as a result. The Red Sea is characterized by a longitudinal gradient of environmental conditions, with salinity and temperatures more extreme to the north and productivity higher to the south, driving differences in community structure and endemism along its coastlines (Berumen et al., 2013; Edwards, 1980). In contrast, the environment of the adjacent Arabian Sea is largely dictated by the summer monsoon, with cool sea temperatures associated with upwelling resulting in a pseudo-high latitude effect on many of its reefs (Burt et al., in review; This issue; Sheppard et al., 1992). In the Arabian Gulf (also called the Persian Gulf), shallow

depths (mean <30 m) and its relative isolation from the Indian Ocean result in extreme seasonal temperature fluctuations (>20 °C range each six months) as well as high salinity (often ≥4 ppt) (Coles, 2003; Riegl and Purkis, 2012a,b). Given the relatively extreme and varied thermal conditions experienced by reefs around the Arabian peninsula, the region is gaining interest from the science community for its value in providing insights into how reef fauna cope with extreme environmental conditions at the molecular, physiological, and ecological levels (Bauman et al., 2012; Feary et al., 2013; Hume et al., 2015). There is also growing interest in using Arabia's reefs as a proxy for climate change in order to understand how reefs in other parts of the world may respond to future thermal stress (Baker et al., 2004; Burt et al., 2014; Feary et al., 2010), as well as consideration of assisted migration and/or cross-breeding of thermally tolerant species into other regions (Coles and Riegl, 2013; D'Angelo et al., 2015).

Despite their ecological, economic and scientific importance, coral reefs throughout Arabia are becoming increasingly degraded by human activities and natural stressors. Impacts from eutrophication, industrial pollution, coastal reclamation and dredging, as well as fishing damage and over-exploitation have resulted in widespread degradation of reefs throughout the region in recent decades (Burt, 2014; Burt et al., 2014; in review; this issue; Jessen et al., 2013; Loya, 2004; Rinkevich, 2005; Sale et al., 2011b; Sheppard et al., 2010a,b). However these relatively localized impacts have been, in large part, exacerbated by recurrent natural events that have arguably resulted in greater large-scale decline of regional coral reefs. For example, in the past decade alone there have been recurrent mass bleaching events in the Arabian Gulf (Riegl and Purkis, 2015), a super-cyclone and large-scale harmful algal bloom event in the Gulf of Oman and Arabian Sea (Burt et al., in review; This issue), and multiple outbreaks of predatory *Drupella*

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gastropods and Crown of Thorns starfish in the Red Sea (Bruckner and Dempsey, 2015; Riegl et al., 2012c; Schoepf et al., 2010). Individually, these anthropogenic and natural stressors have caused impacts to reefs in many areas, but their cumulative and combined impacts have resulted in substantial shifts in coral demographics and community structure throughout much of the region (Riegl and Purkis, 2015; Riegl et al., 2012c).

Together the unique biogeographic nature of this region as well as the increasing fragility of these ecosystems is drawing increasing attention from the international scientific community, and there has been rapid growth in research on the coral reefs of this previously understudied region in recent years (Berumen et al., 2013; Burt, 2013; Loya, 2004). There has also been growing calls for enhanced trans-regional collaboration among the scientific community, not only to allow assessment of biological patterns across larger geographic and environmental scales, but also in recognition that many of the stressors affecting reefs are common across all nations in the region and that development of proactive management strategies will require concerted research efforts that span across numerous national borders (Burt et al., 2014; Feary et al., 2013; Sale et al., 2011; van Lavieren et al., 2011). The purpose of this study was to provide an assessment of the current status and historical trends in coral reef research across the Arabian region. While the growth of scientific interest has been recognized (Berumen et al., 2013; Burt, 2013), to date there have been no region-wide assessments of the status and trends in coral reef research. We performed a literature review of coral reef research in the Red Sea, the Arabian Sea (here including the Gulf of Oman and Gulf of Aden), and the Arabian Gulf in order to develop an understanding of the overall status of reef science in the region and to assess commonalities and differences in research foci between these regions over time. Determining which geographic areas, research themes, or taxa are being underrepresented can allow identification of opportunities for future research that could enhance collaboration among regional scientists and improve coral reef management across Arabia.

2. Materials and methods

This study focuses on coral reef research carried out in the three major biogeographic water bodies that border the Arabian Peninsula (referred to hereafter as provinces): the Red Sea, the Arabian Gulf, and the Arabian Sea here including the Gulf of Oman, Gulf of Aden and the western Arabian Sea. Publications were identified through Google Scholar and Thomson Reuter's Web of Knowledge using search terms that included each of the major and minor water body names and/or names of countries bordering these water bodies, as well as a standardized list of reef-relevant search terms (e.g. coral; reef; reef fish; zooxanthellae, etc.). In addition, these lists were cross-referenced against bibliographies provided in recent review papers focused on sub-regional coral reefs (Berumen et al., 2013 and Burt, 2013) to maximize inclusion of relevant literature. Searches were primarily focused on peer-reviewed science literature, but where reef-related books/chapters and gray literature were listed in Google Scholar, and were accessible for verification of content, these were also included. The dataset included all publications available historically (earliest record found was 1936) through to 2014 inclusive.

Individual publications were collated in EndNote and duplicate records removed prior to analyses. Each individual publication was aligned with several categories to allow comparisons across the data set. Publications were classified into several geographic categories (province of study [Red Sea, Arabian Gulf, Arabian Sea, and 'Multiple' for studies which included data from more than one province]; Study country [including 'Multiple' for multinational research] to illustrate where the reefs under study were located; and First-author Country and First-author Region to indicate where the lead researcher was physically based). Publications were also classified by Theme (Biological Survey; Disturbance/Recovery; Ecology/Interactions; Environmental

Biology; Geology; Impact Assessment/Pollution, Management/Conservation; Man-made structures; Molecular Biology/Physiology), see Supp. Table 1 for criteria used, and they were also classified by the Primary Taxa under study (Algae; Coral; Ecosystem; Physical Environment; Fish; Non-Coral Invertebrates; Various). For comparative purposes, data were assessed across the whole Arabian region in some instances (e.g. total publication output), and were also broken down by sub-regional Province in cases where comparison of data across the distinct water bodies was appropriate (e.g. trends in Provincial research themes over time).

3. Results and discussion

3.1. The history and geography of regional reef science

Since the first descriptions of Red Sea reefs in the 1930s (Bertram, 1936; Crossland, 1939) there has been considerable growth in coral reef science across the Arabian region. Although reef-related science grew only slowly during its first half century (only 8 publications before 1970), research has grown exponentially in subsequent decades (Fig. 1a), averaging 39.6% growth per decade thereafter. In total, 633 reef-related publications have been produced across the region with nearly half of these in the last decade alone (2005–2014: 44.4%; Fig. 1a). Although the total volume of research in Arabia is currently lower than regions such as the Great Barrier Reef and the Caribbean (Berumen et al., 2013), the relatively recent onset of research here explains much of this difference, and current growth trends suggest that this region is on track to become a relatively well studied reef ecoregion in the coming decade.

Although reef science has increased regionally, growth has been highly variable among Arabia's marine provinces. Prior to the 1990s, regional reef science was heavily dominated by studies originating from the Red Sea (Fig. 1a), with these mainly from the Gulf of Eilat/Gulf of Aqaba area. However, in subsequent decades, the relative proportion of regional research originating from the Arabian Gulf has increased substantially, and during the past 5 years the quantity of publications from the Arabian Gulf surpassed that of the Red Sea for the first time in history, contributing 55% of all regional publications in 2010–2014 (Fig. 1a) and exhibiting the fastest growth of all of the regional provinces in the past decade (95.2% increase from 2004 to 2014). This suggests that despite the Red Sea currently having the highest total number of historic publications (Fig. 1b), it is likely that the Arabian Gulf will be better studied by the end of the current decade if this trend continues. There are various reasons for the rapid growth in reef science in the Arabian Gulf (see Trends in research themes below), but much of this growth has drawn from increasing interest in using the Arabian Gulf as a model ecosystem in which to study climate change and the biology of reef fauna in extreme environments (Burt et al., 2014). In contrast to the other provinces, the Arabian Sea has continuously been understudied throughout the history of reef research in the region (Fig. 1a), and today only 6% of all historic publications have focused on reefs in the Arabian Sea, including the Gulf of Oman and Gulf of Aden (Fig. 1b). Prior to the 1980s virtually nothing was known about the coral reef ecosystems in the Arabian Sea province, and although there was some improvement in the early 1990s, mainly as a result of publications associated with an IUCN-led marine biodiversity survey in Oman (Glynn, 1993b; Salm, 1993; Salm et al., 1993), research has remained relatively static in subsequent decades (Fig. 1a). Given the large extent of reefs and the unique nature of the marine environment in Oman and eastern Yemen, the relatively understudied nature of these systems could seem surprising. However, both of these countries have relatively long coastlines with discontinuously distributed reefs making research logistics more difficult and they also lack the high diversity and endemism of the Red Sea and the financial resources and environmental extremes of the Arabian Gulf which have attracted international scientists to those areas. Together with long-standing

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