



Mesophotic Coral Ecosystems of the Great Barrier Reef Are Understudied and Underexplored

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Mesophotic coral ecosystems (MCEs) are characterized by the presence of photosynthetically active organisms such as corals and algae, and associated communities at depths ranging from 30 to 150 m in tropical and subtropical regions. Due to the increased awareness of the potential importance of these reefs as an integral part of coral reef ecosystems (i.e., deep reef refuge, specialized biodiversity, transition zone between shallow and deep-sea environments, and recreational and intrinsic values), interest from the scientific community has grown around the world over the last two decades. Several nations have already made management declarations and started to extend marine protected areas and fishery management to MCEs. The estimated area of Australian MCEs is likely equivalent to that of shallow reef ecosystems down to 30 m; however, Australian MCEs attract limited research effort compared to other major coral reef regions around the world. In this perspective, we briefly explore the reasons for this scarcity of research on mesophotic ecosystems of the Great Barrier Reef (GBR) of Australia (e.g., strict diving regulations, new researchers' involvement, and logistics and cost). At present, research efforts on the mesophotic ecosystems of the GBR are in decline and if this trajectory is maintained, the global disparity in knowledge between MCEs near Australia and those from the other main coral reef regions worldwide will sharpen deeply. We call for action from the research community, grant agencies, and decision-makers toward a wider understanding of these important ecosystems in Australia.

Keywords: deep coral reefs, deep reef refuge hypothesis, Australia, Red Sea, prioritize research, management needs, trend projection, Holt-Winters model

INTRODUCTION

Australian coral reefs in general, and the Great Barrier Reef (GBR) in particular, have been studied extensively for almost a century. Pioneers explored these reefs in the historic 1928–1929 GBR expedition (Yonge, 1930) and the GBR became one of the most prestigious locations for coral reef studies (Day and Dobbs, 2013). The Australian Coral Reef Society (ACRS) was established in 1922 to protect the GBR and is considered the world's oldest organization concerned with the study and conservation of coral reefs (ACRS, 2020). Coral reefs in the region are still at the forefront of global research, with 135–195 papers published in the Web of Science Core Collection (WOS, 2020) every year (search terms: [coral] and

[Australia]; 2010–2019). Those trends are on par with the Caribbean Sea (178–253 publications) and the Red Sea (93–189 publications).

Mesophotic coral ecosystems (MCEs) have never been the main focus of GBR researchers (apart from a very few dedicated researchers), even though over the last decade there has been a bloom in mesophotic studies worldwide (**Figure 1**). While the ecological study of MCEs historically started in the Marshall Islands, Jamaica, Cuba, and Hawaii (reviewed in Pyle and Copus, 2019) in the 1960s–70s and in the Red Sea in the early 1980s (reviewed in Fricke, 1996), research at mesophotic depths on the GBR only started in the mid-1980s. In fact, very few mesophotic studies were published from the GBR until 2011, with a sharp increase to 10 publications that year (Bongaerts et al., 2019). Unfortunately, this relatively high publication output has not been sustained.

In this perspective, we forecast the future trends of mesophotic ecosystem studies and the involvement of researchers in studying these ecosystems around the main coral reef regions of the world. In addition, we discuss the possible reasons for the disparities in these trends between the GBR and the other major coral reef regions around the world.

METHODS AND RESULTS

Global Distribution of Mesophotic Studies

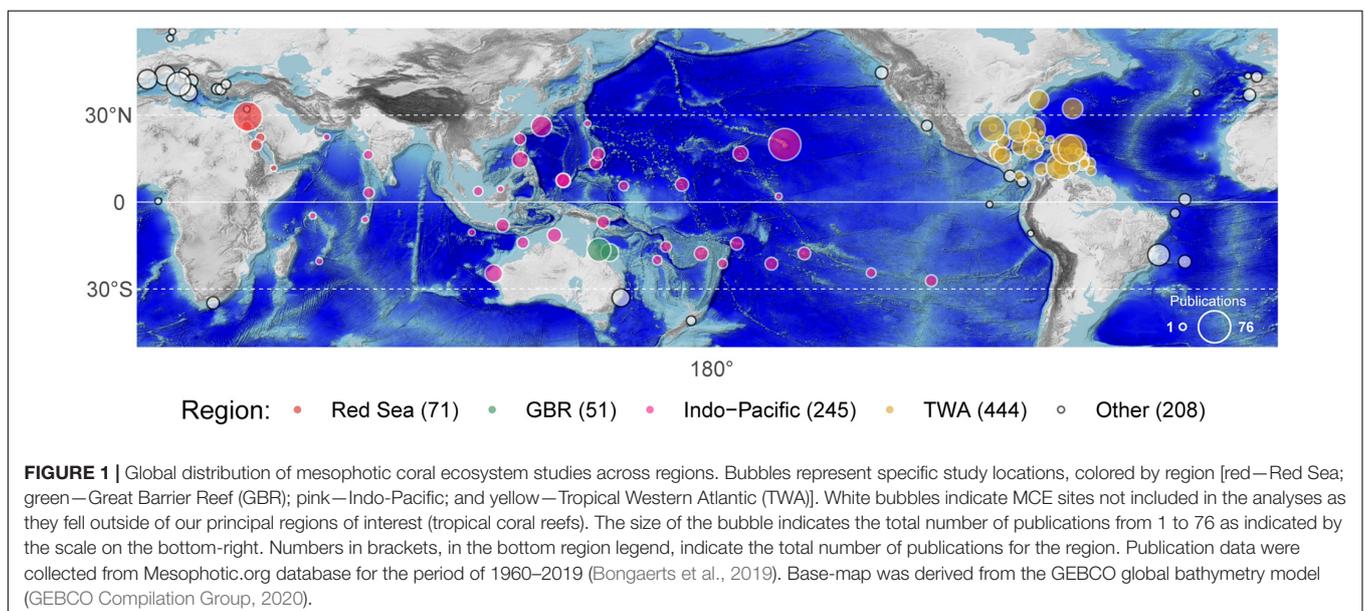
A concerted effort has been underway by mesophotic researchers to comprehensively collate both the historical and contemporary literature on mesophotic reefs into a database called Mesophotic.org (Bongaerts et al., 2019). This curated resource is openly available and allows us to quantify trends in the literature (Laverick et al., 2016, 2018; Turner et al., 2017; Lesser et al., 2019). We have divided the mesophotic literature

into four major coral reef ecoregions: (I) the Red Sea, (II) the GBR including the Coral Sea, (III) the Indo-Pacific region, and (IV) the Tropical Western Atlantic (TWA) (**Figure 1**). These ecoregions were also chosen based on regional influences of closed-by nation or several nations on the coral reef research in the area. While the first two ecoregions, the Red Sea and the GBR, have been studied almost entirely by a single nation, the other two ecoregions, the Indo-Pacific and TWA, represent a wider area and are exposed to multinational influences. Using the programming language R (R Core Team, 2013) and the *tidyverse* packages (Wickham et al., 2019), we summarized the meta-data in Mesophotic.org into annual time series of publications and unique first authors by region.

Projected Trends in the Near Future

Records of mesophotic publications started in the beginning of the 1960s with a small number of studies each year until the 1980s. Since 2010, publication rates accelerated over all regions. This can be attributed to the notable influence of the “International Workshop to Prioritize Research and Management Needs for Mesophotic Coral Ecosystems” in 2008 (Puglise et al., 2009) with mesophotic-specific funding for American-based territories that came from the National Oceanic and Atmospheric Association in the following years (e.g., NOAA, 2011, 2012, 2019). In the Red Sea, this increase came half a decade later and was partly driven by the “Second International Mesophotic Coral Ecosystems Workshop” in 2014 (Loya et al., 2016).

Analyses were performed on the individual time series for each coral reef region. We used the *forecast* package (Hyndman and Khandakar, 2007; Hyndman et al., 2018) in R to perform Holt–Winter’s filtering (Winters, 1960; Holt, 2004) without a seasonal (γ) component as our time series are annual. We then projected how these trends in yearly new publications and unique first authors may change over a 5-year prediction



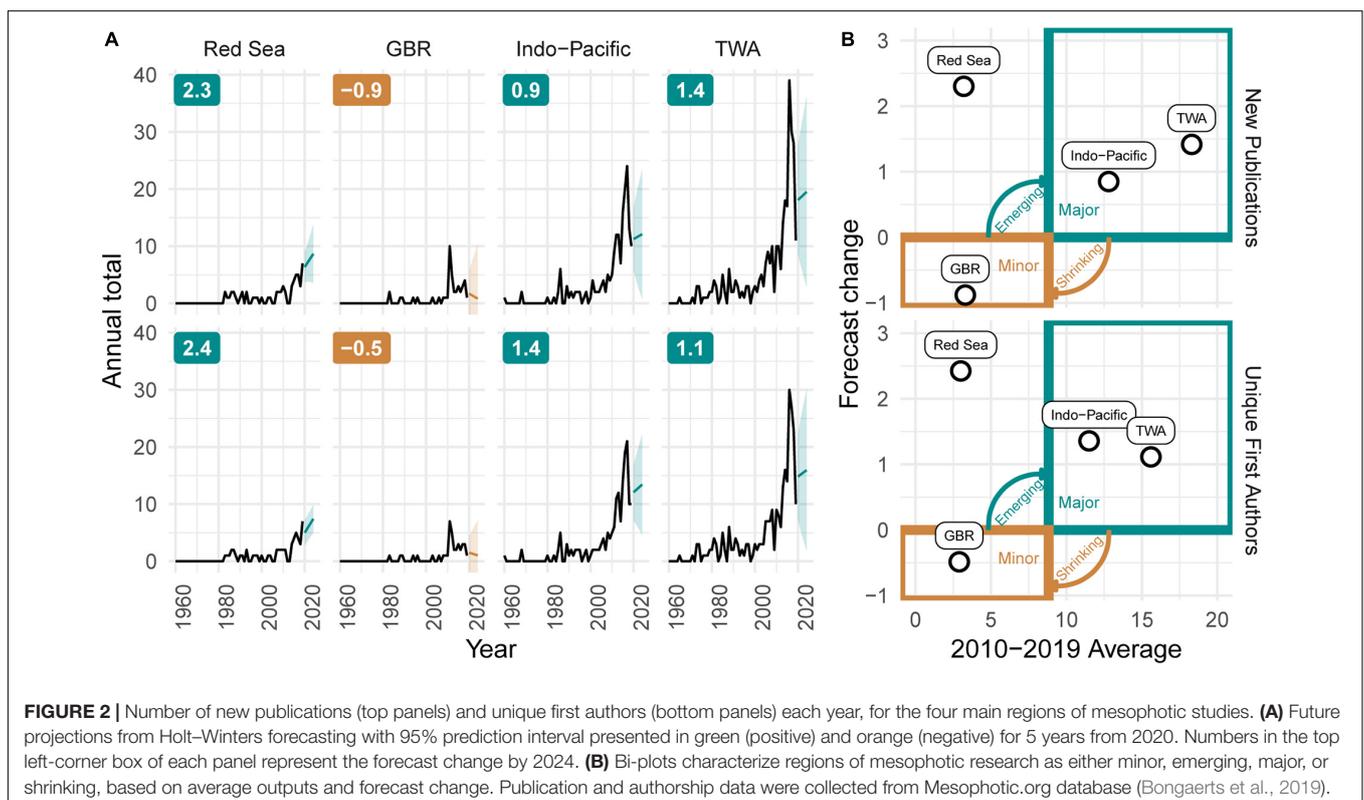
horizon (Figure 2). We found increases in the number of new publications published each year in all regions except the GBR (Figure 2A top). In addition, we forecast a slight decline of 0.5 in unique first authors over our forecast window to 2024 for the GBR compared to 2.4 more first authors in the Red Sea at the same period (Figure 2A bottom). The larger and multinational Indo-Pacific and TWA regions are the main sources of studies on mesophotic reefs, publishing more papers from more researchers than the Red Sea and the GBR. Nonetheless, both the Indo-Pacific and TWA are forecasted to continue to increase both metrics, though not as rapidly as the Red Sea (Figure 2). When considering the average values over the last decade alongside predicted rates of change, the GBR stands alone as a region with lower-than-average output and no growth (Figure 2B). We describe the other small region, the Red Sea, as an emerging region as it has below average output, which is similar to the GBR, but is growing the fastest of any region. Last, both the Indo-Pacific and TWA have above average output, as expected from larger regions, but also continue to grow.

DISCUSSION

Mesophotic coral ecosystems are the link between shallow reefs and deep-sea habitats, and host diverse depth-generalist and depth-specialist taxa, with many unique taxa as well (Eyal and Pinheiro, 2020 and the references within). New species are discovered on MCEs at a high rate, but reviving biodiversity of most regions/depths is not possible yet due to the lack of

data (Pyle and Copus, 2019; Turner et al., 2019). Marine spatial planning and adaptive management based on empirical data is needed to secure the health and protect these ecosystems. The motivation for this perspective piece is to highlight the possible causes for the disproportionately low levels of mesophotic research on the GBR, given its significance for coral reef research more generally. We also want to encourage the local and research communities, funding agencies, NGOs, and governmental authorities in Australia to bring forward mesophotic studies from the world's largest reef system. With overall decline in the health of shallow reefs over the last decades, it is important to understand the value and role of MCEs on the GBR, as well as in the context of reef ecosystems globally. Recent studies showed major shifts in cover and size-structure of corals along shallow reefs of the GBR over the last 30 years (e.g., Dietzel et al., 2020), but knowledge about these changes in MCEs is virtually non-existent for the GBR. Though historical decline has been caused by a host of factors associated with human interaction (Pandolfi et al., 2003), the current cause of this coral decline is anthropogenic climate change and recurrent bleaching events (Hughes et al., 2017, 2018a,b). The effects of heat and light stress on corals generally decrease with depth (Lesser et al., 2009) and although there is some evidence of bleaching and mortality from MCEs, this mortality is significantly lower than in shallow reefs (Frade et al., 2018).

While the rest of the world is expected to produce increasing numbers of new publications and involvement of new researchers (as measured by unique first authors per year), our forecasts suggest a stagnation of the GBR research community and even



a decline in their research efforts on MCEs. These projections are cause for concern as MCEs may play an integral role in the ecological function of coral reef ecosystems (Bridge et al., 2013). Understanding the whole coral reef ecosystem is vital for effective management and future conservation efforts (Rocha et al., 2018).

There are several reasons for the lack of growth in mesophotic research efforts on the GBR. Scientific diving in Australia is covered by the occupational divers AS/NZS 2299.2 regulations, which currently limit activity to a maximum depth of 39 m and prevent the use of closed-circuit rebreathers and decompression dives (Benjamin and MacKintosh, 2016). These regulations curtail the ability to conduct scientific diving at mesophotic depths. In most parts of the other three major regions for which we produced forecasts, the regulation of scientific diving is conducted under the American Association of Scientific Diving (AAUS) standards that specifically allow all of the above activities, and are regularly updated to include newly developed technologies and procedures (Pyle, 2019). Additionally, conducting any coral reef research in most parts of Australia is costly. This is partly because of the geographical distance and isolation of MCEs, with many of the more developed systems occurring on the edge of the continental shelf. Mesophotic research is already considered costly due to more complicated logistics and technological requirements in contrast to shallow reef studies (Armstrong et al., 2019; Pyle, 2019), and is not affordable for most researchers.

Without a doubt, climate change is the most urgent and important topic for coral reef research and society in general. The devastating effects of global warming on coral reefs are known to diminish with depth, although they are not absent from the mesophotic zone (Frade et al., 2018; Rocha et al., 2018). In Australia, anthropogenic climate change is a major concern on a daily basis (Hughes et al., 2017). Investing more effort in studying mesophotic ecosystems or conducting surveys and experiments with a wide depth range could be fruitful for protecting coral reefs for two reasons. Understanding the impacts of global change and other stressors such as overfishing, urbanization, and sedimentation on those unique ecosystems will first promote protection and management and second help to verify whether reefs from deeper depths can provide refuge to reef organisms from shallower depths (Bongaerts et al., 2010; Bongaerts and Smith, 2019).

In this perspective, we explored some possible reasons for the scarcity of research on the GBR mesophotic ecosystems (e.g., strict diving regulations, logistics, and cost). We further called upon the local and research communities, granting agencies, NGOs, and national authorities to act for the enhancement of mesophotic studies globally, with particular emphasis on efforts in Australia. In addition, we recommend the following specific actions to facilitate mesophotic research in Australia:

- 1) To increase researchers' involvement, we recommend a review of the scientific diving regulations to allow safe, but feasible, scientific diving activity on MCEs in Australia, perhaps adopting similar protocols to those of the AAUS standards or joining the AAUS.
- 2) To design research that directly meets the management needs of MCE services, and inclusion in marine spatial planning and adaptive management (Day, 2008). To understand these needs, it is critical to obtain data on the distribution and diversity of mesophotic ecosystems and the ecosystem services they provide (Turner et al., 2019). For example, the Israeli Nature and Parks Authority are responding regularly to new discoveries of MCEs in the Red Sea and Mediterranean Sea by extending Nature Reserves and prioritize protection areas with high biodiversity or unique species (G. Eyal, per. com; Bridge et al., 2013). Although a relatively large part of the mesophotic waters of the GBR and Coral Sea areas are protected by marine parks (Parks, 2020), areas assigned high protection levels (e.g., *pink*—no entry zone and *green*—no collecting zone) are more common proportionally in shallow habitats (Bridge et al., 2013). This is likely because of the larger amounts of data available for justifying protection for shallow reefs in contrast to MCEs, rather than stakeholder pressure from external groups.
- 3) To encourage combining resources and cost sharing for shallow and mesophotic research. This can be accomplished by increasing the depth range of approved surveys and long-term monitoring. Local groups, NGOs, and governmental agencies should encourage collection depositions in museums. More, joint projects could be beneficial for shallow reef surveys and collections that could be done on the ascending time from deeper depths. Furthermore, specific grant support for MCEs research could facilitate the topic in Australia and encourage MCEs research in this region. These activities are required to create a strong foundation for mesophotic research on the GBR and the Coral Sea.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

GE, JL, OL, and JP conceived the idea of the study. GE, JL, and PB collected and processed the data. All authors wrote and revised the manuscript.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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