Microbial oceanography studies in the context of climate change in the Philippines

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Studying ocean microbiomes is important in understanding the effects of the changing environment on our seas. The Philippines, being an archipelago, has been regarded as one of the most vulnerable regions under climate change scenarios, and understanding of the functions and diversity of microbial communities is a paramount step toward mitigating and adapting to the impact of globally or locally catastrophic environmental changes. We explore the current state, challenges, and potentials for microbial oceanography or marine microbial studies in the Philippines, particularly in the context of climate change, and suggest measures on how we can best move forward to upgrade and contribute to the development of this field in the country. Despite the great diversity in the marine provinces in the country and the answers they hold in unlocking the secrets of microbial communities, this review highlights that Philippine-based microbial or marine research in general has been limited. Previous microbial studies focused on applications in aquaculture and fisheries, while more basic aspects such as on diversity and ecological interactions and functioning are sorely lacking. Limited recognition and support for basic research, lack of expertise, and insufficient infrastructure (e.g., properly equipped oceangoing research vessels) were identified as critical bottlenecks in the progress of ocean research in general. The heightened national interest in the country's oceans and greater awareness of climate change threats can be a means to further spur Philippine oceanographic research that can be strengthened through the mobilization of research networks around the country.

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INTRODUCTION

The ongoing human-induced global climate change mainly associated with the greenhouse effect due to the unabated increase in atmospheric carbon dioxide (CO_2) (Solomon et al. 2009) poses great threats to the earth's physical and biological systems (see Rosenzweig et al. 2008). Oceans specifically absorb and serve as reservoirs of a significant portion of the earth's CO_2 through several processes (see Heinze et al. 2015). Thus, investigating mechanisms concerning carbon transport in the oceans has been one of the key challenges in further understanding, predicting, and possibly mitigating the effects of climate change. Consequently, several studies have been done to understand physical and biological mechanisms involved in carbon sequestrations (Sarmiento and Gruber 2006 and references therein). These studies have shown that, in the wake of the changing climate, changes in the physicochemical regimes in oceans would have profound implications on the structures and functions of the microbial communities. Since microbial organisms are at the base of the food web, they are also at the frontline of being affected by climate change. Studying ocean microbiomes then is important in understanding the effects of the changing environment on our seas (Bowler et al. 2009) and would be a paramount step toward mitigating the impact of globally or locally catastrophic man-made changes (Paerl et al. 2003).

The Philippines, being an archipelago, has been regarded as one of the most vulnerable regions under climate-change scenarios. The Philippines is a highly vulnerable region with the different seas expected to experience varied changes such as increased surface temperatures, salinity change, and decreased upwelling (David et al. 2015). Changes such as strengthened stratification and weaker upwelling will significantly have an impact on the microbial food webs and ultimately the food and energy flows in these ecosystems. Studies on fish populations, for example, showed that the current and predicted decline in fisheries has been associated not only with unsustainable fishing practices but also with the decreasing global primary productivity (i.e., phytoplankton chlorophyll *a* as proxy for phytoplankton biomass) due to the changes in the physicochemical regimes of oceans (Brander 2007; Chassot et al. 2010; Stock et al. 2017). This would ultimately affect food supply and human consumption. Further, changes in rainfall patterns can affect runoff and stratification conditions, favoring the toxic or harmful algal species that could have direct negative impact on coastal inhabitants, and indirectly affecting ecosystem balance and energy dynamics of coastal environments (Anderson 2012). There is a great need for a country such as the Philippines, which is highly dependent on the bounties and productivity of its seas, to be more concretely cognizant of the consequences of the changing environment at the very base of the food webs. The effects of man-made and natural changes, however, remain difficult to disentangle and delineate from each other for lack of multiyear or long-term and large-scale data as indicators for such changes.

Recent advances in molecular approaches (e.g., microarray, automated ribosomal intergenic spacer analysis (ARISA), high throughput sequencing) to the study of microorganisms have allowed the dissection and exploration of ocean microbiomes at the local, oceanic, or even planetary scales. In fact, many collaborative and interdisciplinary research expeditions—the Long-Term Ecological Research in Antarctica (Moline and Prezeline 1993), Global Ocean Sampling (GOS) (Kopf et al. 2013), Tara Oceans Expeditions (Karsenti et al. 2011; Zhang and Ning 2015), Malaspina Expedition (Duarte 2015), Beaufort Gyre Exploration Project-Joint-Ocean Ice Studies (Li et al. 2009), and the continuous plankton recorder programs in Southern Oceans, North Atlantic, and North Sea (Hosie et al. 2003), to name a few (see Salazar and Sunagawa 2017)—have been carried out toward this goal. Results of these studies generated significant information on the potential trajectories of the microbial food webs in different oceans in response to the changing climate. However, such studies are still limited or nonexistent in the western Pacific Ocean, inland seas of the Philippine Archipelago, and West Philippine Seas. Despite the great diversity in the marine provinces and the potentials they hold in unlocking the secrets of microbial communities, Philippine-based microbial oceanographic or marine research in general has been limited to the use of conventional microscopic or flow cytometry approaches (see succeeding sections). Also, very few long-term phytoplankton records exist and are limited to certain localities, with most focusing on species that are harmful algal bloom (HAB) forming (e.g., Azanza et al. 2006). While understanding certain taxa could reveal specific trends with the changing environment (i.e., increased nutrient input), understanding of ecosystem-level responses toward regime shifts is still limited.

Our understanding of the implications of the changing environments on the future of our oceans will also have profound implications on our ability potentially to prepare and adapt to their consequences. The recent advances in molecular technologies, and the availability of infrastructure and computing resources to Filipino oceanographers, microbiologists, and ecologists, can provide opportunities further to explore the Philippine seas. Thus here we explore the current state, challenges, and potentials for microbial oceanography or marine microbial studies in the Philippines, particularly in the context of climate change, and suggest measures on how we can best move forward to upgrade and contribute to the development of this field in the country.

Environmental studies on microbial communities in the Philippines

The Philippine archipelago is known to be a hot spot for biodiversity. In fact, the country has been recognized as the global epicenter of marine biodiversity. This is particularly true for corals, gastropods, other marine invertebrates, and reef fishes. For these marine macroorganisms, studies showed that diversity seems to be highest in the Verde Island Passage between Mindoro Island and Luzon (Carpenter and Springer 2005), tagging it as the "Amazon of the Seas." Further, a recent and probably the only survey so far of large benthic foraminifera revealed that the Central Philippines also emerged as the bull's-eye for the highest diversity in this taxonomic group (Forderer et al. 2018). However, descriptions on the larger-scale spatial and temporal patterns of microbial abundance and diversity, and the potential drivers of their community structuring in the archipelago, have not yet been investigated, especially in the context of the changing climate. In this section, we give an overview of the state of science from available relevant published papers and articles on studies carried out either entirely or partly in the Philippines. However, we exclude unpublished proceedings, graduate school theses and dissertations, workshops, and book reports.

A. Ecology and diversity

Microbial communities are considered "masters" of biogeochemical processes in all ecosystems, making them important indicators of the changing environment, which has been further elucidated by new and emerging technologies such as those utilizing the *-omics* approaches (i.e., metagenomics, metatranscriptomics). These technologies revealed the underlying molecular mechanisms on how microbial communities drive ecosystem functions. For example, high throughput amplicon sequencing of waters collected from all oceans revealed an unprecedented diversity of microbial taxa across domains of life in the sunlit upper waters (e.g., Lopez-Garcia et al. 2015; de Vargas et al. 2015). The vast diversity of microorganisms could translate to many ecological niches and functions that are driving many environmental processes. Metatransciptomic profiling further revealed the high expression of genes involved in photosynthesis, carbon fixation, and nitrogen acquisition in open oceans (Firas-Lopez et al., 2008). These new insights from *-omics* approaches indicate the potentially unknown and underappreciated processes and roles played by microbes in the marine environment. For example, microbes mainly through the photosynthetic phytoplankton contribute a significant portion to carbon sequestration or the biological carbon pump (BCP), which regulates global CO_2 levels. Particularly 100% of the particulate organic carbon

(POC) found in the surface layer of the oceans is derived from this process. Of these, around 50% is transferred and lost through the higher trophic levels, while about 25% sinks to the deeper layers with about 1% to 3% becoming stored in the sediments (de la Rocha and Passow 2007). Another important mechanism of carbon removal in the pelagic waters is through the bacterial or microbial carbon pump (MCP) (Jiao et al. 2010; Polimene et al. 2017), where dissolved organic matter (DOM) is converted to compounds recalcitrant to microbial oxidation (RDOM). The conversion of dissolved inorganic carbon (DIC) to POC or RDOM is mainly driven by a myriad of interactions and trophic upgrading in the microbial food web composed of species across the domains of life (Guidi et al. 2016; Polimene et al. 2017). These carbon sequestering processes emphasize the role of the microbial communities not only in supporting productivity of marine or oceanic environments but also in their significance in the global biogeochemical cycles. However, climate change affects the physicochemical regimes of oceans. Strengthened stratification in the upper layers of the oceans is being observed due to either freshening (e.g., polar regions) or thermal warming (e.g., Pacific Ocean, Mediterranean), causing less mixing and nutrient limitation in the photic zone (Moore et al. 2013; Muller et al. 2017). This in turn affects the biological productivity of the large-cell taxa (e.g., diatoms), which are then replaced by small-cell species (i.e., picophytoplankton) due to their surface area to volume ratio advantage (Li et al. 2009; Comeau et al. 2011; Peter and Sommer 2013). Increased influx of CO_2 into the ocean is also predicted to cause decline in pH resulting in ocean acidification especially in the surface waters or the photic zone where most productivity is occurring (Doney et al. 2009). Limited available studies have also shown negative effects of acidification on microbial functions such as calcification, quorum sensing, nitrogen cycling, and extracellular enzyme activity (Das and Mangwani 2015; Muller et al. 2017), although results remain inconclusive due to multiple effects (Bach et al. 2017; Irwin et al. 2015). Others also reported increased dissolved inorganic carbon (DIC) consumption of the phytoplankton community with rising CO_2 levels in mesocosm experiments (Riebesell et al. 2007). Modeling studies further suggest that acidification might have more deterrent effects than nutrient limitation or warming, resulting in shifts in the structure of the community due to changes in competitive fitness and altered interactions among phytoplankton types (Kroeker et al. 2012; Dutkiewicz et al. 2015). All of these changes have significant implications on the availability of prey selection for larger heterotrophs (e.g., zooplankton) and for carbon transport as small cells do not sink efficiently, which in the long term could have cascading effects on the higher trophic levels and benthic communities (Bach et al. 2017; Griffiths et al. 2017).

Another player in the microbial community that is just starting to be understood are the viruses. In any environment, viruses are the most abundant entities, being 5 to 25 times more abundant than bacteria (Proctor and Fuhrman 1990; Fuhrman 1999). For example, they were reported to be 10^7 to 10^9 g^{-1} in sediment/topsoil (Ashelford et al. 2003), 10^{10} L^{-1} in surface waters (Bergh et al. 1999), and 10^{30} particles in the marine environment (Suttle 2005, 2007). It is in this context that they also serve as major channels of genetic exchange in oceans (Rohwer and Edwards 2002), affecting biogeochemical cycles, food webs, and metabolic balance (Weitz and Wilhelm 2012). Changing climate can directly and indirectly influence the activity of these viruses toward their hosts and environment. The International Committee on Taxonomy of Viruses (ICTV) listed a wide variety of viruses infecting different organisms but tending to be most abundant in the oceans due also to the abundance of their bacterial, archaeal, and eukaryotic hosts (Fuhrman 1999; Weinbauer 2004; Weitz and Wilhelm 2012). Viral infections usually result in death of host cells, causing the release of microbial biomass into the environment in the form of DOM and particulate organic matter (POM) (Danovaro et al. 2011; Weitz and Wilhelm 2012). These organic matter are eventually used up by the heterotrophs and thus have an impact on nutrient cycling, and change the pathways of organic carbon (OC) used by prokaryotes (Wommack and Colwell 2000; Weitz and Wilhelm 2012). The viral-induced changes in the biogeochemical cycle were referred to as the "viral shunt" (Wilhelm and Suttle 1999), and, as later studies showed, the viral shunt releases 0.37–0.63 Gt carbon year^{-1} on a global scale (Danovaro et al. 2008). The metabolism and nutrient turnover in the microbial community is augmented when the lysis of host cells release cellular components such as proteins and nucleic acids, which are rich in phosphorous and nitrogen compounds (Fuhrman 1999; Wilhelm and Suttle 1999; Middelboe and Jorgensen 2006; Middleboe and Brussard 2017). This virus-induced lysis not only supplies nutrients to the prokaryotes but also enhances the growth of some organisms such as the phytoplankton that are competing for resources in the environment, especially in the surface waters (Proctor and Fuhrman 1990; Fuhrman 1999). However, according to recent evidence, this shunt is also significantly contributing to carbon flux in the North Atlantic by allowing aggregation of the lysed cells (Weitz and Wilhelm 2012). There is still a scarcity of papers to support the role of viral decay in the algal community in the oceans, but available data are enough to support claims that viral lysis promotes the regeneration of inorganic nutrients and trace elements (i.e., iron) (Gobler et al. 2007) for both groups of organisms. However, these observations on the role of microbial communities in ecosystem functioning were mainly based on temperate or Arctic investigations, and no detailed studies have been done yet in Philippine waters, which respond differently to climate change.

From a literature search for publications of research carried out in the Philippines on marine phytoplankton, nonphotosynthetic protists, fungi, bacteria, and viruses spanning 1995–2017, a total of 103 journal articles were retrieved. Most of these were about bacteria (39%), followed by the phytoplankton (27%), viruses (24%), fungi (8%), and nonphotoynthetic protists (2%) (fig. 1). A majority of the publications on microalgae were in relation to HABs (61%), while the remaining 39% were on phytoplankton diversity, growth, and bioactivity (fig. 2). For marine bacteria, most of the papers were related to aquaculture—fish and shrimp diseases (56%), followed by associations with corals and other invertebrates (20%), HABs (15%), and water and sediment (7%). One study looked at microbial community populations in Benham Bank. Results of a survey of Benham Rise in 2014 revealed a high diversity of bacteria with structuring reflective of the characteristic stratification of the ocean, suggesting that the Philippine microbial communities might also be experiencing the same changes as those in other regions (Gajigan et al. 2018). For the viruses, all the studies were related to aquaculture—viruses infecting marine fish and shrimp.

These publication patterns show that most Philippine studies on marine microorganisms were in relation to applied aspects: on fish and shrimp health and HABs (figs. 2 and 3). Most of the studies related to aquaculture were on the detection, characterization, and control of bacterial fish and shrimp pathogens (Fernandez et al. 1996; Leaño et al. 1996; Lio-Po et al. 1996; Alapide-Tendencia and Dureza 1997; Lavilla-Pitogo 1998; Lavilla-Pitogo and de la Peña 1998; Lavilla-Pitogo et al. 1998; Leaño et al. 1998; Tendencia 2001; Tendencia and de la Peña 2001; Leaño et al. 1998; Lio-Po 1998; de la Peña et al. 2001; Tendencia and de la Peña 2002; Kim et al. 2003; Tendencia and de la Peña 2003; de la Peña et al. 2003;

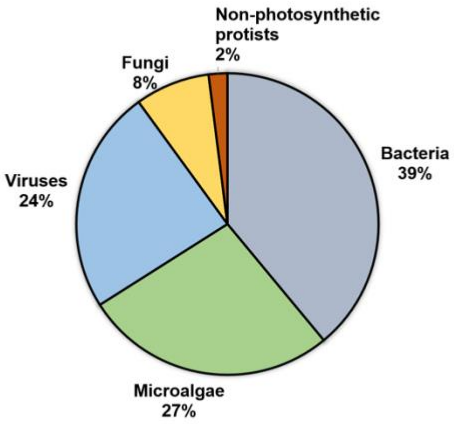

Figure 1: Percentage of marine microbiology or microbial oceanography papers from a total of 103 published from 1995 to 2017 classified into the main topics microalgae, bacteria, viruses, fungi, and nonphotosynthetic protists.

Tendencia 2004a, 2004b; Maluping et al. 2004; Lio-Po et al. 2005; Tendencia et al. 2005; Tendencia et al. 2006a, 2006b; Tendencia et al. 2006; Maluping et al. 2005; Tendencia 2007; Reichardt et al. 2013; Lazado et al. 2015; Laranja et al. 2017). The microalgal studies related to HABs, by contrast, were mostly looking at life history, ecological dynamics, cyst distribution, and mitigation (Azanza and Taylor 2001; Azanza et al. 2004; Sombrito et al. 2004; Gedaria et al. 2007; Azanza et al. 2008; San Diego-McGlone et al. 2008; Siringan et al. 2008; Tang et al. 2009; Padilla et al. 2010; Baula et al. 2011; Santos and Azanza 2012; Azanza et al. 2013a; Azanza et al. 2013b; Orizar et al. 2013; Manset et al. 2013; Onda et al. 2014; Onda et al. 2015; Subong et al. 2017). Some papers were focused on the diversity and culture of phytoplankton (Asis et al. 2006; Lacuna et al. 2012; de la Peña 2007; Yap-Dejeto et al. 2013) and on fungal diversity (Su et al. 2014). A number of papers were on bacteria in the sediment and water column (Santander et al. 2008; Sombrito et al. 2009; Suzuki et al. 2013) and on bacterial associations with corals (Arboleda and Reichardt 2009; Garren et al. 2008; Garren et al. 2009), sponges (Pimentel-Elardo et al. 2008), bivalves (Brissac et al. 2011), shipworms (Distel et al. 2017), snails (Torres et al. 2017), and seaweeds (Martinez and Padilla 2016). From a total of 25 studies for both shrimp and fish viruses, only 6 papers were published on the latter (fig. 3). Studies on shrimp viruses show an increasing trend from having only 2 publications from 1995–2000 to 9 publications between 2011 and 2017. Publications on fish viruses did not show a similar trend as they had decreased from 2001–2005 to 2011–2017 (Maeno et al. 2002; Maeno et al. 2004; Azad et al. 2006; Kiryu et al. 2007; de la Peña et al. 2008; de la Peña et al. 2011). Occurrence and prevalence of the viruses infecting shrimp were mostly studied in earlier years (Tapay et al. 1999; Magbanua et al. 2000; Catap et al. 2003; de la Peña et al. 2003; Natividad et al. 2006; de la Peña et al. 2007; de la Peña et al. 2008; Caipang and Aguana 2010; Tendencia et al. 2010a; Tendencia et al. 2010b), but publications from 2011–2017 focused more on the detection (Caipang et al. 2011; Maralit et al. 2011; Alenton and Maningas 2011; Tendencia et al. 2011; Sibonga et al. 2013; Nicolasora et al. 2014; Maralit et al. 2014; Orosco and Lluisma 2017a; Orosco and Lluisma 2017b). The papers on fish viruses mainly focused on prevalence, distribution, and characterization. The trend toward application is also seen in the two protist publications, which were on thraustochytrid fatty acid production (Leaño et al. 2003; Arafiles et al. 2011), in some of the algal papers (Leaño et al. 2005; Cremen et al. 2007; Seraspe et al. 2012; Bosma and Tendencia 2014; Tendencia et al. 2015), and in a number of fungal (Yao et al. 2009; Ramirez et al. 2010; Solis et al. 2010;

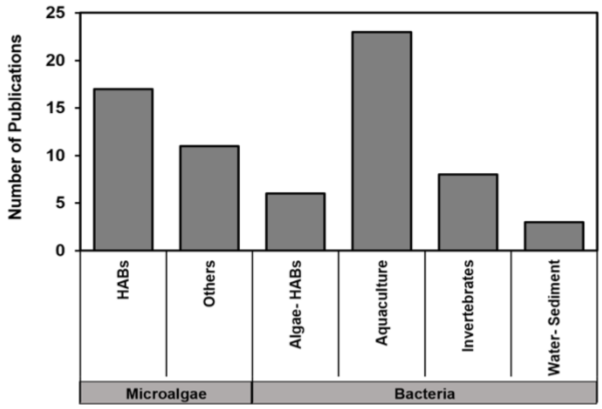

Figure 2: The number of Philippine-based papers related to the microalgae and bacteria and published from 1995 to 2017.

Torres et al. 2011; Lavadia et al. 2017) and bacterial papers (Ferrer et al. 2017; Marquez et al. 2015). This observation underscores the importance of aquaculture to the Philippine economy and highlights the major issues and opportunities to be addressed in this industry.

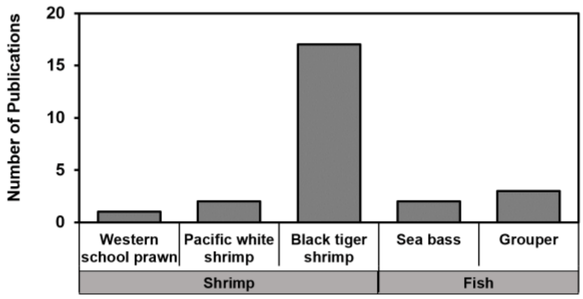

Figure 3: The total of number of scientific articles related to viruses and published by Filipino researchers or Philippine-based researchers from 1995 to 2017.

That there has been an increasing trend in the number of marine microbiology papers published over the last 20 years (fig. 3), reflecting more researchers and funding going to this field, is encouraging to see, but there are still gaps needed to be filled in terms of focus and approach. Among all the microbial groups, there is much less attention given to marine fungi and protists than to the algae, bacteria, and viruses. Perhaps this may be because they do not figure as much in diseases of cultured species, although they are important contributors to several processes, such as organic matter transformations in the marine environment. Further, because many of the papers were associated with aquaculture animals, there is much less knowledge on microbial diversity present in the water column and sediments. Finally, published papers from Philippine institutions were generally focused on species- or cellular-level types of studies, with very few, if any, on community- or ecosystem-level dynamics. These latter approaches are important because what can have significant implications to the ocean ecosystem are the interactions of these microbes with one another.

B. Long-term monitoring studies

Microbial communities exhibit immense variability in both time and space, and both pose challenges in studying microbial ecology. Several studies demonstrated the strong relationship between seasonality of microbial communities and global change (e.g., Weitz and Wilhelm 2012). Thus, understanding of their seasonality could also lead to insights into the changes in environmental conditions that broadly affect global cycles such as CO_2 (e.g., Lindemann and St. John 2014; Iida and Odate

2014; Deppeler and Davidson 2017). However, despite the scale and the magnitude of the effects of the changing climate on the oceans and their biogeographic regions, our understanding of the implications of these changes on the marine environment compared to the terrestrial environments is still lagging (Rosenzweig et al. 2008). Temporal variability, specifically including seasonal or interannual turnovers, requires periodic sampling to detect patterns clearly. This is due to the considerable uncertainty regarding the spatial and temporal details of these effects on aquatic environments (Jones et al. 2012). Most of what we know on the global changes in oceans are mainly based on remote sensing, predicting, and correlating changes in sea surface temperature, weather patterns, ocean currents, and CO_2 partial pressure with primary productivity using Chl *a* fluorescence as a proxy (e.g., Behrenfeld et al. 2014; Kostadinov et al. 2010; Head and Peppin 2010; Rousseaux and Gregg 2015; Gregg et al. 2017). Despite these limitations, gathered observations still yielded new and valuable insights about the environment. For example, modeling studies derived from remote sensing data have shown alarmingly that regions with higher biodiversity are also the areas to be most affected by the changing climate and industrial fishing (Ramirez et al. 2017). However, ground truthing and studies based *in situ* are still needed to verify these observations.

Although useful in inferring and detecting global patterns, remote sensing data do not provide fine-scale resolution on the taxonomic groups that might be directly responding and affected, and thus resulting in incoherent understanding of the roles played by species-species interactions (Rocchini et al. 2015). Recent advances, however, showed promising applications in this direction (He et al. 2015). *In situ* sampling and analyses are still needed to generate taxonomically resolved profiles and species-based understanding of community changes, providing another layer of information not possible using remote sensing. Seasonal sampling allows detection of patterns in community succession and the factors that drive these patterns, which are further useful in estimating system productivity, timing of growth, and succession of species. All of these in turn could be linked to fisheries such as in upwelling regions. Temporal studies could also provide insights to predict occurrences of certain species such as the toxic phytoplankton or HABs-causing organisms (Anderson et al. 2012; Shen et al. 2012). Interannual studies, by contrast, allow detection of long-term changes associated with weather, climatic anomalies, or physicochemical regime shifts of the oceans (e.g., Beare et al. 2013; Head and Pepin 2010; Maillet and Pepin 2017). In the Arctic, for example, interannual sampling and cell count showed that small phytoplankton were becoming more dominant while the large phytoplankton were diminishing with increasing stratification (Li et al. 2009). These observations were complemented with high throughput sequencing molecular data, and mixotrophic species such as ciliates and dinoflagellates were shown that they could become more important in this paradigm shift in response to events that are low-ice related (Comeau et al. 2011; Onda et al. 2017). These ground-truthing observations have complemented modeling studies that predicted such changes in community dynamics based on parameters derived from *in situ* measurements (Head and Pepin 2010; D'Alelio et al. 2016).

In Europe, America, eastern-northern Pacific, and Southern Oceans, a series and network of monitoring stations have been established, dedicated to the understanding of the biological changes in the context of climate change (e.g., Karl and Lukas 1996; Matsumoto et al. 2016; for other stations, see http://ijgofs.whoi.edu/Time-Series/LTTS.html). The time-series sampling, coupled with a molecular approach, could even elucidate abrupt changes in response to small perturbations or disturbances associated with alternate stable states (Faust et al. 2015). Further, they could generate invaluable insights on the long-term changes happening in the marine environment, providing opportunities to infer the possible trajectories of these systems.

In the Philippines, long-term monitoring and studies for phytoplankton communities are rare, with most attention focused on economically important species such as the HAB-forming phytoplankton and limited to some embayment such as Manila Bay and Bolinao (Azanza and Miranda 2001; Azanza et al. 2005; Azanza and Benico 2013). These historical data allowed for the correlation of HABs occurrences with meteorological patterns and regional atmospheric oscillations such as El Niño (MacLean 1989; Wang et al. 2008). Monthly sampling also established the patterns of HABs occurrences in Manila Bay, where the trade winds cause mixing in the water column that resuspend and induce regeneration of the cysts, resulting in bloom formations that are transported from the south to the north of the embayment (Azanza and Miranda 2001; Villanoy et al. 2006). These *in situ* collected data were also helpful in parameterizing and improving general HABs models (Yñiguez et al. 2012, 2018; Cayetano et al. 2013). Thus *in situ* long-term monitoring studies highlight the importance of basic research in the understanding of ecological systems to prepare ourselves better for the effects of climate change, and this will be helpful in crafting policies and management strategies for our marine ecosystems—a much-needed initiative in the Philippines.

Resource needs for microbial oceanography and climate change research

Clearly, compared to the progress in the field of microbial oceanography and climate change research in other countries and regions, the Philippines is behind. Endeavors to improve and enhance our capacity to conduct marine or oceanographic studies would need investments in physical laboratories, equipment, technologies, seagoing capabilities, and manpower. This also entails recognition of the role of basic science in paving the way for new discoveries, innovations, applications, and development, especially in the era of accelerated environmental changes and human-induced climate change. Here we looked at the three most crucial factors that might be affecting our pace in moving forward in marine or oceanographic research studies, namely, funding, expertise, and infrastructure.

Funding for basic research in the country remains dependent on public funds. The Philippine government, through the Philippine Council for Agriculture, Aquatic and Natural Resources Research and Development (PCAARRD) under the Department of Science and Technology (DOST), remains one of the biggest funders for environmental, aquatic, and oceanographic types of studies. From 2000 to 2018, the agency (formerly Philippine Council for Aquatic and Marine Research and Development, or PCAMRD) supported and granted a total of 156 marine and oceans-related research projects (projects within programs considered separately) (fig. 5). DOST's budget has also been increasing throughout the years with \$32 million in 2017 from \$30 million in 2016, but the allocation for the research component did not change from the \$12 million since 2008 (Ilano 2017). Interestingly, available data showed that the number of approved and funded projects related to these fields under PCAARRD, for example, has increased throughout the years (fig. 5). The common sentiment among the local scientific community is the necessity to embed basic researches into an overarching goal of producing an application or development of a product at the end of the project (Ilano 2017). Although there is justification that research funded by taxpayers' money should

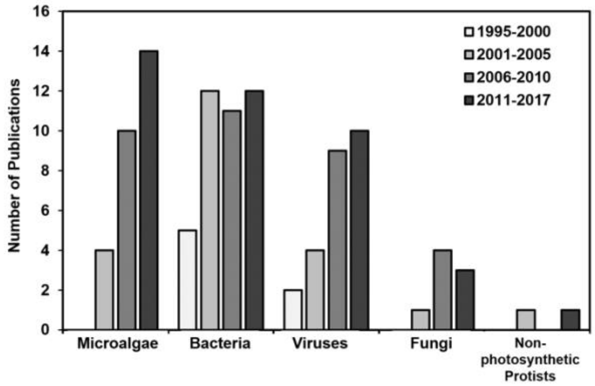

Figure 4: Growth in the number of scientific papers related to marine microbiology or microbial oceanography published every five years from 1995 to 2017.

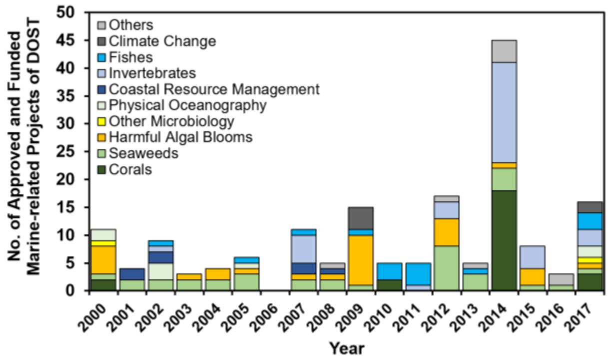

Figure 5: A summary of the marine-related projects funded by the Department of Science and Technology through the Philippine Council for Aquatic and Marine Research and Development (PCAMRD, 2000–2010) and Philippine Council for Agriculture, Aquatic, and Natural Research and Development (PCAARD, 2010–2017). The counts were based only on the start year and separately considered each project component within the programs.

provide some direct benefit, there should also be a recognition that applied science relies ultimately on the foundations upon which it lies—basic science. Most of the funding for purely basic research comes from the National Research Council of the Philippines (NRCP), also under DOST. However, compared to grants-in-aid (GIA), NRCP's budget is small with only around $450,000 per year (Ilano 2017). The projects that cannot be funded by NRCP are still referred to DOST-GIA. There is a growing recognition of a need to invest in basic or pure research before producing innovations and applied sciences. Thus, with that recognition, there should be a strategy for DOST and other funding sources to support both basic and applied research not only in microbial oceanography but also generally in oceans research to help move scientific developments in the country.

The second important factor that hinders our progress in the field of microbial oceanographic research is the lack of experts in marine microbiology and allied fields in oceanography. To date, the Philippines, which has one of the highest number of islands and several seas, still has limited training institutions for inspiring researchers in the field of basic oceanography or marine sciences, in addition to fisheries and agriculture. Filipino oceanographers in the country are currently estimated to be below 20, a very low number given the area needed to be studied. The Marine Science Institute of the University of the Philippines (UP MSI) remains to be one of the most significant producers of scientists trained in such fields but still falls low for microbial or biological oceanography. The lack of experts or the institutes capable of carrying out microbial oceanography studies potentially translates to the low number of DOST-funded projects focused on these topics. In figure 5, for example, HABs or other microbiology projects were mainly proposed and implemented by the UP MSI, with most of the marine-related studies and programs also only being led by UP-based scientists hosted in UP campuses especially after 2000. Further, most of these studies were on aquaculture (e.g., seaweeeds, invertebrates), fisheries, physical oceanography, corals, and coastal management. Full understanding of phenomena in the open and connected systems requires more physicists, biogeochemists, oceanographers, and biologists working together and approaching scientific questions from a trans- and interdisciplinary perspective. Expertise and knowledge on new and emerging technologies in microbial research should also be built up, especially the *-omics* approaches (i.e., transcriptomics, genomics, metagenomics, proteomics, metabolomics). Most if not all studies recently published on diversity, biogeography, functions, and interactions have been using these technologies but remain little utilized or implemented in Philippine-based studies. The recent establishment of the Philippine Genome Center (PGC) at the University of the Philippines, Diliman, could help in accelerating the transfer of these technologies. However, compared to foreign-based companies or institutions, services being offered by PGC are still more expensive than their foreign counterparts and become inaccessible to most local researchers.

Ocean studies are challenging to carry out primarily because there is a need for seagoing missions to collect data, conduct experiments, or verify observations. This entails the necessity for open-ocean and research-capable vessels. While there had been significant improvements in infrastructures in terms of new technologies, laboratories, and computing capabilities (i.e., PGC, DOST Advanced Science and Technology Institute) in different parts of the country, our seagoing capabilities for research remain limited. For example, the UP MSI, which is the national center for marine science, does not have a dedicated open-ocean research vessel and still depends on collaborations (local or international) to carry out expeditions. These were emphasized during the senate hearing on Marine Scientific Research (MSR) permits in the West Philippine Sea and Philippine Rise (Terrazola 2018). Despite these limitations, Filipino scientists were still able to contribute significantly to the understanding of our oceans through collaborations, which led to some increase in research activities in the field of microbial oceanography. For example, collaborations with United States researchers resulted in the Philippine Straits Dynamics Experiment (PhilEx), which investigated circulation and productivity patterns around the archipelago through four major expeditions aboard the Scripps Institution of Oceanography's R/V *Melville* (Gordon and Villanoy 2011). The results from the physical oceanography studies were published in a special issue of *Oceanography* (Gordon and Villanoy 2011), while still-to-be-published results for plankton on the northeast side of the Philippines have shown spatiotemporal variations likely due to shifts in the bifurcation latitude of the North Equatorial Current (Cordero-Bailey et al. in prep.). DOST local support was also provided for oceanographic research that investigated for the first time the physics, phytoplankton, larvae, and sardines in a major upwelling area in the Philippines. This allowed for the optimization of a flow cytometry and imaging instrument in the characterization of phytoplankton in the upwelling areas (Camoying and Yñiguez 2016; Camoying 2016). The Bureau of Fisheries and Aquatic Resources (BFAR) has also frequently allowed the use of its ship, the M/V DA-BFAR, while the Philippine Navy has been providing the BRP Gregorio Velasquez (previously the R/V Melville). However, research is not the priority for these agencies and vessels, and the research equipment on-board these ships are limited, outdated, or in need of repairs. Support technicians familiar with oceanographic research work are also very much needed. Clearly the necessity to train more people in science and their supporting manpower is eminent to move forward with oceans research in the country.

Future directions and perspectives

The Philippines is a unique archipelago with thousands of islands and vast regions of open oceans and seas. Within these heavily unexplored ecosystems are the world of microbes providing a wealth of ecosystem services, genetic resources, and products that remain underappreciated and untapped. The potential roles of the microbial communities in the productivity of our seas, stability of ecosystems, and resiliency to changes warrant their further understanding. The heightened political and national interest in the country's oceans and greater awareness of climate change threats seem to have helped spur Philippine oceanographic research somewhat. Support from government institutions for oceanographic research cruises in the Benham Rise and the West Philippine Sea has been and is still being provided. However, out of the 32 microbial research projects funded by PCAMRD-PCAARRD from 2000 to 2018, only 2 were focused on basic research on microbial ecology and 2 on climate-related studies (fig. 5). These include the newly funded programs proposed also by UP MSI. First is a new HABs program that started in April 2018 and focused on consolidating valuable time-series data on phytoplankton and physicochemical parameters to get a better handle on long-term trends and potential climate change signals, as well as looking into other microbes in HAB-affected areas. Meanwhile, the country's first research program on ocean acidification entitled "Coastal acidification: how it affects the marine environment and resources in the Philippines" also just started in February 2018, also through DOST funding. Included in this program is a project dealing with the effects of ocean acidification on the planktonic community in a natural setting and in mesocosms using microscopy and molecular approaches.

One institute or research group, however, is not enough to investigate all the issues the country is facing. We should start building up a road map and training more experts. While the UP, as the national premier university, does well to take the lead in these endeavors, its limited manpower and scope could also impede progress in expanding to other areas of research. There is a need to decentralize or even create a complex network of experts where research, mentoring, and publication will be targeted nationally with international partners. This can be done through a national research program where experts from new and emerging fields partner with researchers from related fields to generate data and in the process train local scientists in new tools and techniques while producing new scientific knowledge. Such framework will allow local science to progress while building new capacities and opening new areas of research. Further, we need to invest in experts in unexplored fields not only in oceanography but also across fields in marine science, both ultimately going hand-in-hand to understand microbial dynamics. A network of universities, institutes, laboratories, or hubs working in synergy will help cover the entirety of research needed to be done in an archipelagic country. This could be achieved by partnering with scientific societies (e.g., Philippine Society of Microbiology, Philippine Association of Marine Sciences) or by hosting a national meeting to create a road map and open up opportunities for early career researchers in these fields of study (i.e., environmental studies).

The Philippines being a highly vulnerable country, more studies on biological mechanisms that influence, and control biogeochemical cycles related to carbon exchanges between the atmosphere and land-ocean systems are still needed to be done to predict the direct consequences and implications of these man-made changes in the country (Heimann and Reichstein 2008). In doing so, we need not only to focus on the upper waters where most of carbon fixation and assimilation are happening but also to explore the depths of the oceans where corresponding processes affect carbon storage. There is also a need to relate terrestrial influences (i.e., runoffs, leaching) that would ultimately affect microbial assemblages with the changes occurring in the oceans—adapting a more holistic "ridge to reef" approach. The Philippines is home to a diverse population of microbial species, and through this review we have seen that these have been barely explored by the Filipino scientific community. This also translates to more opportunities for scientific researchers and future science graduate students. With that, there is an urgent need to determine the following: (1) biodiversity of viruses, prokaryotes, and protists in our oceans, (2) their roles in forming structural components of our marine food webs and ecosystems, (3) their involvements in the biogeochemical processes and correlations with local productivities (i.e., fisheries), and (4) construction of holistic ecosystem-scale models that include not just large microplankton but also protists and viruses. The unique hydrographic patterns and diversity of Philippine seas serve as natural laboratories or background to test several hypotheses related to the changing climate, and this will be significant not only to the local setting but also to the international community. Being at the center of the center of marine biodiversity is both a privilege and a responsibility, and part of fulfilling that responsibility is to understand these systems through scientific research to manage them sustainably better for the generations to come.

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CONTRIBUTION OF INDIVIDUAL AUTHORS

Deo Florence L. Onda, Mary Ann G. Santos, and Donna de la Cruz-Papa conceptualized, conducted the review, generated the graphs, and prepared and finalized the manuscript; Aletta T. Yñiguez contributed in some of the sections and finalized the manuscript; Ma. Auxilia T. Siringan and Rhodora V. Azanza reviewed and contributed to the finalization of the manuscript.

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