

Polychaetes of the Coral Triangle: Told and Untold Richness

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ABSTRACT. – This paper comprehensively reviews polychaete species in the Coral Triangle (CT), documenting 750 species across 60 families. The Philippines stands out for the highest species diversity, reflecting more extensive exploration than in other ecoregions. Limited publications in specific regions result from heightened sampling needs and taxonomic expertise. Nereididae and Syllidae, each constituting 11% of the total, are prominent polychaete families, alongside others like Polynoidae, Terebellidae, Eunicidae, Spionidae, and Sigalionidae. The genus *Syllis* is the most speciose, contributing 4% to the overall tally. Since 1750, polychaete species and publication numbers in the CT show an upward trend, reaching its peak from 2000 to the present. Increased marine biodiversity awareness, using SCUBA diving and ROVs, and advanced technology for species identification have significantly contributed to the continuous increase in recorded species. Despite these advancements, polychaetes in the CT remain relatively understudied compared to other taxa, underscoring the need for additional focused research on polychaetes within the region.

KEYWORDS: Coral Triangle, Ecoregions, Philippines, Polychaetes, species diversity

INTRODUCTION

The Coral Triangle (CT), spanning the tropical coast and ocean territories of Indonesia, Malaysia, Papua New Guinea, the Philippines, Solomon Islands, and Timor-Leste, is remarkable for being one of the most biodiverse marine ecoregions worldwide (Clifton, 2009; Al-Asif et al., 2022). This expansive triangular marine habitat covers approximately 5.7 million square kilometers, representing 1.5% of the Earth's oceans. Positioned at the convergence of the Western Pacific Ocean and the Indian Ocean near the equator, the CT has earned recognition as a focal point for marine conservation due to its remarkable marine biodiversity, often referred to as the "Amazon of the seas" (Green et al., 2011). The significance of the CT is underscored by its hosting of a staggering 76% of all known coral species (Veron, 2000), over 3,000 fish species (Green et al., 2011), 50% of razor clams (Saeedi et al., 2017), six of the seven sea turtle species (Asaad et al., 2018), and one of the world's largest mangrove forests (Veron et al., 2011). The recognition of the CT as a hotspot for marine biodiversity primarily stems from the extensive research on these taxa, which are among the most thoroughly investigated taxonomic groups. In contrast, polychaetes, despite being significant contributors to marine ecosystem diversity, remain comparatively less understood within this context.

Among the 12,343 valid species of polychaetes cataloged in the World Register of Marine Species (WoRMS; <https://www.marinespecies.org/>), only 6% (750 species) have been documented in the diverse ecosystems of the CT. This revelation not only raises

an intriguing question but also signals a potential research gap that merits exploration. The CT stands as an acknowledged epicenter of marine biodiversity, renowned for its richness in corals, fish, and mollusks. However, in stark contrast, the representation of polychaete species within this remarkable region appears surprisingly modest. Considering the kaleidoscope of habitats defining the CT, including vibrant coral reefs, lush seagrass beds, intricate algal mats, and a mosaic of muddy and rocky substrates, it seems paradoxical that polychaetes, known for their adaptability and diversity (Giangrande et al., 2020), are not more prevalent. This apparent discrepancy may be attributed to the relative scarcity of research dedicated to polychaetes in the CT when compared to the more conspicuous and frequently studied taxa such as corals, fish, and mollusks. Hence, it becomes increasingly pertinent to rally the efforts of polychaete taxonomists and researchers, fostering a deeper understanding of these enigmatic organisms. Such endeavors are essential to uncover the true extent of polychaete diversity within the CT, allowing us to decipher the intricate tapestry of life in this biologically extraordinary region.

Polychaetes, segmented worms belonging to the phylum Annelida, are predominantly inhabitants of marine environments, although a few species can be found in freshwater and terrestrial groundwaters (Glasby and Timm, 2008). The nomenclature of polychaetes predates the official commencement of taxonomy, which is marked by the tenth edition of Linnaeus' *Systema Naturae* in 1758 (Kükenthal, 2019). Fauchald and Rouse (1997) and Rouse and Pleijel (2001) have meticulously examined the historical

progression of polychaete taxonomy, scrutinizing seminal publications on each family. In a significant contribution to the field, Hartman (1959) meticulously compiled a vast array of Polychaeta names predating the 1960s. This dataset was later digitized by Fauchald and made publicly accessible in 2007 through the WoRMS online database (Pamungkas et al., 2019). This digitization effort has played a crucial role in facilitating the accessibility and dissemination of valuable information related to polychaete taxonomy, providing a foundation for subsequent research endeavors in this field.

The taxonomic endeavors crucial for uncovering new species form the cornerstone for subsequent biodiversity research. Knowledge of species numbers offers pivotal insights into the pace of Earth's life discovery (Costello et al., 2013). Species richness, denoting the variety of species within specific areas, represents a fundamental metric for gauging species diversity, forming the basis for diverse ecological, biogeographic, and conservation studies (Pamungkas et al., 2019). The examination of species discovery rates serves as a valuable tool for estimating total species diversity or the number of species documented up to a specific point in time (Costello and Wilson, 2011). Utilizing a statistical model, Appeltans et al. (2012) estimated the potential number of marine species to be between 200,000 and 500,000. This projection indicated around 6,320 undiscovered polychaete species, suggesting a conceivable global total of 25,000 to 30,000 polychaete species yet to be identified. Such estimations highlight the vastness of undiscovered biodiversity, emphasizing the ongoing significance of taxonomic efforts in advancing our understanding of Earth's diverse life forms.

This review represents the inaugural and comprehensive examination of polychaete assemblages within the CT. A discernible observation derived from the literature referenced in these publications emphasizes the scarcity of documented records of polychaetes in the CT. The primary objective of this literature review is to facilitate the analysis of marine biodiversity specific to polychaetes in this region. The insights gleaned from this review are anticipated to be a valuable foundation for prospective taxonomic investigations, shedding light on the ecological significance of this species that is frequently overlooked in marine ecosystems.

MATERIALS AND METHODS

A systematic literature search was carried out between July 2022 and January 2023 to identify relevant studies about polychaetes in CT. A predefined

set of keywords, specifically formulated to capture studies related to polychaetes in the CT, was utilized. The selected keywords, including terms such as "polychaete," "marine worms," "benthic annelids," and "Coral Triangle," and their variations, were strategically combined using Boolean operators to maximize the breadth of the search.

The process of data collection involved the retrieval of pertinent studies on polychaetes from prominent scholarly databases, including Web of Science, Scopus, PubMed, Google Scholar, Elsevier, and the World Polychaeta Database (WPD), which constitutes a core element of the WoRMS platform (Read and Fauchald, 2023). The search was confined to peer-reviewed articles. Initially, 998 articles were screened based on their titles and abstracts. Articles that did not relate to polychaetes in the CT or were irrelevant to the objectives of the review were excluded. Subsequently, the full texts of the remaining articles were evaluated for eligibility, and duplicates were eliminated. The final selection comprised 144 articles encompassing research conducted from 1750 to the present.

To maintain data integrity, the selection criteria excluded polychaete species exclusively mentioned in master's or doctoral theses, as well as those solely discussed in unpublished technical papers. After the data collection phase, a meticulous validation process was implemented. The polychaete species identified within each article underwent cross-referencing with the WPD and WoRMS databases, focusing specifically on taxa possessing accepted status. This validation procedure enhanced the credibility of the dataset by exclusively incorporating taxa with validated accepted status. In instances where species identifications had been previously synonymized with other taxa, the guidelines outlined by Read and Fauchald (2023) were adhered to. This approach employed the presently accepted nomenclature of polychaete species, aiming to ensure consistency and accuracy in polychaete nomenclature.

RESULTS AND DISCUSSION

The analysis of research endeavors within the CT ecosystem reveals a notable incongruity in the level of scientific scrutiny applied to various taxonomic groups. As depicted in Figure 1, it becomes apparent that polychaetes have received comparatively less attention compared to their more charismatic counterparts, such as corals, fish, and mollusks. Surprisingly, only 6% of the 12,343 valid polychaete species listed in the global repository (<https://www.marinespecies.org/>; Table S1, Supplement Materials) were documented within the CT. The extent of this disproportion is unexpectedly

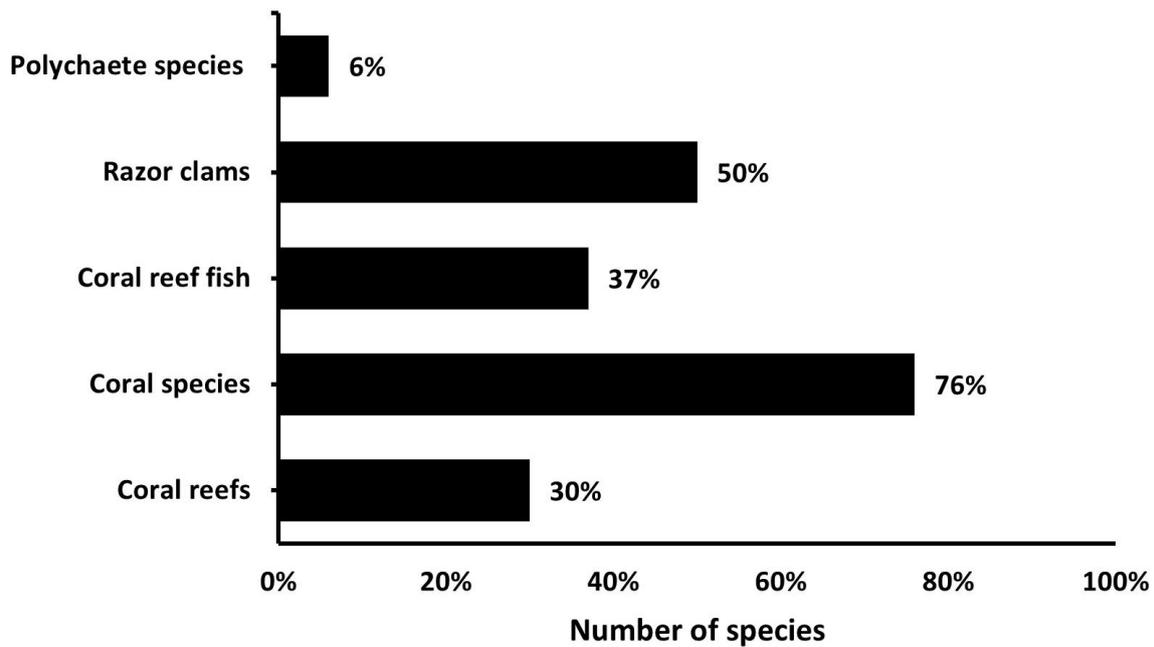


FIGURE 1. Displays the proportion of marine organisms in the CT in comparison to the global record.

pronounced, given the CT's well-established status as a global hotspot for marine biodiversity. The limited scientific attention directed toward polychaetes in comparison to corals, fish, and mollusks represents a noteworthy aspect of this observation. This imbalance may be attributed to varying degrees of interest and research emphasis that different taxonomic groups have received over time. Consequently, this scarcity of study on polychaetes within the CT may offer a plausible explanation for the seemingly low representation of these organisms in the region. These findings underscore the pressing need to broaden research efforts dedicated to polychaetes in the CT. It is imperative to cultivate a larger community of polychaete taxonomists to comprehensively explore the ecological intricacies of these organisms. Their thorough investigations will not only rectify the existing scientific imbalance but also yield crucial insights into the population dynamics and ecological roles of polychaetes within the CT's marine ecosystems, enriching our understanding of the region's remarkable biodiversity.

The existence of endemic polychaetes within the CT serves as a testament to the extraordinary biodiversity of this marine hotspot. Comprising a total of 405 endemic species (Table S1), they constitute a significant proportion, representing 54% of the polychaete diversity in the region. These unique species are exclusively confined to the boundaries of the CT, highlighting the region's ecological distinctiveness and its pivotal role as a crucible for marine evolution. The

substantial number of endemic polychaete species is not only intriguing but also crucial for comprehending the ecological dynamics of the CT. Endemic species are recognized for adapting to specific environmental conditions and niches over extended periods of isolation (Wang et al., 2018). The presence of these 405 endemic species highlights the historical stability of the region and the intricate evolutionary processes that have shaped its biodiversity. Furthermore, it emphasizes the vital importance of conserving these distinctive species to uphold the ecological integrity of the CT's ecosystems.

In addition to the endemic species, the CT also hosts 107 cosmopolitan polychaete species (14%) and 238 species (32%) distributed across other oceanic regions (Table S1). The presence of cosmopolitan species within this region suggests a certain level of connectivity (Cerca et al., 2018) between the CT and other marine areas. This connectivity can be attributed to various factors such as ocean currents, migratory patterns, and the ecological adaptability of these species, contributing to their distribution across various oceanic territories (Tremblay et al., 2008; Jönsson and Watson, 2016). The rich biodiversity of the CT, particularly its endemic polychaetes, is a subject of profound scientific interest and holds considerable importance in terms of conservation efforts. The coexistence of 405 endemic species, 107 cosmopolitan species, and 238 species from other oceans paints a complex ecological landscape within the CT.

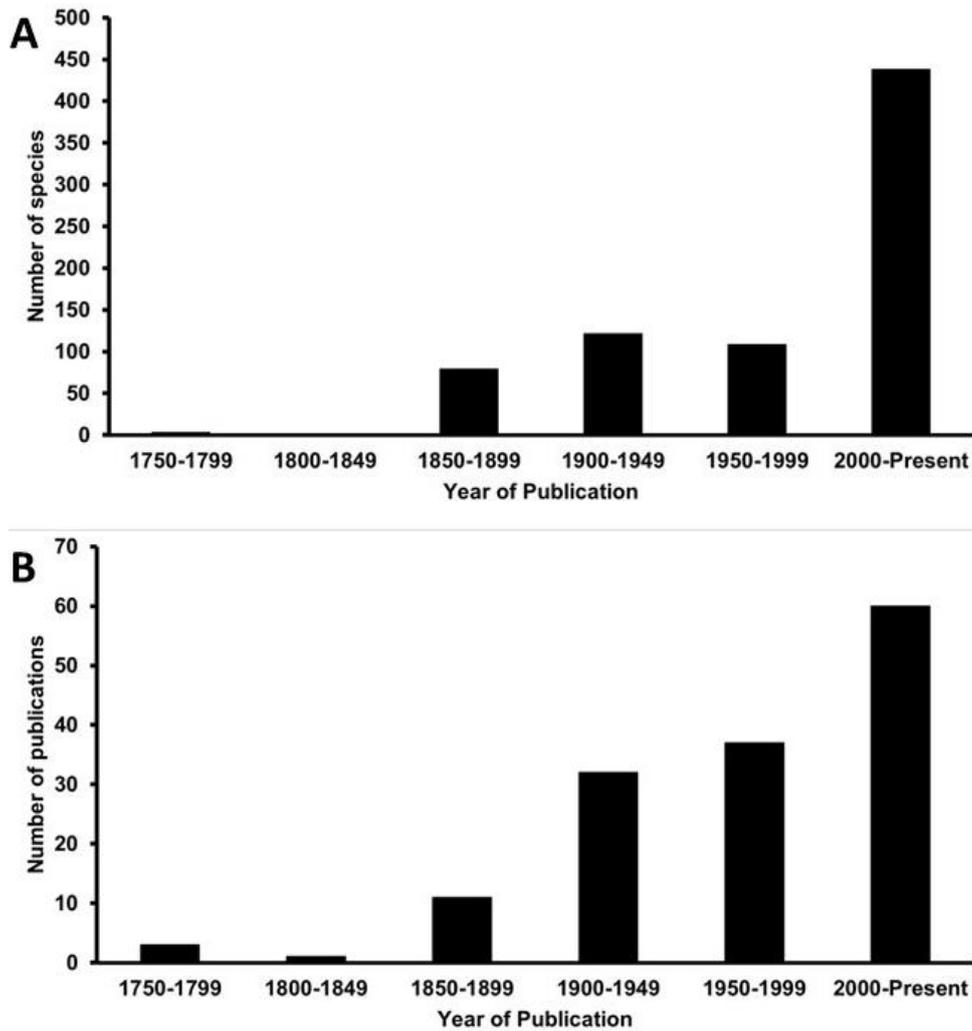


FIGURE 2. Illustrates the number of polychaetes in the CT from 1750 to the present, showcasing: A. The number of species discovered. B. The number of publications generated.

Determining the presence of species introduced by human activities among the 107 cosmopolitan species and 238 species inhabiting other oceans poses a significant challenge, primarily due to constraints in available data. Moreover, the introduction of cosmopolitan and non-native species into the CT through various human activities introduces novel dynamics and potential challenges to the region's unique marine ecosystem. These introductions can occur through several pathways: (1) Often used to stabilize ships during voyages, ballast water can inadvertently carry a diverse array of marine organisms, including polychaetes (Gollasch et al., 2002; Gollasch et al., 2015; Hughes et al., 2020). Discharge of this ballast water in CT ports can introduce non-native species, potentially disrupting local ecosystems. (2) The expansion of the Suez Canal has facilitated the movement of marine species between the Mediterranean Sea and the Red Sea (Bédry et al., 2021). Some of these species, including

polychaetes, may find their way into the CT through natural migration routes or shipping pathways. (3) The intentional introduction of polychaetes for aquaculture purposes (Pombo et al., 2020) into the CT, such as bait or food for farmed fish and shrimp, can inadvertently lead to their escape into the wild due to inadequate containment measures. This may result in the potential establishment of invasive populations. (4) Some introduced species may exhibit invasive or parasitic behavior, impacting local species, including polychaetes, shells, and other marine life (Alvarez-Aguilar et al., 2022). Such interactions can induce changes in local ecosystems, potentially leading to ecological imbalances.

The number of newly discovered polychaete species in the CT has exhibited a consistent upward trajectory since 1750, reaching its pinnacle between 2000 and the present with 438 species (Fig. 2A). A parallel pattern is observed in the publication of research on polychaetes in the CT, demonstrating a continual increase (Fig. 2B).

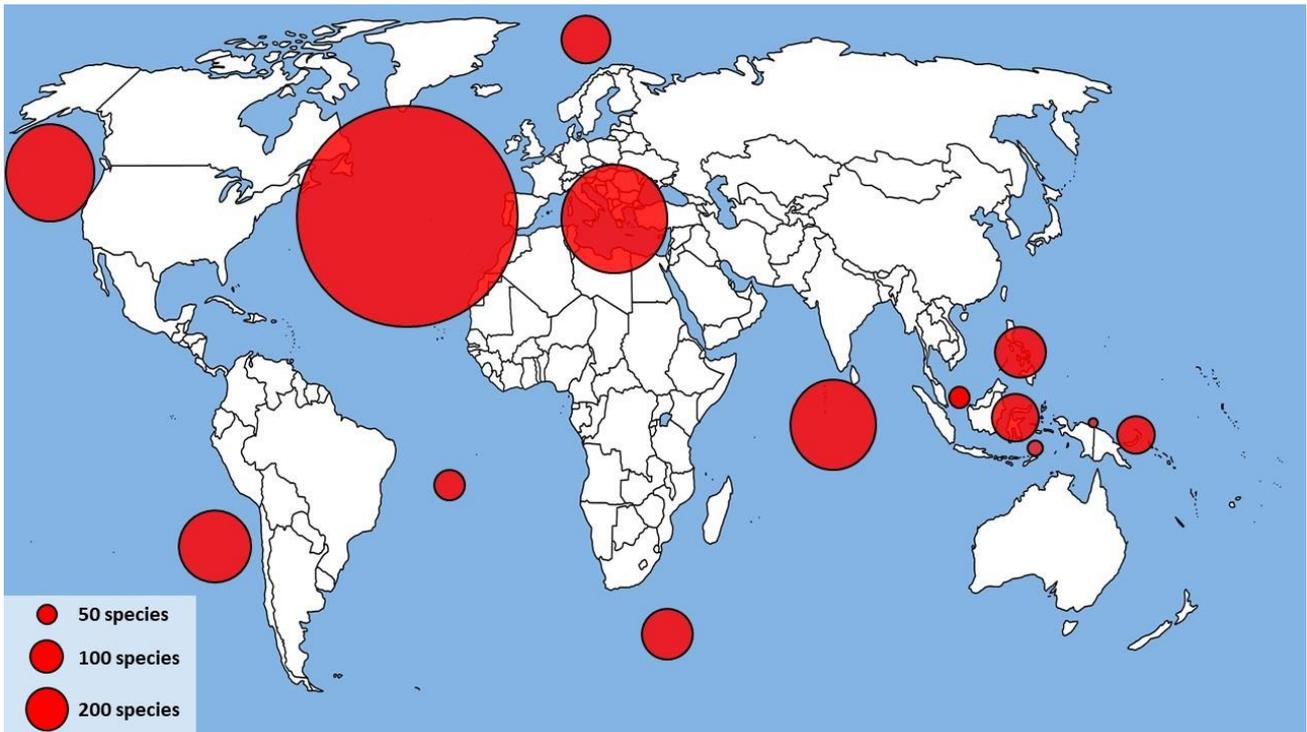


FIGURE 3. Depicts the global distribution of polychaete species.

The highest number of publications (60) was recorded between 2000 and the present, with the lowest number observed between 1800 and 1849 (1 publication). Despite the comparatively fewer researchers dedicated to polychaetes in contrast to other taxa, such as charismatic species like fish, seagrass, corals, and mangroves, both the number of publications and newly discovered species in the CT show an upward trend. This trend aligns with patterns observed across various taxa, alluding to an all-time peak in publications and new species discovered in recent decades (Costello et al., 2012). This trend is evident in mammals (Burgin et al., 2018), amphibians (Glaw and Kohler, 1998), birds (Jetz et al., 2012), reptiles (Pincheira-Donoso et al., 2013), fish (Eschmeyer et al., 2010), parasites (Costello, 2016), and amphipod crustaceans (Arfianti et al., 2018). According to Miloslavich et al. (2010), the sustained growth in the number of known polychaetes in the CT can be attributed to increased awareness of marine biodiversity and the adoption of new sampling methods such as Self-Contained Underwater Breathing Apparatus (SCUBA) and Remotely Operated Vehicles (ROVs). Additionally, advancements in technology, including improved microscopes, digital drawing and photography tools, molecular methods, and the rapid increase in the accessibility of scientific journals (Pamungkas et al., 2019), have contributed to this trend. The ongoing rise in known polychaetes in the

CT suggests that the number of polychaete species is not approaching an asymptote, indicating that some species remain undiscovered and await exploration.

The data extracted from the WoRMS indicates that, in comparison to other regions globally, the CT has only a limited fraction of recorded polychaete species, totaling 750 species (Fig. 3). The North Atlantic Ocean exhibits the highest number of polychaete species (4,070), followed by the Mediterranean Sea (1,165) and the Indian Ocean (868). The substantial number of polychaete species in these three oceans might be attributed to a more extensive sampling effort. Conversely, the CT's relatively modest count of known polychaete species may primarily result from a deficiency in sampling efforts. Despite being recognized as a hotspot for marine biodiversity, the CT reflected to have the lowest counts of polychaete species in comparison to other global regions. To gain a comprehensive understanding of the polychaete population and substantiate their richness in this area, it is imperative to undertake further exploration. The expectation is that the polychaete fauna of the CT harbors a significantly greater diversity of species than currently known. This anticipation aligns with the findings of the statistical model developed by Appeltans et al. (2012), suggesting that more polychaete species are yet to be discovered in the CT.

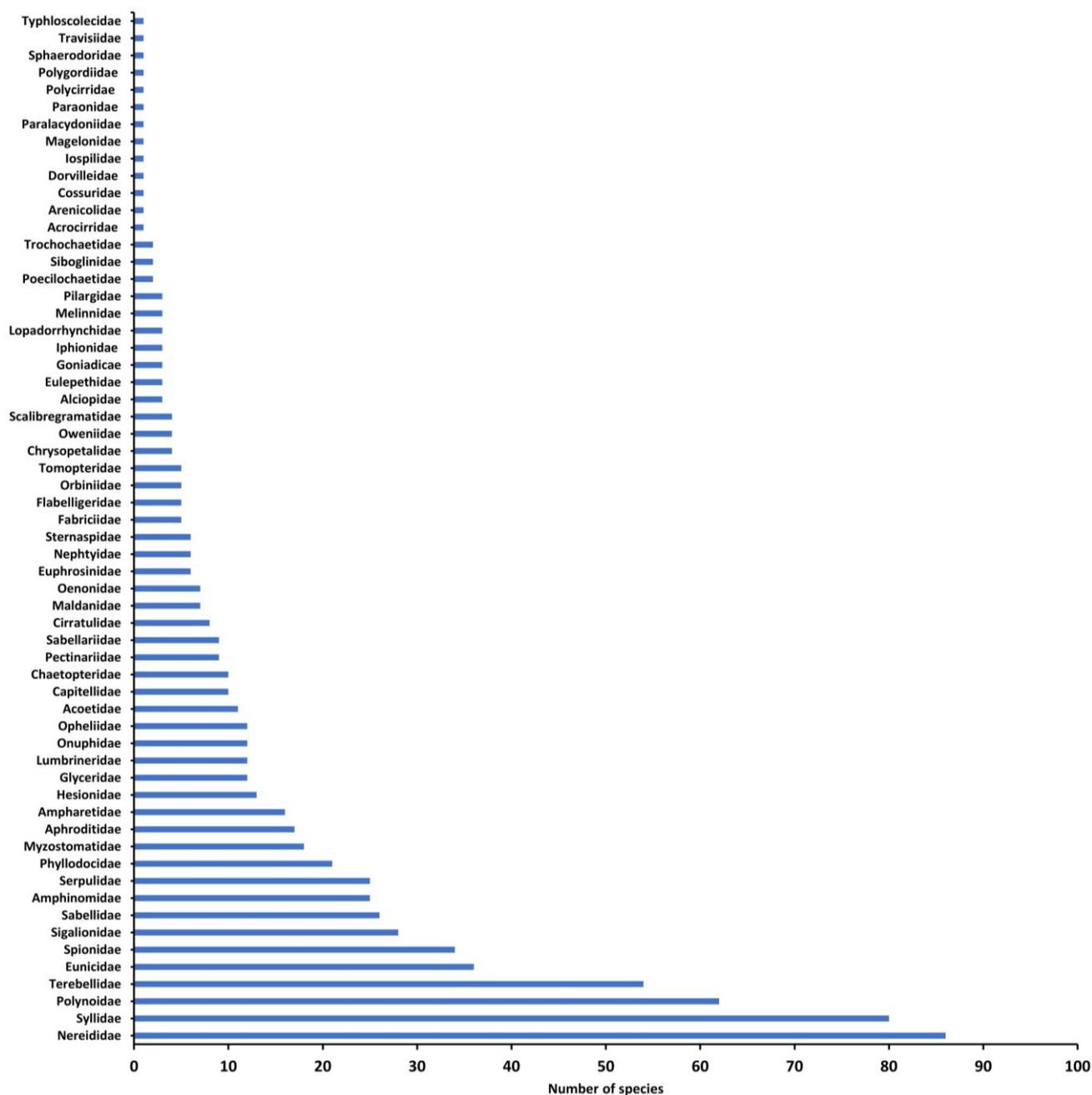


FIGURE 4. Presents a comprehensive list of all polychaete families in the CT, along with the corresponding number of species found in each family.

The compilation from the different literature reveals the presence of 750 validly named polychaete species distributed across 60 families in the CT (Table S1 and Figs 4, 5, and 6A). When considering ecoregions, the Philippines exhibits the highest number of recorded families, with 42, followed by the Solomon Islands (41), Indonesia (40), Malaysia (28), Papua New Guinea (14), and Timor-Leste (9) (Fig. 5 and 6A). Additionally, in terms of recorded species, the Philippines leads with 275, followed by Indonesia (249), the Solomon Islands (196), Malaysia (54), Timor-Leste (36), and Papua New Guinea (29) (Fig. 6B). Within the CT, the

Philippines emerges as the region with the highest diversity of polychaetes in both families and species. This outcome suggests that the Philippines has undergone more thorough exploration in terms of polychaete studies compared to other regions within the CT. As highlighted in the study by Dean et al. (2012), the limited publications on polychaetes in specific areas are likely a result of insufficient sampling efforts and taxonomic expertise. This scenario might be applicable to other ecoregions within the CT, such as Papua New Guinea and Timor-Leste.

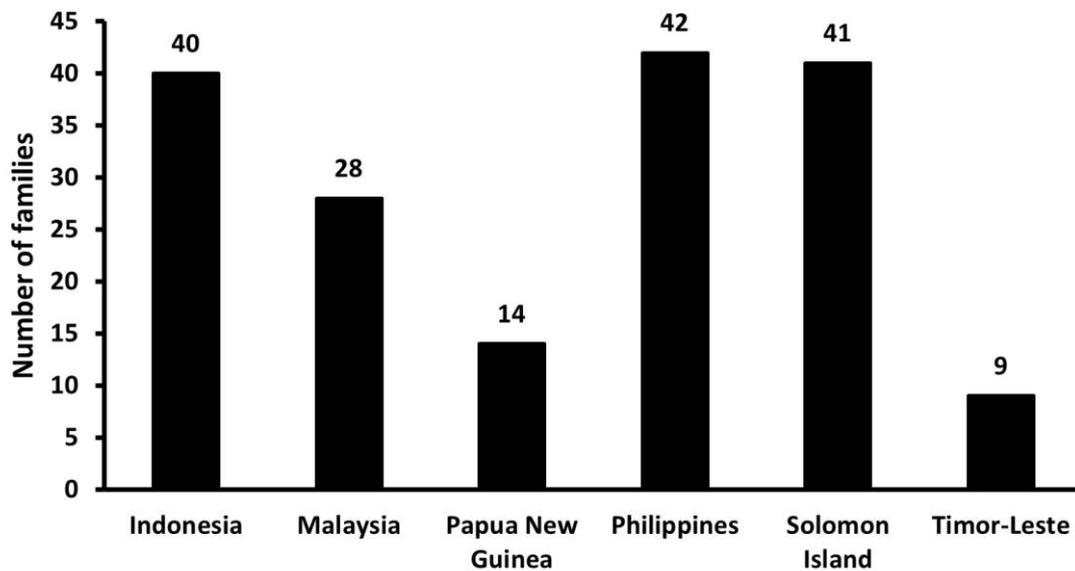


FIGURE 5. Showcases the number of families found in each ecoregion of the CT.

The CT displays a varied distribution of polychaete species, with seven families dominating the region's composition. Notably, Nereididae (11%), Syllidae (11%), Polynoidae (8%), Terebellidae (7%), Spoinidae (5%), Eunicidae (5%), and Sigalionidae (4%) emerge as the most prevalent families (Fig. 7A). The remaining species, collectively categorized as "others," constituting less than 4%, collectively contribute to 49% of the total. This distribution pattern aligns with findings from previous studies. In the Caribbean Sea, Dean (2012) identified the same four prevalent families—Syllidae, Eunicidae, Nereididae, and Polynoidea. Pamungkas et al. (2019), in their global review of polychaetes, noted that the family Syllidae takes precedence, followed by Polynoidae, Nereididae, Spoinidae, and Terebellidae. Additionally, Çinar's (2012) exploration of alien polychaetes worldwide found that four of the dominant families (Nereididae, Syllidae, Eunicidae, and Spoinidae) are widespread across global regions. Additional insights into the distribution of these families reveal intriguing patterns. Syllidae emerges as the most species-rich family in tropical reefs within the eastern Indian and western Pacific Oceans (Paxton and Chou, 2000). In contrast, other species-rich families such as Polynoidae, Nereididae, Terebellidae, Spoinidae, and Eunicidae thrive predominantly in shallow water and hard substrate environments (Bailey-Brock, 2003). Notably, except for Syllidae, the families Nereididae, Polynoidae, Terebellidae, and Spionidae are characterized by their large size and widespread distribution in intertidal and shallow-water hard

substrate habitats. These findings collectively underscore the significance of specific polychaete families in shaping the biodiversity of the CT. The observed dominance aligns with global trends, emphasizing the adaptability and prevalence of these families across diverse marine ecosystems. Further research could delve into the ecological roles and interactions of these dominant families to deepen our understanding of the CT's polychaete biodiversity. Such investigations would contribute valuable insights into the intricate dynamics of these families within the CT's marine environment.

The examination of polychaete genera within the CT reveals distinct patterns of species abundance. Notably, the most speciose genera include *Syllis* (4%), *Eunice* (3%), *Perineris* (3%), *Myzostoma* (2%), and *Neanthes* (2%) (Fig. 7B). Genera accounting for less than 2% were collectively grouped as "others," constituting a substantial 86% of the total polychaete population. Remarkably, the prevalence of *Syllis* and *Eunice* aligns with global trends observed by Çinar (2012), who identified these two genera as the most abundant worldwide, emphasizing their status as alien species. Çinar's study highlights the role of human activities, particularly ship water ballast and aquaculture, in introducing polychaete species to specific areas. This anthropogenic influence is evident in the estimation that 15% of polychaete genera are alien, underscoring the potential impact of such activities on the global distribution of these organisms. While the study by Çinar (2012) provides a broader context for the prevalence of certain genera, the

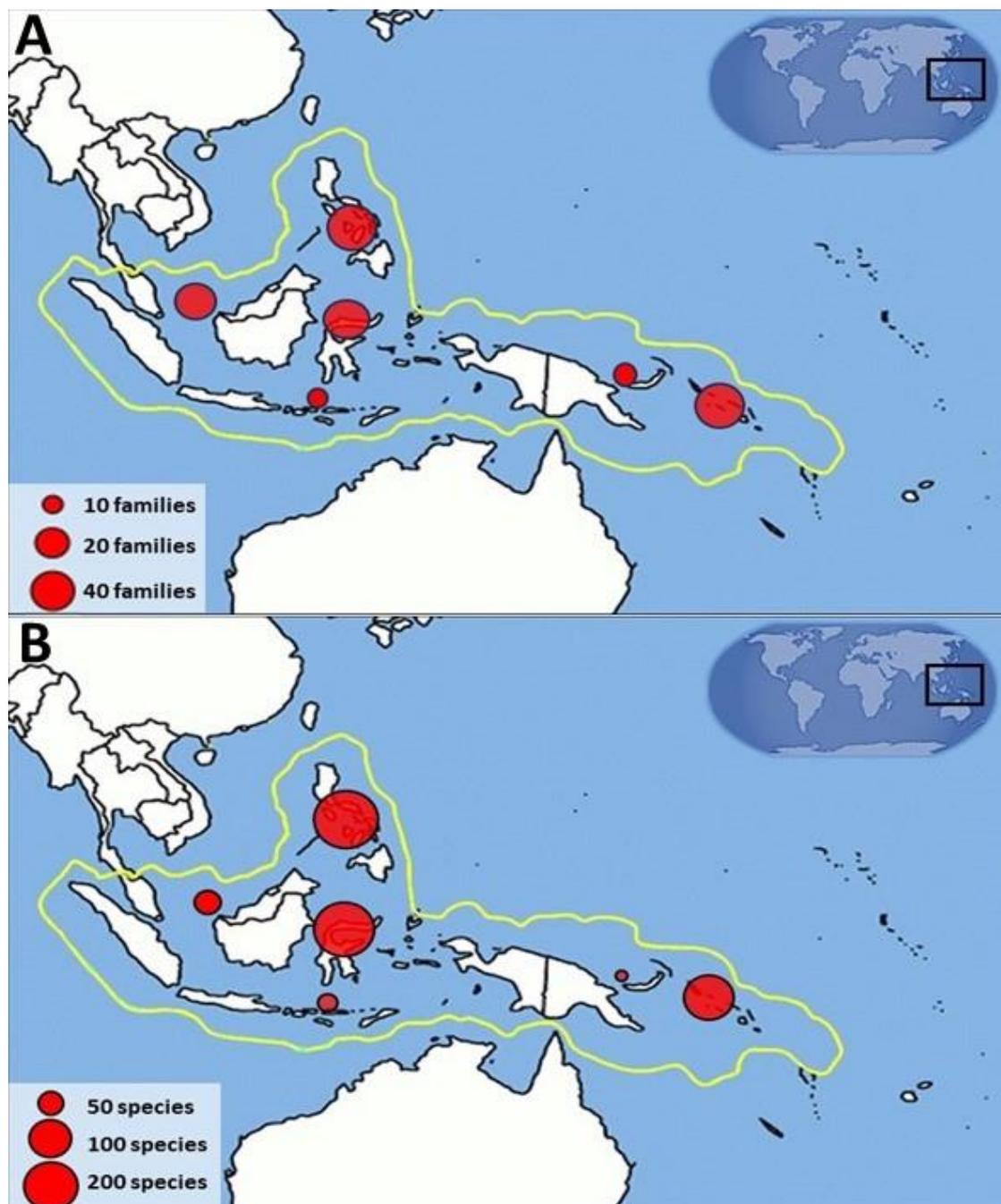


FIGURE 6. Illustrates the distribution of polychaetes in each ecoregion of the CT, featuring: A. Families; B. Species. The yellow contour delineates the area covered by the CT.

specific abundance observed in the CT raises questions about the origin of these species. The lack of data regarding the alien status of the most abundant genera in the literature reviewed necessitates caution in attributing their abundance solely to anthropogenic introductions. Further research and data collection are crucial to unraveling the complexities of the origins and ecological roles of these highly abundant polychaete genera in the CT.

The heightened prevalence of *Syllis* can be attributed to its recognition as the most species-rich genus in the tropical reefs of the Indian and Pacific regions (Paxton and Chou, 2000). This richness extends to the CT, where *Syllis* thrives in intertidal and shallow-water habitats with both soft and hard substrates (Bailey-Brock, 2003). *Syllis* exhibit significant abundance and diversity among various ecosystems, including sponges, seaweed, seagrass, coral, or hydrozoans, as well as in soft bottoms. This is

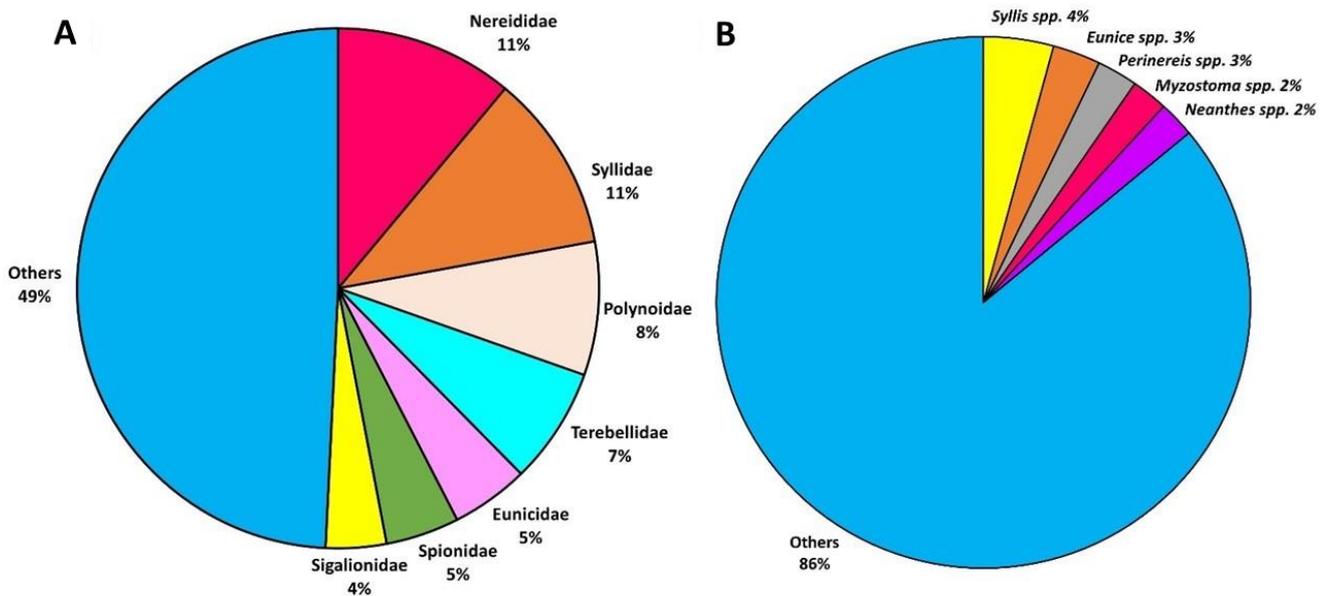


FIGURE 7. Portrays the relative abundance of polychaetes in the CT: A. Families; B. Genera.

attributed to their generalist feeding strategy and active mode of life, navigating through interstitial spaces or crevices (Martins et al., 2013). The cosmopolitan nature of *Syllis*, characterized by its generalist habitat preferences, further contributes to its widespread presence.

CONCLUSION

A comprehensive examination of polychaete diversity in the CT reveals the documentation of 750 species distributed across 60 families. Nereididae and Syllidae emerge as the two most common polychaete families, each constituting 11% of the total polychaete population in the CT. Other abundant families include Polynoidae, Terebellidae, Eunicidae, Spionidae, and Sigalionidae. The genus *Syllis* stands out as the most species-rich, comprising 4%, followed by *Eunice* (3%), *Perinereis* (3%), *Myzostoma* (2%), and *Neanthes* (2%). The prevalence of *Syllis* is notable, possibly attributed to its generalist habitat preferences, thriving in intertidal-shallow water areas and hard substrate habitats. The Philippines stands out as the region with the highest diversity of polychaetes in terms of both species and families, suggesting that more polychaete research has been conducted in the Philippines compared to other CT ecoregions. Furthermore, there is an increasing trend in the number of new polychaete species discovered and scientific papers published in the CT from 1570 to the present. This upward trajectory in knowledge may be attributed to advancements in marine biodiversity awareness, the

utilization of technologies such as SCUBA and ROVs, and the rapid publication and easy accessibility of scientific journals. The constant growth in the number of known polychaetes in the CT emphasizes the ongoing exploration and discovery of marine biodiversity in the region.

This study underscores the limited research conducted on polychaete species in the CT. The information presented here emphasizes the paramount importance of conducting additional research on polychaetes in the CT. Further investigations would provide a clearer understanding of the population status, prevalence, and the potential for discovering new polychaete species in the region. Despite the current scarcity of research on polychaetes in the CT, the study reveals a growing number of species and publications, indicating that the knowledge in this field is expanding and has not reached an asymptote. This suggests that there are still undiscovered polychaete species awaiting exploration in the future. In comparison to more charismatic species, polychaetes are found to be understudied in the CT. Given their susceptibility to anthropogenic activities and the introduction of invasive species from other geographic areas, understanding the species composition of polychaetes becomes crucial for the effective management and conservation of marine resources in the CT. This study underlines the need for increased attention and research efforts dedicated to polychaetes to enhance our understanding of their ecological roles and contribute to the sustainable management of marine ecosystems in the CT.

As tourism and development continue to expand within the vast ecological region of CT, the looming threats from pollutants such as sewage, chemicals (e.g., oil and petroleum hydrocarbons), industrial waste, plastics, and pesticides are anticipated to intensify. This emphasizes the critical importance of understanding biodiversity for the successful execution of conservation management and policies. The literature review on polychaetes serves as a valuable resource for conducting an in-depth analysis of marine biodiversity in the CT. The study reveals the presence of 750 polychaete species in the region, a likely underestimated number, accentuating the significance of this biotic component in any regional marine biodiversity analysis. The findings underscore the imperative for more polychaete taxonomists and systematic biologists to engage in further research. Additional studies are essential not only for discovering undiscovered polychaetes but also for enhancing our understanding of benthic processes and providing insights to inform conservation decisions in this biologically significant and environmentally threatened region. The information presented in this review significantly contributes to a broader understanding of CT's marine ecosystem and highlights the urgency of addressing the environmental challenges it faces.

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