Unveiling Deep-Sea Fish Relationships: Analysis of Existing Data Reveals Potential Commensalism

Arai Nazarova

Received March 21, 2024
Accepted May 03, 2024
Electronic access May 31, 2024

The number of marine fish species decreases as depth increases in the deep-sea, and the density of marine ray-finned fish species (Class Actinopterygii) within functional space decreases with greater depth, resulting in a lower density of potential mates. Nowadays, deep-sea research is gradually shifting from the identification of species and environmental characteristics to the temporal-spatial dimension of deep-sea fauna and biological interactions, and exploring deep-sea ecosystems and connectivities between them. There are few examples documenting a relationship between deep-sea fishes, highlighting a need for more detailed studies. This research focused on the central equatorial Pacific near the Hawaiian Islands and Clarion Clipperton Zone where there was a high density of records of at least two different fish genera, with the records happening either on the same date and at a similar depth. The Clarion Clipperton Zone (CCZ) is an abyssal area of about 6 million square kilometers in the north-east Pacific Ocean, which contains nodules of rare metals. A potential impact of the nodule mining activity on the deep-sea megafauna and biodiversity has led to an increased level of research in CCZ. Cameras captured nine different genuses, three families, one superclass, and one gigaclass of fish forming a variety of non-predatory assemblages. It can be hypothesized that the potential nodule mining activity in the CCZ might have a potential to influence the availability of prey, which might lead to the change in the predator/scavenger behavior patterns of the abyssal megafauna. This research can help lay the ground for future research to accentuate the mutual/commensal fish-fish interactions with a focus on the anthropogenic impact on such relations, and on the potential changes in such interactions with an effect on the density and biodiversity of benthic megafauna.

Keywords: deep-sea, ray-finned fish, mutualism, deep-sea mining impact, Clarion Clipperton Zone

Introduction

The deep-sea is defined as all marine waters on Earth that have depth of over 200 meters[1]. This area is the largest living habitat on earth, covering 71% of the planet's surface and having a mean depth of 3,800 meters[1–5]. There have been discoveries of the new habitats such as hydrothermal vents, cold seeps, and cold-water reefs[6]. Although the ocean is the largest living space on Earth, it has only been explored to a small extent[5]. For example, just 16% of marine species have been identified and categorized, only 5% of the deep-sea has been examined with remote instruments and less than 0.01% of the deep-sea floor has been sampled, including with the help of new technologies such as submersibles, sub-cameras, or mobile samplers, which allowed for *in situ* sampling[5,7,8]. The deep-sea technological advancements of the past several decades resulted in the development of modern-day submersibles, remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), deep-sea permanent observatories, and high-pressure simulators, with ever increasing capabilities for exploration, sampling and experimentation, as well as cost-efficiency[5,8,9]. Molecular tools, sensor tagged animals, and *in situ* and laboratory experiments, too, can facilitate unparalleled advancement of deep-sea research, as well promote sustainable management of deep ocean use under global climate change[4]. Through this expensive work, the discovery rates of deep-sea habitats and species have been higher than those of the terrestrial ones and remain high[5,10].

The ocean has been continuously explored by people since ancient times, and its waters played an important role in the development of human civilization[5]. The first discovery of the fauna deeper in the ocean, which differ greatly from the organisms inhabiting shallow marine waters, was made by Sir John Ross in 1818, when he collected the ophiuroid *Gorgonocephalus caputmedusae* (as *Astrophyton linckii*) at the depth of 1,600 meters[5,8]. Deep-sea fishes likely diversified following a settlement of shallow water species to the depths[11].

An estimated 10-15% of all fish species dwell in the deep-sea[12]. Most of them have unique morphological and physiological adaptations due to the ambient pressure and limited food availability caused by the lack of light, which precludes photosynthesis in the deep-sea[4]. One factor influencing deep-sea communities is the need of heterotrophic organisms for organic food material synthesized in the photic zone[5]. Pressures in the range of 20 to over 1,100 atmospheres, near freezing temperatures overall and extremely high temperatures at hydrothermal vents (up to 450°C) impose additional challenges to the deep-sea communities[4,8]. There are specific life history adaptations of many deep-sea and benthopelagic fish species, such as slow growth, delayed maturity, high longevity, as well as low fecundity and low rate of replacement[4,5,13]. Several behavioral aspects, such as mating and predation occur almost as if they were in slow motion[4]. These might be reflected in the deep-sea fishes' vulnerability to the human impact and global climate change[4]. Additionally, density of marine ray-finned fish (Class Actinopterygii) species within functional space decreases with increasing depth, leading to a decreased density of mates[11,14]. There are diverse and highly specialized communities of species in many deep-sea ecosystems, some of which are commercially important, while some are threatened[5,15]. Deep-sea habitats can represent a variety of seascapes (either of a geological origin, like seamounts or canyons, or of a biological origin, like coral reefs) and forms of life, and Costello and Chaudhary (2017) call for the conservation prioritization of the habitats with a higher heterogeneity and a higher number of different species[16].

Despite technological advancements, there is scant evidence of the commensal or mutualistic interactions between deep-sea fishes. Much of deep-sea research focuses on the physical adaptations of deep-sea species that allow them to survive in the harsh conditions of extreme depths, as well as documenting deep-sea biodiversity[5,16–18]. Other research concentrates on the anthropological effect on deep-sea communities, including the expansion of fisheries into deeper offshore waters, as well as oil drilling and the mining of valuable mineral deposits[5,19,20]. As mentioned in the section above, studying deep-sea fish is not easy due to the advanced technologies and significant funding needed to access the ecosystem. Overall, global technological innovations, combined with such a potential anthropogenic impact on deep-sea ecosystems, are allowing the investigation of the deep-sea to occur at an unprecedented rate[6].

A review analyzed over 60,000 articles published between 1970 and 2020 and found that biodiversity has been the most researched topic in deep-sea ecology[8]. The research started with microorganisms but has slowly moved into macroorganisms. Research has shifted from analyzing stomach contents and creating deep-sea food webs and sediment sampling to long-term observations, pressure-tight reactors, and offshore cultivating with the imitation of the ecosystems' conditions[8,21]. Thus, deep-sea research is gradually shifting from the identification of species and environmental characteristics to the temporal-spatial dimension of deep-sea fauna and biological interactions, and exploring deep-sea ecosystems and connectivities between them.

Relationships including individual behaviors and species interactions influence community dynamics to a large extent, whereas symbiotic relationships play a crucial role in spurring host functions, nutrition, health, and evolution[4,22]. So far, inter-species interactions research has been mainly focused on the trophic relations between species, and predator-prey interactions, while not much has been written on commensalism or mutualism between fishes. One example studied 144 species of marine ray-finned fishes on Baited Remote Underwater stereo-Video (stereoBRUV) footage and used quantitative methods of analysis to check their hypothesis of the influence of abiotic filtering and biotic interactions on the functional diversity[14]. They concluded that biotic interactions such as interspecific and intraspecific competitions represent dominant processes that shape functional space and functional diversity of fishes at lower depths, whereas abiotic filtering may be a key factor that structures communities with increasing latitude.

Micheli et al. (2002) used manipulative field experiments to determine the effect of predation on the structure of hydrothermal vent benthic communities[23]. Vent benthic communities were shaped jointly by the biotic interactions and abiotic gradients. Also, across the time intervals and locations where the experiments were held, community producing patterns were repeatable. They provided direct evidence of the role that biotic interactions play in the early development of deep-sea hydrothermal vent communities. Submarine canyons, like the deep-sea hydrothermal vents, are one type of geological structure embedded within the continental slopes and abyssal plains of the deep-seafloor[5]. De Leo et al. (2012) studied demersal fish assemblages in the main Hawai'ian archipelago aiming at investigating the potential role of habitat heterogeneity and enhanced detrital input on the structure of demersal fish communities in submarine canyons[24]. The authors concluded that submarine canyons on oceanic islands were likely to be sites of enhanced fish abundance and species richness. However, these effects may be offset by lower oxygen concentrations in oxygen minimum zones, along with canyon-related disturbance.

Previous research focusing on interspecies relationships has focused mostly on fish-invertebrate interactions. One study analyzed a series of time-lapse photographs taken *in situ* with the help of a camera vehicle at a depth of 625-1525 meters around Shag Rocks and South Georgia in the Southern Ocean[25]. The authors observed the relationships between a species of snailfish and the lithodid crab, where the snailfish was "riding" on the stone crabs. The scientists concluded that such a life-long interaction might serve the snailfish as protection from potential predators and as a means of transportation at no evident cost to the crab. Research on deep-sea cusk eels and pancake urchins was done by utilizing both video and still frames in seamounts located in the western North Atlantic at a depth between 1410 and 1775 meters[26]. By using an ROV *in situ*, the foraging habits of juvenile cusk eels and their refuge at the base and among the long spines on the aboral surface of pancake urchins were documented. Fish-fish relationships have been studied less. One study described how communication in the deep-sea happens with the help of sound and chemical and light signals[4]. For instance, bioluminescence is present in a broad range of organisms, including fishes, and is employed to find food, attract mates and evade predators. This is one of few examples documenting a relationship between deep-sea fishes, highlighting a need for more detailed studies.

While these examples document positive deep-sea relationships, there is a lack of information on fish-fish interactions, even though fishes make up the top level of the abyssal food web and are a crucial component of a complete ecological baseline study[27,28]. This research seeks to fill in this gap using similar methods while focusing on bony ray-finned fishes (Class Actinopterygii), as they comprise the majority of the aquatic biodiversity and are found in the waters at the depth levels of over 8,000 meters, contributing significantly to the deep-sea ichthyofauna despite making the most input into the diversity of the shallow water species[11,12,29]. This research focuses on studying the *in situ* obtained documentary evidence of the deep-sea fish-fish interactions from the area near the Hawaiian Islands and the Clarion Clipperton Zone, as unique lives often remain inactive when removed from the original living environment during the sampling process[8]. It is necessary to acknowledge that reaching an inference about relationships of fishes in this research, which is based on analyzing publicly available data, might carry bias to a certain extent. Without directly observing or communicating with the fish, assumptions must be made to categorize any potential relationships.

The Clarion Clipperton Zone (CCZ) is an abyssal area of about 6 million square kilometers in the north-east Pacific Ocean, which is known for the significant deposits of polymetallic nodules, containing high quantities manganese, copper, nickel, cobalt, and rare earth elements[30–32]. These metals are essential for the electronics and new technologies, such as renewable energy infrastructure. Therefore, CCZ is one of the main target areas for the large-scale deep-sea mineral mining with an accelerating interest in deep-sea nodule mining in this area[33,34]. Mining activity might involve the large-scale removal of nodules and sediments at the seafloor[35]. A potential impact of the nodule mining activity on the deep-sea megafauna and biodiversity has led to an increased level of research in CCZ.

Previous research held by the scholars in the CCZ focused on the biodiversity of benthic and demersal fauna and megafauna. Several studies have found correlations between the coverage of polymetallic nodules and the abundance of deep-sea megafauna, with nodule fields contributing to habitat heterogeneity and increasing the biodiversity of benthic megafauna in the abyssal seamounts and on the abyssal seafloor[28,36]. The megabenthic communities in the CCZ have a relatively high biodiversity of megafauna with the density not being solely dependent on food availability, but with the abundance of the dominant fauna being enhanced by the presence of nodules[37,38]. However, there is no significant correlation between the density or diversity of scavengers and the size of the polymetallic nodules[33]. These studies, despite somewhat diverging findings, help to establish a baseline for further research and ecological management strategies. Jones et al. (2021) confirmed existing knowledge gaps, which include faunal interactions, megafaunal biodiversity, species functioning, and the impact of anthropogenic factors, among others[39].

Here, the previously collected ROV, AUV, and bait camera records of deep-sea fish in the equatorial Pacific were used to predict positive fish-fish relationships. The presence of these relationships highlights the importance of further ecological studies of the deep-sea, especially as these habitats are slated for exploitation for rare metals.

Methods

To conduct this research, publicly available data was used and analyzed in a novel way. The research was based on the available data gathered and recorded by a large number of scholars on the basis of their exploration of the ocean. The data were published in the Ocean Biodiversity Information System (OBIS) database, as it is one of the most comprehensive sources of accessible data focused on the world's ocean biodiversity and biogeography. This database is an open-access information hub with thousands of records of animals worldwide. As this research focuses on bony ray-finned fishes (Class Actinopterygii) at a depth of 4,000 meters and below, the OBIS data was filtered accordingly (Figure 1).

From OBIS, a set of all the Actinopterygii occurrences recorded by the scientists globally and obtained through different methods such as human observation or material samples were downloaded. Manually going through each record, the data was further filtered to contain only the records with the identified genus. This allowed for the data to be narrowed down to more identifiable fishes.

The first step of data analysis, was focused on the central equatorial Pacific near the Hawaiian Islands and CCZ where there was a high density of records of at least two different fish genus with the occurrences happening either on the same date (year) or at different dates, and at a similar depth (Figure 2). If records occurred within 10 minutes of each other, this was counted as an encounter. After sorting out the data in the initial dataset, separate datasets for each of the identified geographical areas were downloaded. For a more precise identification of the areas, the decimal longitude and latitude parameters of each dataset entrance in each specific zone was used and the areas were marked on the map. These groupings were chosen because there had been some inconsistencies in the data entries in OBIS. Presumably, as some records were put in by various parties, some variation in the longitude and latitude data occurred. By identifying the areas on a map, it was managed to decrease any noise caused by incorrect latitude and longitude.

With the list of fish as well as the date and depth at which they were recorded, the identification of potential relationships

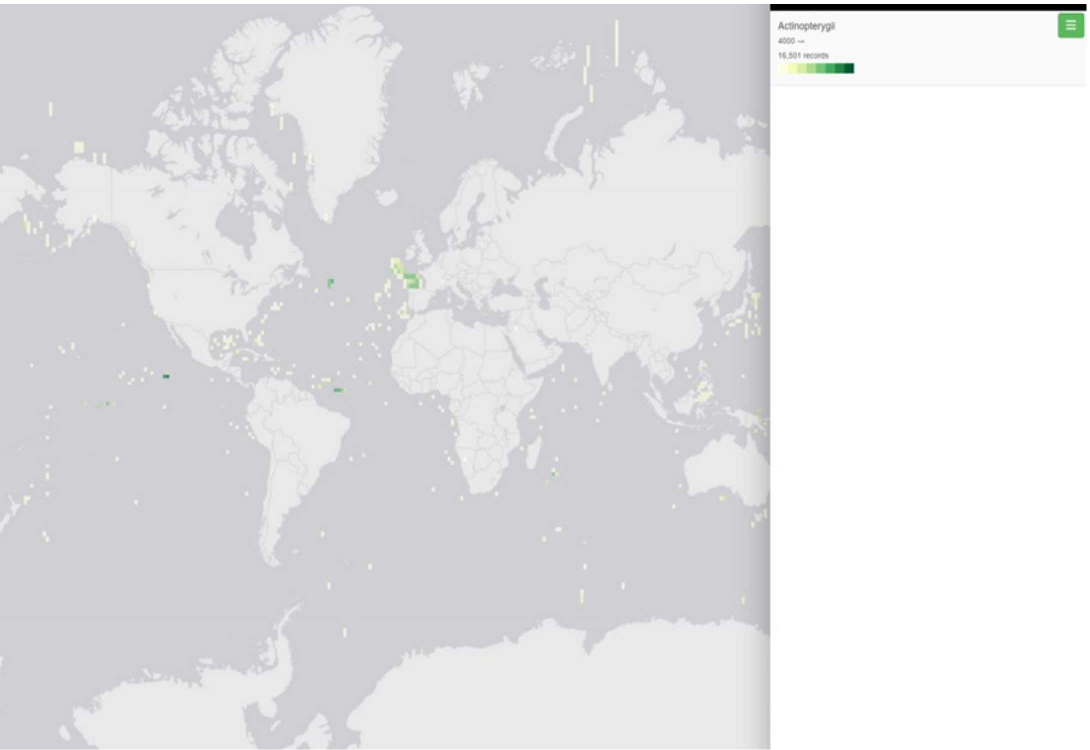

Fig. 1 Filtering OBIS data.

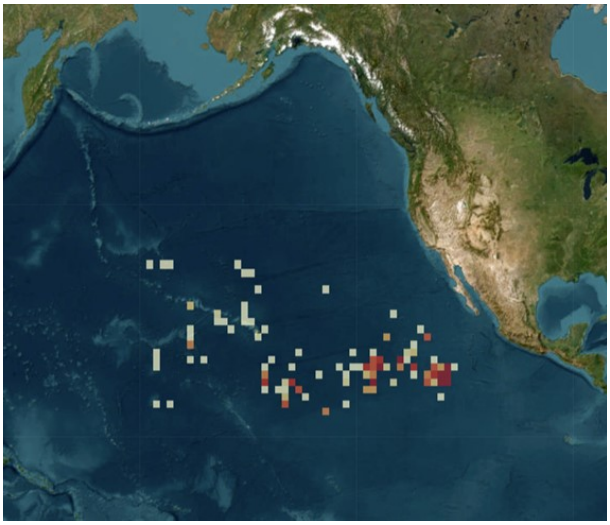

Fig. 2 Map of Hawaii and Clarion-Clipperton Zone.

started. The assumption of this research is that fish coexisting without preying upon, fighting with, or harming each other are likely engaging in neutral or even beneficial relationships with one another. Pivot tables were created for the dataset of each of the identified areas in order to group and analyze the data in accordance with the depth. This allowed for the distribution of all the recorded fish occurrences across the depth range based on the depth parameter they were recorded at. With this data, the research questions were addressed by understanding fish assemblages over time and across the range of depths in the certain geographical areas. This allowed for the identification of the patterns and for making assumptions and conclusions about the relationships (commensal, mutual, or other) between different fish species.

To confirm fish associations and potential relationships, the existing research publications referring to the specific genus, family, or species recorded in the chosen area were reviewed. Many OBIS records have associated publications containing photographic records. The purpose of such a review was to look for any documented evidence of the predator-prey or other types of relationships between the recorded fish. Although photos do not exist for every relationship, they can help deny antagonistic behavior between species.

As a second step of the research with the aim of inferring commensal and/or mutual relationships between fishes, the existing published research materials on the bony ray-finned fishes in general and the genus identified in the dataset for the selected geographical area were reviewed, looking through and analyzing the photos of the two or more of the genus photographed together. Such photo evidence might serve as a visual basis for assuming the types of relationships the specific genus might have.

Overall, there are certain challenges in conducting deep-sea research, despite the advancements in technology. The use of baited cameras allows for capturing the deep-sea organisms and obtaining photo and video evidence, however, the presence of baits might create a distraction and influence the interactions between different species. This might suggest a biased perception of the video and photo materials that capture two or more fishes of different species. Further, the fish might move away from the human operated vehicles, remotely operated vehicles, and autonomous underwater vehicles that are used for deep-sea research. Moreover, the data that are put into the open extensive databases might contain some inconsistencies due to the data being entered by different researchers at different times and from different locations. Therefore, there might be variations in measuring techniques applied by different scholars, which requires extra effort in reducing the data noise and might create some level of bias in the data analysis.

Furthermore, despite certain above-mentioned challenges when using the data obtained from publicly available crowd-sourced data depositories, such data cannot be considered unreliable and not usable for the initial research. Research based on the analysis of such data might set the ground for further surveys aiming at obtaining a better understanding of deep-sea positive interactions between fishes. A somewhat smaller scope of data was available to the author and was analyzed for this research (without an access to the additional video materials obtained with the help of ROVs/AUVs and/or behavioral observations), and the analysis of OBIS data made in the course of this research might serve as a first step of prospective further deeper studies with the use of additional resources.

Results

In order to analyze the mutual or commensal interactions between fishes of different genera, the documented occurrences of each genus at each depth in the selected geographical area around Hawaii and the Clarion Clipperton Zone were looked through. The occurrences of each separate depth level were grouped in accordance with the genus, date and time of occurrence, and coordinates. Then, it was analyzed whether fish of different genuses were recorded together at the same time, date, depth, and coordinates. In case of the bait camera records, the records of several genus together were straightforward, as the species are recorded at the bait at the same time and the cameras were not moving. In case of ROVs or AUVs, organisms were considered to be in the same place if the records had been made within the time range of ten minutes, at the depth range of 5 meters, and if the GPS coordinates were within 0.01 latitude and longitude, with an assumption that the fish might have been moving around the vehicle while involved in the interactions with each other. The earliest record in this dataset is from 2013 when the baited cameras and ROV/AUV technology became more widely used. Previous records used catch records or museum specimens.

For the Hawaii and Clarion Clipperton Zone area, based on all the parameters described above, the genus (plus one gigaclass and and three families) identified in the records were as follows: ***Actinopterygii (gigaclass); Barathrites; Bassozetus; Bathyonus; Bathysaurus; Coryphaenoides; Halosauridae (family); Histiobranchus; Ipnops; Ophidiidae (family); Osteichthyes (superclass); Pachycara; Pisces; Zoarcidae (family).*** There were nine different genuses, three families, one superclass, and one gigaclass represented in the records. The records analyzed were made at depths ranging from 4,026 meters to near the bottom, around 4550 meters (Figure 3).

Bait Camera and AUV/ROV records:

- - 2,057 of records analyzed;
- 2,026 records for bait cameras;
- 21 records for AUV;
- 10 records for ROV.

For bait cameras, there are eleven different combinations of fish, seven of which occurred once, whereas the rest happened two times or more (Table 1).

The chart below demonstrates the number of bait camera records across different genera/families that were analyzed during this research (Figure 4).

For AUV records, there were two assemblages, one was unique and the other occurred twice, and for ROV records, there were two assemblages and both were unique (Table 2).

Based on the data collection and analysis, the biggest number of records (25) made were the bait camera records, followed by the AUV (3) records and ROV (2) records. Noticeably, nine out of eleven groups of the assemblages of different genus caught by the bait cameras contained the *Coryphaenoides sp.* Moreover, in eleven out of twenty-five bait camera occurrences of different combinations, the *Coryphaenoides sp.* were of an overwhelming majority. Both of the AUV combinations contain the *Coryphaenoides sp.*, whereas none of the two of the ROV combinations had this genus. Notably, *Ipnops sp.* and *Bathysaurus sp.* had been recorded in the assemblage with other genus only with the help of ROV and AUV. Most fish assemblages which occurred more than once occurred with baited cameras, but in the absence of food some fish assemblages still occurred.

Images of the fish attracted to the bait have been the most common type of occurrences when the fish of different genus and/or family were imaged on the same date, at the same time and at the same coordinates. These images were also used to confirm the amicable nature of the fish relationships. Notably,

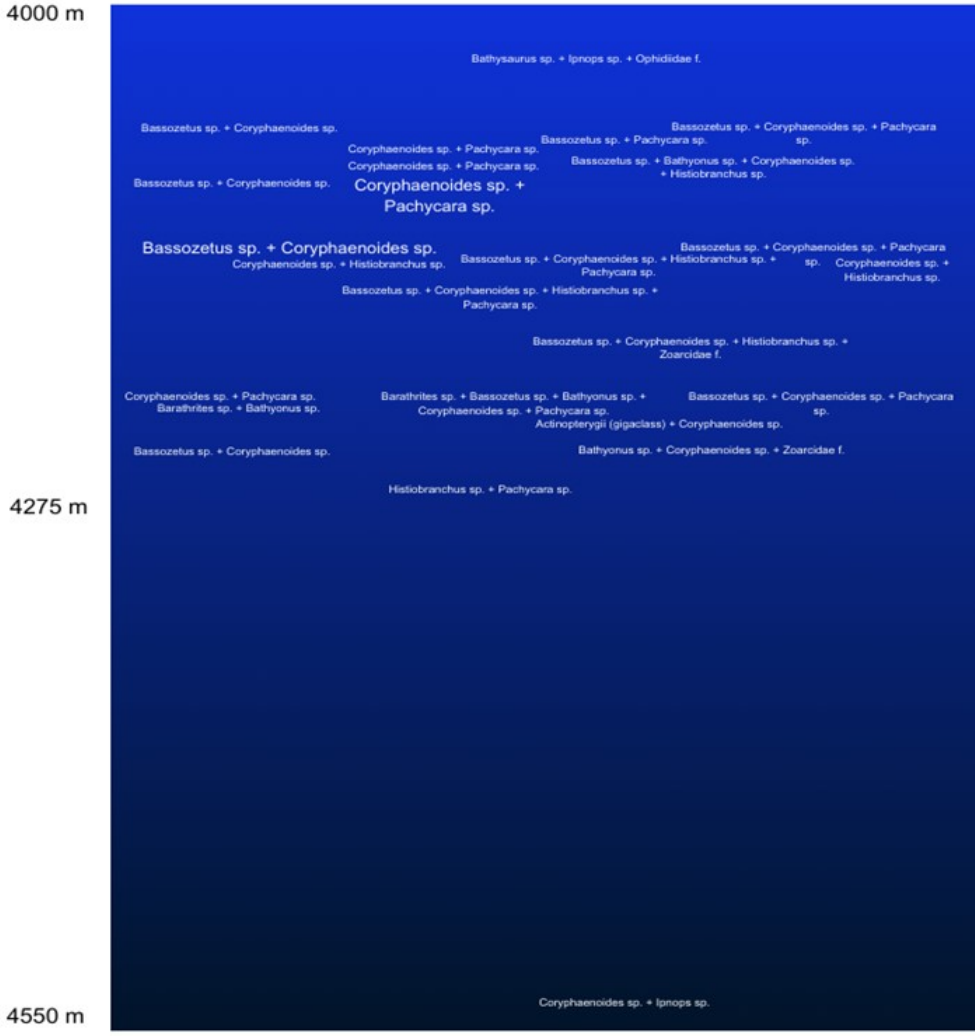

Fig. 3 Distribution of the OBIS records across the depths. Larger text size indicates several groupings of the same fishes within 5 meters of each other.

Table 1 A summary table of in-situ observations at depth recorded from the Hawaii and Clarion Clipperton Zone. Results from Bait Camera data. If photographs of the fish intermingling exist, that is indicated in the fourth column as further validation of species interactions.

Bait Camera			
Group	**Genuses involved**	**# of occurrences**	**Photo evidence?**
1	*Bassozetus sp. + Coryphaenoides sp.*	7	None
2	*Bassozetus sp. + Coryphaenoides sp. + Pachycara sp.*	3	Yes [33]
3	*Coryphaenoides sp. + Pachycara sp.*	6	Yes [28]
4	*Bassozetus sp. + Bathyonus sp. + Coryphaenoides sp. + Histiobranchus sp.*	1	None
5	*Bassozetus sp. + Coryphaenoides sp. + Histiobranchus sp. + Pachycara sp.*	2	None
6	*Coryphaenoides sp. + Histiobranchus sp.*	1	Yes [28,40,41]
7	*Bassozetus sp. + Coryphaenoides sp. + Histiobranchus sp.* + Zoarcidae f.	1	None
8	*Barathrites sp. + Bassozetus sp. + Bathyonus sp. + Coryphaenoides sp. + Pachycara sp.*	1	None
9	*Barathrites sp. + Bathyonus sp.*	1	None
10	*Bathyonus sp. + Coryphaenoides sp.* + Zoarcidae f.	1	None
11	*Histiobranchus sp. + Pachycara sp.*	1	None

Table 2 A summary table of in-situ observations at depth recorded from the Hawaii and Clarion Clipperton Zone. Results from ROV and AUV data. If photographs of the fish intermingling exist, that is indicated in the fourth column as further validation of species interactions.

AUV		
Group	**Genuses involved**	**# of occurrences**
1	Actinopterygii (gigaclass) + *Coryphaenoides sp.*	1
2	*Coryphaenoides sp.* + *Ipnops sp.*	2
ROV		
1	*Bathysaurus sp.* + *Ipnops sp.* + Ophidiidae f.	1
2	*Bassozetus sp.* + *Pachycara sp.*	1

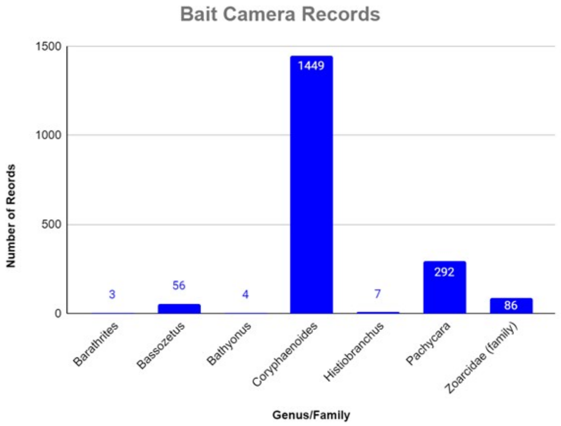

Fig. 4 Visualization of the number of Bait Camera records.

some publications had photos of fish interactions that were not listed on OBIS, suggesting that this dataset is incomplete (for example, Zoarcidae f. and *Pachycara sp.* from[28]).

Discussion

The findings of this research contain the vast majority of the records made with the help of bait cameras. Scholars find using bait cameras to be a practical approach to studying abyssal communities as the deep-sea scavengers tend to constantly swim while looking for food[33]. Clarion Clipperton Zone deep-sea is characterized by a relatively low density of fish over large areas with only hundreds of fish per square kilometer, which, together with the constant moving of the abyssal scavenger, allows for the assumption that employing the ROVs and AUVs becomes less efficient in terms of the volumes of data that can be gathered[28].

At the same time, for the bait camera records used for this research, the fish of different genus and/or family were likely imaged on the same date, time, and place because of the fish's attraction to the bait. It is logical that the images of the fish attending the bait have been the most common type of assemblages of the fish of different genus and/or family, as the baits attract a large number of fish and other fauna, which makes it relatively easy to make videos and photographic images.

In the case of the bait camera records, as the fishes of different genus have not been recorded in the natural conditions but rather lured to the same area with food, there might have been some space for biased interpretation of the potential mutualism or commensalism between them. While they were not antagonistic toward each other with ample food, hunger could drive them to predation as food is a scarce resource in the deep-sea. However, there is still space for the assumptions about mutualism/commensalism, as the fish were demonstrating attraction to the bait rather than a predator-prey interaction between each other. Moreover, the records indicate different combinations of genus recorded together. Interestingly, Harbour et al. (2020) discovered that the *Pachycara sp.* were attracted to the amphipods attending the bait rather than bait itself[33].

Other research has indicated that *Coryphaenoides sp.* and *Pachycara sp.* were the most common species attending the bait cameras in CCZ[28,33]. Moreover, according to Harbour et al. (2020), the *Coryphaenoides sp.* were recorded as the species arriving to the bait the fastest after the lander touch-down and stayed there the longest[33]. The results of this research are in line with the abovementioned findings, as nine out of eleven bait camera records of the assemblages of different genus contained the *Coryphaenoides sp.*, five out eleven bait camera records of the assemblages of different genus contained the *Pachycara sp.*, and in eleven out of twenty-five bait camera occurrences of different combinations the *Coryphaenoides sp.* were of an overwhelming majority.

Indeed, this research relies on the assumption that fishes coexisting without a negative interaction may be engaging in a neutral or beneficial relationship, and this assumption could add bias into the data analysis. Ideally, these relationships would be studied long term *in situ*, but these types of projects are expensive and also potentially biased due to the effect that a camera would have on fish behavior. Thus, there is not a perfect way to explore these relationships, but this study should serve as a first step in understanding mutualism and commensalism between deep sea fishes, and a call to action to study these relationships further.

Venrausel et al. (2016) discussed in their investigation of the impacts of previous experimental mining disturbances in CCZ on the epifaunal communities that the mineral resources and biological composition of abyssal ecosystems were not to be considered in isolation from one another[35]. They identified higher densities of mobile epifauna in nodule-rich zones and concluded that the removal of a hard substrate during polymetallic nodule mining in CCZ would lead to the significant long-term loss of biodiversity with a slow rate of recovery[35]. Uhlenkot et al. (2023) highlighted a high sensitivity of deep-sea to physical disturbances and, on the basis of the case studies conducted on the benthic megafauna of the Eastern part of the polymetallic nodules exploration contract area issued to the German Federal Institute for Geoscience and Natural Resources (BGR-E) in CCZ, confirmed a threatening effect of deep-sea mining activities on megafaunal community of the CCZ[38]. Moreover, nodule mining activities are expected to include nodule removal at a large scale and changes in turbidity[33,35]. At the same time, megafauna embody a significant element of the abyssal deep-sea biodiversity and are an important part of the functioning of the deep-sea ecosystem[40]. Scholars have identified correlations between the coverage of polymetallic nodules and the abundance of megafauna, hinting to it potentially leading to the abundance of prey on and around nodules[28,36,40]. It can be hypothesized that the factors listed above have a potential to influence the availability of prey to deep-sea megafauna, which might lead to the change in the predator/scavenger behavior patterns of the abyssal megafauna. This might further amend the mutual/commensal relations between the fishes, which might have further negative impact on the biodiversity of the deep-sea. Analyzing existing publicly available data in the attempt to understand potentially beneficial relationships between deep-sea fishes may add to a better understanding of the overall wellbeing of the abyssal ecosystem.

Conclusion

Based on the data analysis held for this research and the photo evidence of the non-predatory assemblages of the ray-finned fish in the deep-sea at the depth greater than 4,000 meters, it is possible to raise an assumption about existing mutual or commensal relationships between deep-sea fishes of different genera. Despite the existing scarcity of food resources in the deep-sea, the findings of this research can serve as a demonstration of an existence of the communities of benthic megafauna that function in reliance on each other. This research contains certain limitations, such as the use of only publicly available data from a major crowdsourced data depository. The data analyzed contained records made within a limited timeframe with the help of bait cameras, ROVs and AUVs, which might have created some disturbances to the natural behavior of fish. Therefore, in the conditions of longer-term *in situ* behavior observations being unavailable to the author, assumptions were made to categorize potential relationships. However, highlighting such mutual/commensal relationships might serve as an additional incentive for further research, which might focus on obtaining a better understanding of the functioning of the deep-sea ecosystems as a whole. Further investigation might be made to discover how much the deep-sea fish rely on each other and whether there are factors of the relationships that affect the ecosystem and how they might be affected by human activity. The polymetallic nodules in the CCZ present a substantial economic interest, and the nodule mining activity might affect the functioning of such communities of fishes, besides impacting their density and the biodiversity in this area. Future research could make an input to accounting for the fish-fish interactions aspect in developing the ecological resource management and protection measures and mechanisms. Such research might include more frequent bait camera surveys across the CCZ, as well as more frequent and more lengthy in time surveys made by the ROVs and AUVs at different depths, as well as long-term *in situ* behavioral observations. Moreover, an increased volume of data collected and consistently uploaded to the publicly available databases would widen the possibilities for scholars to analyze the fish-fish interaction accounting for the change of depth, seascape, biodiversity and community composition, and human activity.

References

1 C. Armstrong, N. Foley, R. Tinch and S. Hoven, *Ecosystem Services*, **2**, 2–13.

2 M. Costello, A. Cheung and N. Hauwere, *Environmental ScienceTechnology*, **44**, 8821–8.

3 M. Costello, B. Vanhoorne and W. Appeltans, *Conservation Biology*, **29**, 1094–1099.

4 R. Danovaro, C. Corinaldesi, A. Dell'Anno and P. Snelgrove, *Current Biology*, **27**, 431– 510.

5 E. Ramirez-Llodra, A. Brandt, R. Danovaro, B. Mo, E. Escobar, C. German, R. Levin, P. Arbizu, L. Menot, P. Buhl-Mortensen, B. Narayanaswamy, C. Smith, D. Tittensor, P. Tyler, A. Vanreusel and M. Vecchione, *Biogeosciences*, **7**, 2851–2899.

6 U.N.E.P.-W.C.M.C., *Deep-sea biodiversity and ecosystems: A scoping report for their socio-economy, management and governance*.

7 *PLoS One*, **8**, 51629.

8 J. Feng, J. Liang, Y. Cai, S. Zhang, J. Xue, Z. and Yang, *Science Bulletin*, **67**, 1802–1816.

9 T. Sato, K. Kim, S. Inaba, T. Matsuda, S. Takashima, A. Oono, D. Takahashi, K. Oota and N. Takatsuki, *Exploring hydrothermal deposits with multiple autonomous underwater vehicles*, IEEE Underwater Technology (UT) Conference, New York.

10 M. Costello, S. Wilson and B. Houlding, *Systematic Biology*, **61**, 871–883.

11 I. Priede and R. Froese, *Journal of Fish Biology*, **83**, 1528 – 1550.

12 M. Melo, R. Caires and T. Sutton, *Brazilian Deep-Sea Biodiversity. Brazilian Marine Biodiversity*, Springer, Cham.

13 J. Koslow, G. Boehlert, J. Gordon, R. Haedrich, P. Lorance and N. Parin, *ICES Journal of Marine Science*, **57**, 548–557.

14 E. Myers, M. Anderson, L. Liggins, E. Harvey, C. Roberts and D. Eme, *Ecology and Evolution*, **11**, 10600–10612.

15 J. Edwards, J. Pratt, N. Tress and N. Hussey, *Deep Sea Research Part I: Oceanographic Research Papers*, **146**, 24–43.

16 M. Costello and C. Chaudhary, *Current Biology*, **27**, 511– 527.

17 J. Drazen and B. Seibel, *Limnology and Oceanography*, **52**, 2306–2316.

18 F. Busserolles, L. Fogg, F. Cortesi and J. Marshall, *Seminars in Cell Developmental Biology*, **106**, 20–30.

19 T. Morato, R. Watson, T. Pitcher, D. Pauly and D., *Fish. Fish*, **7**, 24–34.

20 P. Hoagland, S. Beaulieu, M. Tivey, R. Eggert, C. German, L. Glowka and J. Lin, *Marine Policy*, **34**, 728–732.

21 M. Carrassón and J. Cartes, *Marine Ecology-Progress Series*, **241**, 41–55.

22 F. Girard, S. Litvin, A. Sherman, P. McGill, C. Lovera, A. DeVogelaere, E. Burton and J. Barry, *Deep Sea Research Part I: Oceanographic Research Papers*, **196**, 104048.

23 F. Micheli, C. Peterson, L. Mullineaux, C. Fisher, S. Mills, G. Sancho, G. Johnson and H. Lenihan, *Ecological Monographs*, **72**, 365–382.

24 F. Leo, J. Drazen, E. Vetter, A. Rowden and C. Smith, *Deep Sea Research Part I: Oceanographic Research Papers*, **64**, 54–70.

25 C. Yau, M. Collins and I. Everson, *Journal of the Marine Biological Association of the UK*, **80**, 379–380.

26 J. Moore and P. Auster, *Bulletin of the Peabody Museum of Natural History*, **50**, 381–386.

27 J. Drazen, B. Popp, A. Choy, T. Clemente, L. Forest and K. Smith, Jr, *Limnology and Oceanography*, **53**, 2644–2654.

28 A. Leitner, A. Neuheimer, E. Donlon, C. Smith and J. Drazen, *Deep Sea Research Part I: Oceanographic Research Papers*, **125**, 65–80.

29 L. Sallan, *Biological Reviews*, **89**, 950–971.

30 A. Wegorzewski and T. Kuhn, *Marine Geology*, **357**, 123–138.

31 T. T, A. Wegorzewski, C. Rühlemann and A. Vink, *Deep-Sea Mining: Resource Potential, Technical and Environmental Considerations. Sp.*

32 J. Hein, A. Koschinsky and T. Kuhn, *Nature Reviews Earth Environment*, **1**, 158–169.

33 R. Harbour, A. Leitner, C. Ruehlemann, A. Vink and A. Sweetman, *Frontiers in Marine Science*, **7**, 458.

34 A. Leitner, J. Drazen and C. Smith, *Frontiers in Marine Science*, **8**, 636305.

35 A. Vanreusel, A. Hilario, P. Ribeiro, L. Menot and P. Arbizu, *Scientific Reports*, **6**, 1–6.

36 E. Simon-Ledó, B. Bett, V. Huvenne, T. Schoening, N. Benoist, R. Jeffreys, J. Durden and D. Jones, *Progress in Oceanography*, **170**, 119–133.

37 E. Simon-Lledó, C. Pomeeb, A. Ahokavab, J. Drazen, A. Leitner, A. Flynne, J. Parianosf and D. Jones, *Progress in Oceanography*, **187**, 102405.

38 K. Uhlenkott, K. Meyn, A. Vink and P. Arbizu, *Marine Biodiversity*, **53**, 22.

39 D. Jones, E. Simon-Lledó, D. Amon, B. Bett, C. Caulle, L. Clement, D. Connelly, T. Dahlgren, J. Durden, J. Drazen, J. Felden, A. Gates, M. Georgieva, A. Glover, A. Gooday, A. Hollingsworth, T. Horton, R. James, R. Jeffreys, C. Laguionie-Marchais, A. Leitner, A. Lichtschlag, A. Menendez, G. Paterson, K. Peel, K. Robert, T. Schoening, N. Shulga, C. Smith, S. Taboada, A. Thurnherr, H. Wiklund, C. Young and V. Huvenne, *Progr. Oceanogr*, **197**, 102653.

40 G. Amon, A. Ziegler, J. Drazen, A. Grischenko, A. Leitner, D. Lindsay, J. Voight, M. Wicksten, A. Young and C. Smith, *Biodiversity Data Journal*, **5**, 14598.

41 C. Henriques, I. Priede and P. Bagley, *Marine Biology*, **141**, 307–314.