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Climate change to drive increasing overlap between Pacific tuna fisheries and emerging deep-sea mining industry

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In ocean areas beyond national jurisdiction, various legal regimes and governance structures result in diffused responsibility and create challenges for management. Here we show those challenges are set to expand with climate change driving increasing overlap between eastern Pacific tuna fisheries and the emerging industry of deep-sea mining. Climate models suggest that tuna distributions will shift in the coming decades. Within the Clarion-Clipperton Zone of the Pacific Ocean, a region containing 1.1 million km^2 of deep-sea mining exploration contracts, the total biomass for bigeye, skipjack, and yellowfin tuna species are forecasted to increase relative to today under two tested climate-change scenarios. Percentage increases are 10–11% for bigeye, 30–31% for skipjack, and 23% for yellowfin. The interactions between mining, fish populations, and climate change are complex and unknown. However, these projected increases in overlap indicate that the potential for conflict and resultant environmental and economic repercussions will be exacerbated in a climate-altered ocean. This has implications for the holistic and sustainable management of this area, with pathways suggested for closing these critical gaps.

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INTRODUCTION

The ocean constitutes 71% of the Earth's surface, and nearly two-thirds of this are areas beyond national jurisdiction (ABNJ, or for the water column 'the high seas'). Within ABNJ, there are different legal regimes and governance structures for the non-living resources (e.g., minerals) and the living resources (e.g., fishes). The United Nations Convention on the Law of the Sea (UNCLOS) created a central intergovernmental agency, the International Seabed Authority (ISA), that has responsibility to govern activities relating to minerals and the ABNJ seafloor, as well as the resulting potential environmental impacts[1]. The same Convention provides a legal regime for the use, conservation, and management of high-seas fishery resources[2]. These legal rules are generally implemented via regional fisheries management organisations (RFMOs), created to regulate economically-important highly-migratory fish stocks in ABNJ[3]. RFMOs themselves differ in their scope, approach, and mandate, with five RFMOs that address highly migratory tuna stocks and tuna-like species such as marlin or swordfish. While some stocks are considered healthy[4,5], there are significant gaps in coverage and ineffective management for others[6]. These multiple designations have diffused responsibility for ABNJ, creating challenges for the management of marine resources in the high seas, especially when the separate management of the living and non-living resources may result in conflicting strategies.

The Clarion-Clipperton Zone (CCZ) is a large area (4.5 million km^2) located between Hawai'i and Mexico in the eastern Pacific Ocean[7]. There is high environmental heterogeneity across this area, demonstrated by primary productivity increasing west to east and north to south, dissolved oxygen concentrations influenced by the presence of a mobile oxygen minimum zone in the water column, and high densities of polymetallic nodules on the seafloor[8,9]. These nodules have attracted commercial interest in deep-sea mining, with 17 exploration contracts currently issued across the region by the ISA, covering a quarter of the area of the CCZ seabed (1.125 million km^2) (https://www.isa.org.jm/exploration-contracts/exploration-areas/).

There are also commercial fish stocks of tuna in the CCZ, with this region falling under the jurisdiction of two tuna RFMOs: the Inter-American Tropical Tuna Commission (IATTC) and the Western and Central Pacific Fisheries Commission (WCPFC)[10]. These two RFMOs oversee three of the main Pacific tuna species: bigeye (*Thunnus obesus*), skipjack (*Katsuwonus pelamis*), and yellowfin (*T. albacares*) tuna. Together, fisheries targeting these species captured 3.5 million tonnes (IATTC 687,000 tonnes and WCPFC 2.9 million tonnes) in 2022, which was 66% of global tuna catches reported that year[5,11]. Within the CCZ and surrounding waters, catches for these species average 35,000 to 78,000 tonnes per year[10]. These are some of the most profitable fisheries in the world; market price (i.e., dock price) fluctuates between $1,000 USD per tonne for skipjack tuna to over $5,000 USD for bigeye tuna, reaching an end value of over $10,000 USD per tonne[12]. In total, the economic value of these three species within these two RFMOs fluctuate around $5.5 billion USD per year (WCPFC $4.3 billion USD, IATTC $1.2 billion USD)[13] (www.seaaroundus.org).

If deep-sea mineral exploration projects, currently operational in the CCZ, are permitted by the ISA to move to an exploitation phase, substantial environmental impacts would likely be caused[14–17]. Additionally, conflict between fisheries and deep-sea mining will likely occur given the existing spatial overlap within and around the CCZ[10]. There are at least four different mechanisms by which nodule mining in the CCZ could negatively impact fisheries specifically. However, the extent of these impacts is largely unknown and/or debated, especially given the significant scientific gaps in this region[18,19]. First, there will be two plumes, one where sediment is stirred up by the mining of

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the nodules at the seafloor, and a second where unwanted water and material separated from the nodules is discharged into the ocean from the surface mining vessel. The discharge plumes will raise the particle concentration in the water column. This could interfere and harm filter feeding apparatuses and gills of tuna and their prey (which include diurnal vertical migrators), reduce visual communication, and increase stress hormone levels[10,20]. This could extend the impacts of deep-sea mining horizontally for tens to hundreds of kilometres and vertically for hundreds to thousands of meters[10,21,22].

Second, the return-water discharge plume is expected to contain elevated concentrations of metals. As minerals are collected, they will likely fragment with some dissolving into seawater and some adhering to sediment or organic particles. Such particles could be ingested and incorporated into deep-sea food webs entering our seafood supply with bioaccumulation in tuna[21]. Even if there were only localised effects or low risks from toxic accumulation or contaminant presence, this could still have a high impact on tuna fisheries through a negative consumer/market reaction[19,23]. Further, the tuna species fished in the CCZ are highly migratory and any contamination of fish through the food chain could percolate through the wider stock distribution[19]. Third, mining noise could also be extensive and cause physiological impacts in tuna and their prey, leading them to alter their feeding and/or reproductive migrations, and potentially reducing catch rates[21,24,25]. Lastly, an increased density of mining vessels restricted in their ability to manoeuvre could limit fishing vessel operation, as well as result in changes to tuna behaviour (avoidance or attraction). These impacts may extend to further ABNJ biodiversity e.g., seabirds that are dependent on sub-surface facilitated feeding by tuna may themselves shift into higher degrees of overlap with mining activities with uncertain consequences for their health[26,27].

The ocean has absorbed 90% of the extra heat and 20–30% of the CO_2 released from anthropogenic activities over the last decades, resulting in profound geochemical changes[28,29]. As temperature and pH continue to increase, and oxygen concentration decreases, marine species have adopted different coping strategies, shifting their historical distributions, sometimes toward higher latitudes or deeper waters[30]. Specifically, yellowfin, bigeye and skipjack tunas in the Pacific Ocean are expected to shift distribution and abundance towards the equatorial eastern Pacific[31] and poleward, with some studies suggesting shifts are already occurring[32,33]. Such shifts are expected to continue within the current century regardless of the climate-change scenario[34,35], threatening catches of targeted species[36], jobs, and revenues[37], and challenging international fisheries management globally[38,39].

This paper was instigated by recent findings that three commercially-important species of tuna will experience climate redistribution, with the equatorial eastern Pacific acting as a future climate refugia[31]. These changes could have profound risks to the economies, livelihoods, and well-being of Pacific small island developing States and coastal States[31]. Given the emergence of deep-sea mining, a new ocean industry that has the potential to result in biodiversity and habitat loss across large scales in the same area of the Pacific, we explore here the future intersections between tuna fisheries and deep-sea mining under climate change in the CCZ specifically. We also discuss the challenges of effectively managing the living and non-living resources in this area, and end with recommendations to achieve holistic and sustainable management of this area in a rapidly changing ocean.

RESULTS AND DISCUSSION

Potential conflicts between fisheries, deep-sea mining, and climate change

Results show increases in biomass for all three tuna species within the CCZ by the mid-21st century relative to today under both climate-change scenarios tested (Fig. 1). When considering the overall percentage change in biomass for CCZ contract areas and the associated buffer zone, increases ranged from 10% for bigeye tuna under Representative Concentration Pathway (RCP) 4.5 to 31% for skipjack tuna under RCP 8.5, with an average of 21% for all three species for both RCPs (Fig. 1). Overall percentage increases in biomass for the CCZ by the mid-21st century are not projected to show much variation between RCP 4.5 and 8.5, suggesting that tuna will move to the CCZ regardless of the climate-change scenario (Fig. 1). The small difference in projected tuna biomasses

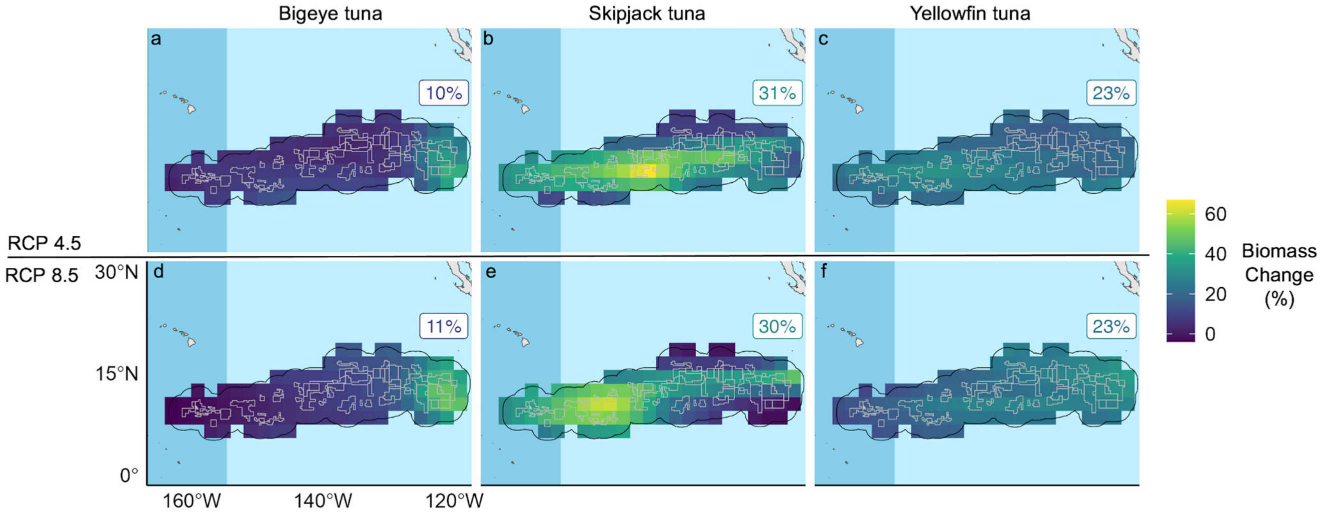

Fig. 1 Percentage change in the biomass of tuna for the Clarion-Clipperton Zone by the mid-21st century (average of 2044 to 2053) relative to present (average of 2009 to 2018). Three species of tuna are included from left to right: bigeye tuna (*Thunnus obesus*), skipjack tuna (*Katsuwonus pelamis*), and yellowfin tuna (*T. albacares*). The black line around the CCZ denotes 200 kilometers from deep-sea mining exploration contract-area boundaries. This buffer was used as several modelling studies have suggested that midwater sediment plumes may spread over such distances. The buffer was created using the geoprocessing tool Buffer in qGIS v3.8. All maps are split into the two relevant RFMOs: the Western and Central Pacific Fisheries Commission (WCPFC) (dark blue) and the Inter-American Tropical Tuna Commission (IATTC) (light blue). Percentage values on the top right of the CCZ in each panel represent the percentage changes in tuna biomass for the entire CCZ. **a**–**c** are under Representative Concentration Pathways (RCP) 4.5 and **d**–**f** represent RCP 8.5.

between scenarios can be seen for most ABNJ of the Pacific region[31] and may be attributed to little variation between RCP pathways throughout the first half of the 21st century[40].

The distribution of biomass change within the CCZ does, however, vary spatially and between species (Fig. 1). Specifically, there is an increase in skipjack and yellowfin tuna biomasses within most of the CCZ, regardless of the climate-change scenario (Fig. 1). On the other hand, bigeye tuna presents a reduction-to-no-change within most of the region, with the exception of the eastern zone where increases will be substantial in both climate-change scenarios (Fig. 1). Spatial patterns show a higher concentration of bigeye tuna in the eastern part of the CCZ under both climate-change scenarios, while skipjack shows a more central (RCP 8.5) or eastward (RCP 4.5) trend (Fig. 1). Finally, yellowfin tuna shows a more homogenous distribution (Fig. 1). However, such spatial variation should be approached cautiously given the high mobility of tuna species and the resolution of these results.

Taking into account the historical expansion of industrial-scale tuna fisheries and the shift in distribution driven by greenhouse-gas emissions by the mid-21st century, these commercially-important species will migrate into an area where deep-sea mining could be underway (Fig. 1)[31,41]. This could result in increasing conflict between the two industries if more tuna catches are obtained from mining areas[10].

Tuna fisheries in the CCZ may be impacted by deep-sea mining in several ways: the direct impacts of nodule mining are predicted to include noise, light, and movement of ships at the sea surface, as well as the benthic and discharge plumes. The level of interaction with and impact from the return-water discharge mining plumes and tuna fisheries will be influenced by the depth of the release of discharge. That is, the deeper the release depth, the smaller the spread of the plumes will likely be and the less chance to impact tunas and the life they depend on. Discharge depths below the mesopelagic zone (200–1000 m depth) will be more likely to avoid deep-diving tuna, such as bigeye tuna that are usually between 0 and 500 m and their prey which can live to 1500 m depth[9,21,42–45]. However, this is likely to be more costly and technically challenging for deep-sea mining operations. Additionally, deeper discharges of plumes will likely still affect non-tuna species present at deeper depths, including benthic species that may still be important components of the functioning and food webs of this area.

Further, differences in ecology, including mobility, distribution, associations with floating objects, diet, predatory behaviour, stock structures, and spawning patterns, could result in varied impacts to each tuna species. Oceanographic factors (such as current flow rates and direction) will also affect the likelihood of impact. In addition to the above specific direct impacts that may be caused to tuna from deep-sea mining, it is also possible that the cumulative environmental impacts of deep-sea mining serve to make the CCZ generally less hospitable for tuna, ultimately lessening their options for climate refugia[21,32].

Any impacts on tuna at a population or stock level could lead to effects on tuna-dependent economies that fish within and around the CCZ, presenting unresolved equity issues. The five countries that obtain the highest average annual tuna catches (in tonnes) in the CCZ are Mexico, Venezuela, Nicaragua, Panama, and Colombia, with Mexico and Venezuela obtaining 21% and 10% of their tuna there respectively[10]. Between 2009 and 2018, ABNJ fisheries of yellowfin, skipjack and bigeye tuna landed 250,000 tonnes, generating $512 million USD for these countries, with yellowfin creating the highest revenue of the three with 109,000 tonnes generating $281 million USD[13] (www.searoundus.org). While these values represent overall ABNJ catches, it demonstrates the economic importance of these species to these countries. As climate change shifts the distribution of Pacific tunas eastwards from Pacific Island national jurisdictions to high-seas areas[31] such as the CCZ, new fishing opportunities will likely arise for those countries fishing in the region. Additionally, nations that do not fish the most in the licensed mining areas of the CCZ may still derive a moderate proportion of their RFMO tuna catches there. For example, China obtains 17% of their RFMO-reported tuna catches in the mining areas and 200-km zone, while Belize and Nicaragua obtain 11%[10]. Given the shifting of these stocks due to climate change, and the potential overlap between fishing and mining activities within and around the CCZ, these percentages are likely to increase, which could represent a substantial economic risk for nations fishing in the region.

There may also be further socioeconomic impacts (e.g., loss of income, decreases in employment, lowered food security, and well-being) to nations surrounding the CCZ if tunas are impacted by mining and their migration patterns into neighbouring Exclusive Economic Zones are altered. Negative impacts to tuna stocks, or even increased consumer concern about toxic accumulation or contaminant presence, could have particularly devastating consequences for several countries whose economies are described as ‘tuna-dependent’[23,31]. Ultimately, deep-sea mining by more economically developed States could lead to small island developing States and other developing coastal States being disenfranchised, with a resulting increased risk of legal challenges and/or conflict. While we focus specifically on the CCZ where deep-sea mining may be more likely to commence, it should be noted that fishery overlap with mining occurs in other regions and ocean basins, and future work is required to identify how industry overlap may be affected by climate change[10]. In addition, while tuna dominate catches obtained in the CCZ[10], there are other commercially-important species, such as billfishes, that occur in the CCZ, and there are other areas of potential mining-fishery overlap such as at encrusted seamounts for seamount-associated fish species.

Scientific gaps

Sustainable resource-management regimes generally rely upon a robust scientific understanding of the environment and the impacts from development activities. However, there is a lack of basic scientific knowledge about the CCZ, especially regarding deep-sea ecosystems[18]. There is also, at this nascent stage of the industry where no large-scale mining operations have yet commenced, little applied knowledge about how deep-sea mining will impact CCZ ecosystems and fisheries. This is linked to the lack of information on environmental baselines, potential responses to mining impacts, and specific deep-sea mining technology and mining processes (e.g., the depth of discharge)[18]. There is also little known about these three focal tuna species with regard to their sensitivities to deep-sea mining activities and climate change, in particular for juveniles and the communities these tuna depend on[31]. More scientific data is needed to understand the spatial and temporal dynamics of the mining discharge plume (including dissolved and particulate metals), their consequences for tuna and fisheries, and climate modelling to increase accuracy of future predictions. The cumulative and/or synergistic impacts of deep-sea mining, fisheries, and climate change are also unknown, but likely important[18].

Governance gaps

Governance of the CCZ is challenging for a number of reasons including, but not limited to, the significant scientific knowledge gaps discussed above and fragmented multi-sectoral governance in this region. These challenges will likely magnify as human activities increase and the impacts of climate change are felt more acutely[46]. The number of legal regimes (e.g., UNCLOS, UN Fish Stocks Agreement, UN Framework Convention on Climate Change, national laws) and governance structures (e.g., ISA, Food and Agriculture Organization, International Maritime Organization, WCPFC, IATTC, those of individual States) applicable to the CCZ results in a fragmented patchwork that prevents a holistic approach to managing human activities in this area. However, it is only three of these organisations that are responsible for applying an ecosystem-based approach – the ISA, the WCPFC, and the IATTC.

UNCLOS continues to evolve, and in March 2023, a text was agreed between States, paving the way for a historic treaty to conserve and sustainably use marine biodiversity in ABNJ (the BBNJ Agreement). This treaty has been designed to avoid undermining existing governance regimes in ABNJ, so it remains to be seen how the new legal regime and structures will interact with management of fisheries and deep-sea mining, and components of the agreement related to area-based management[31,47–49]. Notwithstanding, there are a number of UNCLOS (and other international law) duties relevant to States and the ISA conserving and/or not adversely affecting biodiversity in the water column (including fish stocks), including as a result of deep-sea mining activities (e.g., UNCLOS Articles 145, 192, 194, 206, 209, and UN Straddling Fish Stocks Agreement, the International Convention for the Prevention of Pollution from Ships (MARPOL), the Convention on Biological Diversity Articles 3, 8, 14, and customary international law obligations to prevent transboundary harm).

Further uncertainty arises from the unsettled status of the ISA's rules, regulations, and procedures for exploitation of mineral resources in ABNJ (known as 'the Mining Code'). This complex matrix of rules and legal standards are currently under multilateral negotiation[50]. It has been noted that climate considerations were little featured in the draft text presented by the ISA's technical body to its member States for further negotiation[51]. UNCLOS requires that deep-sea mining must operate with 'reasonable regard for other activities in the marine environment' and vice versa, including fisheries, and specifies that deep-sea mining installations may not be established in areas of intense fishing activity (Article 147). The principle of 'reasonable regard' (often equated with 'due regard' used elsewhere in UNCLOS) requires consideration of a balance of interests on a case-by-case basis, often requiring dispute resolution and interpretation by the Courts[52]. It is not clear how ISA contractors' duty of 'reasonable regard' for fisheries will play out in practice, but would appear to require more detailed regulations to have operational effect, which are not currently in place at the ISA. Indeed, there has been surprisingly limited consideration, engagement, or consultation thus far between the ISA and fishing industries and/or RFMOs in relation to mining activities in the CCZ. The ISA's list of 69 observer organisations features no RFMOs or fishery groups (https://www.isa.org.jm/observers/). The FAO, which has a focus on fisheries, is an intergovernmental organisation observer to the ISA, but has neither attended nor made any submission to ISA proceedings in at least the past five years during which the Mining Code has been negotiated (Authors' own research, from ISA sessions' delegation lists: https://www.isa.org.jm/wp-content/uploads/2023/02/ISBA_27_A_INF_6-List-of-Delegations_Assembly_27th-Session-rev-11082022.pdf, https://www.isa.org.jm/wp-content/uploads/2022/06/ISBA_26_A_INF_3.pdf, https://www.isa.org.jm/wp-content/uploads/2022/06/isba25-a-crp5_0.pdf, https://www.isa.org.jm/wp-content/uploads/2022/06/isba-24a-crp-4_0.pdf). The Regional Environmental Management Plan (REMP) for the CCZ, one of the ISA's principal environmental management tools, does not include assessment of fish stocks or fishing activity in the region, does not consider potential impacts on fisheries, and does not require consultation by ISA contractors or organs with the fishery sector[53–55].

There have also been concerns raised about a lack of transparency at the ISA[56], and a lack of participatory approach in ISA decision-making[56,57]. As an example, Venezuela, one of the nations identified as particularly reliant upon fisheries in the CCZ area, is not a member of the ISA, and as such may need proactive outreach from the ISA in order to be informed about the regime and to engage in its deliberations (in a non-voting capacity). There is no evidence of such outreach, and Venezuela does not currently attend or engage in any way, in the ISA's meetings (Authors' own research, from ISA sessions' delegation lists: https://www.isa.org.jm/wp-content/uploads/2023/02/ISBA_27_A_INF_6-List-of-Delegations_Assembly_27th-Session-rev-11082022.pdf, https://www.isa.org.jm/wp-content/uploads/2022/06/ISBA_26_A_INF_3.pdf, https://www.isa.org.jm/wp-content/uploads/2022/06/isba25-a-crp5_0.pdf, https://www.isa.org.jm/wp-content/uploads/2022/06/isba-24a-crp-4_0.pdf). Additionally, at both the ISA and RFMOs, there are questions around abilities to address critical environmental-management issues given the level of influence by the interests and political will of their constituent members, rather than reflecting truly whole-of-government mandates. However, 16 of 20 States (plus the EU) in the IATTC and all except one in the WCPFC are members of the ISA. Five member States are Sponsoring States in the IATTC and seven within the WCPFC, while six in the IATTC and seven in the WCPFC have called for a ban, pause, or moratorium on deep-sea mining, pointing to a need for dual and holistic consideration.

The remoteness of the CCZ presents an additional challenge with regard to monitoring, control, and surveillance. The ISA has yet to agree on an inspection and monitoring regime for future activities in the CCZ[58], but currently relies upon self-reporting by its contractors without independent data verification[59]. Concerns already exist about inadequacies to combat, and therefore persistence of, illegal, unreported, and unregulated fishing globally[60]; deep-sea mining may be responsible for similarly challenging environmental infractions. It is unclear the extent to which fisheries activities could disrupt deep-sea mining activities in the same region, and what measures may be taken to prevent or remedy this. It is notable that the monitoring, surveillance, and control of fisheries on the high seas (which may include vessel monitoring systems, data collection and reporting, inspection schemes or observer programmes, and sanctions for non-compliant vessels) is largely dependent on the ability and willingness of individual flag States to exercise effective control over vessels flying their flag, and States may have differing degrees of capability in that regard[61,62].

The potential for deep-sea mining to affect fisheries also requires consideration of how the miners will be regulated. To ensure reasonable regard for fisheries operating in the same region, the ISA will need powers not only to monitor, but also to enforce compliance by miners with its Mining Code (once adopted). The practicalities of this part of the regime have received little attention to date at the ISA[63]. There are various legal and political complexities at play. The ISA itself, as an intergovernmental organisation, does not have jurisdiction to create or prosecute criminal offences, nor to conduct inspections, arrests, asset-freezing, etc. within national jurisdictions. The ISA must therefore rely on cooperation from individual States for such measures. However, analysis suggests that some States currently sponsoring ISA exploration contracts do not have relevant measures in place in their national legal regimes, nor clear procedures in their court systems to deal with disputes that may arise in relation to their contractors' actions[64]. An entity holding a deep-sea mining contract with the ISA may itself be a State, which may be unlikely to wish to impose such sanctions upon itself or its officers. An ISA contractor may also be a private-sector entity sponsored by a State. This sponsoring State is required to have its own measures in place to ensure contractor compliance, which can offer an additional layer of regulatory control within the overall ISA regime. There is however concern about a developing trend of 'sponsoring states of convenience' whereby a private-sector ISA contractor partners with a sponsoring State, which may have no meaningful relationship or control over that contractor, and/or may have very limited regulatory capacity in practice[65,66].

To further complicate the enforcement regime for deep-sea mining in ABNJ, the mining operations will occur from a vessel located in the high seas. According to the UNCLOS regime, such a vessel is under the exclusive jurisdiction of the flag State. There is no requirement in UNCLOS (or in the ISA rules currently) for that flag State to be the same State as the ISA contractor / contract's sponsoring State. Nor even for the flag State to be a member of the ISA, and thus bound by its regulations. It can therefore be seen that the compliance regime for deep-sea mining in ABNJ is complex and may be susceptible to governance gaps or abuse to evade monitoring and compliance measures.

Pathways to effective management

The decades ahead will herald a new seascape for ocean management, with many challenges to overcome for multiple marine sectors to be managed synergistically, sustainably, and equitably. Below are recommendations for pathways towards effective ecosystem-based and cooperative management of multi-sectoral human impacts in the CCZ. Given the many outstanding critical scientific gaps related to the impacts of deep-sea mining, fisheries, and climate change, as well as their interactions, in the CCZ, that must be closed through scientific research for effective management to be possible, it would be prudent for the ISA not to permit mining unless and until the likely impacts are properly understood, and manageable within agreed thresholds[18,67,68], including consideration of potential effects on tuna stocks. In this vein, there have been increasing calls for a precautionary pause or moratorium on deep-sea mining, from various sources, including downstream users of minerals, governments, ocean experts, civil society and, most recently and of particular relevance, fishery management organisations and downstream users of fisheries[69,70] (https://seabedminingsciencestatement.org/; https://www.noseabedmining.org/).

There is also the need for the development and evolution of relevant rules, regulations, and procedures of the ISA's Mining Code, as well as the ISA's management tools including the standardisation of the ISA's REMP process. These regional management planning processes should be expanded to ensure all marine life and uses (including fish stocks and fishery activities) are properly mapped and assessed. The planning processes should include future forecast scenarios that take into account climate modelling. All relevant stakeholders, including RFMOs, the fishing industry, and Pacific tuna-dependent States, should be brought into transparent, proactive, and consultative management processes. Generally, the development of mechanisms for information exchange and a formalised inclusive consultation process between the ISA and fishing industries and/or RFMOs, as well as between the WCPFC and IATTC themselves specifically for the CCZ, seems an urgent matter.

As suggested by Goodman, et al.[71], the IATTC and the WCPFC could develop an expanded framework for cooperation and collaboration that would allow them to fulfil their conservation and management responsibilities under international law. Specifically, these could include a formal mechanism for cooperation to enable effective and efficient decision-making and action by the two RFMOs on key issues, such as deep-sea mining and climate change[71]. Further cooperation will be needed on scientific research and modelling to better understand the biology and distributions of Pacific tuna stocks and how they will respond to individual and cumulative human impacts[71]. More seamless work between the two RFMOs will help to facilitate enhanced cooperation and collaboration with the ISA and ultimately could be a key pathway for effective management. Such dialogue could lead to targeted and collaborative scientific research, designed to fill some of the current knowledge gaps that prevent robust science-based rule-setting and decision-making. Better understanding of potential impacts upon fisheries and fish-dependent economies and populations, will in turn assist the individual member States of the ISA to take the difficult decisions facing them about what level of adverse impact from deep-sea mining is considered acceptable versus the forecasted benefits, and whether such impacts and benefits might be distributed in an equitable manner. If fish stocks do appear to be adversely impacted by deep-sea mining in ABNJ, then it seems likely that those affected would wish to seek compensation. However, the legal framework for actioning such a claim requires more robustness, with regards to where such a claim could be brought, by whom, against whom, what damages could be claimed, and what degree of fault and causation would need to be proven[72]. This suggests that litigation in this area could be complex, lengthy, expensive, and multi-party.

The BBNJ Agreement may also prove to be an effective management tool for marine ABNJ. Despite a commitment to "not undermine" existing agreements, without consensus on how this will be implemented in practice, the outcomes of the BBNJ Agreement have potential to influence both fisheries and deep-sea mining in a changing ocean[47]. The Agreement might indirectly strengthen the performance of the RFMOs and the ISA, due to the need to reduce the impact of fisheries and deep-sea mining on marine biodiversity, respectively[47]. Additionally, the BBNJ Agreement could broadly increase capacity building and technology transfer with regard to the ocean, which may enhance the effectiveness of the decision-making related to the use of marine genetic resources (MGRs), area-based management tools (ABMTs), and environmental impact assessments (EIAs)[47]. The BBNJ Agreement also has significant potential to increase cooperation among existing marine governance organizations, including the sharing of scientific data and information[47].

Finally, for the overall benefit of all fisheries and for the planet as a whole, all sustainable and equitable pathways for the reduction of greenhouse-gas emissions to limit warming to 1.5 °C by the end of the century should be considered and implemented[34,73].

METHODS

Study area and species

This study focused on ISA exploration contract areas for polymetallic nodules within the CCZ. The CCZ region was denoted by a spatial shapefile with a buffer zone of 200 kilometers from the border of outer contract areas as per van der Grient and Drazen[10], all falling between 110°W and 158°W and 5°N and 19°N (Fig. 1). The 200-km buffer was used as several modelling studies have suggested that midwater sediment plumes may spread over such distances[74–76] given that the processes of flocculation, which could minimise plume extent, are unlikely to occur in discharge plumes[22,76]. The buffer was created around exploration contract areas using the geoprocessing tool Buffer in qGIS v3.8[77]. Three Pacific tuna species (bigeye, skipjack, and yellowfin), which are overseen in the west Pacific Ocean by the WCPFC and in the east Pacific Ocean by the IATTC, were assessed. Other species captured and covered by these RFMOs were not included but are a small component of the catches.

Data on tuna biomass projections under climate change

We used published projections of the effects of climate change on the distribution and abundance of the three most commercially important Pacific tuna species[31] using the model SEAPODYM (Spatial Ecosystem and Population Dynamics Model; www.seapodym.eu). Briefly, SEAPODYM is a 3D numerical model that simulates changes in biomass over time based on environmental variables, life-history stages, prey density, and their age dimensions[78]. The model relies on underlying advection-diffusion-reaction equations, integrated on a 2° latitude-longitude grid. Fish movements within the model are based on relationships with environmental variables (e.g., temperature, oxygen concentration, primary production) and dependent on life-history stage of the fish species (e.g., larvae and small juveniles drift with currents while adults have active movement based on habitat quality). The model accounts for both natural and fishing mortality and follows a maximum likelihood estimation (MLE) approach to resolve population dynamics, including the effects of fishing and environmental variability. It is important to acknowledge that SEAPODYM is one of the multiple ways that researchers have explored the impacts of climate change on tunas and billfishes, including their associated fisheries[5]. Unlike most existing models, SEAPODYM provides a mechanistic approach that includes both population dynamics and trophic interactions thus providing biomass estimates in the water column.

The environmental variables used to run SEAPODYM were temperature, dissolved oxygen concentration, zonal/meridional currents and primary production, and two-dimensional euphotic zone depth[31]. Environmental variables to simulate the historical oceanic environment (1979 – 2011) were taken from the Nucleus for European Modelling of the Ocean (NEMO) ocean framework[79], while future ocean projections (2011–2100) were taken from four Earth System Models (ESMs). Specifically, the Institute Pierre Simon Laplace Climate Model 5 (IPSL-CM5A)[80], the Model for Interdisciplinary Research on Climate (MIROC)[81], the Geophysical Fluid Dynamics Laboratory Earth System Models (GFDL-ESM2G)[82], and the Max Planck Institute for Meteorology Earth System Model (MPI-MR)[83]. Results are presented as the average of all four ESMs. The ESMs followed two Representative Concentration Pathways (RCPs, a high emission scenario (8.5))[84] and a medium emission scenario (4.5)[85]. RCPs are greenhouse gas concentration trajectories adopted by the Intergovernmental Panel on Climate Change. RCP 8.5 is considered a worst-case climate-change scenario where emissions continue to rise throughout the 21st century. RCP 4.5 is an intermediate scenario where emissions peak around 2040, then decline.

Estimating biomass change within the CCZ

The future percentage change in biomass within the CCZ relative to present was estimated. First, the yearly biomass outputs within the CCZ for each species and average for a present time (2009–2018) and mid of the 21st century (2044–2053) were aggregated by grid-cell within the CCZ. Biomass percentage change ($\Delta B_{i,j}$) was estimated for each tuna species j within a grid cell i as follow:

$$\Delta B_{i,j} = \frac{MB_{j,i} - PB_{j,i}}{PB_{j,i}} * 100 \tag{1}$$

where MB is the biomass in the grid cells at the middle of the 21st century and PB is the biomass in that same grid cell at present time. In addition, we estimate the percentage change within the whole area. For that, we first aggregated all pixels within the CCZ per species, then averaged by timeframe and applied the previous equation. All analyses were done in R-Studio version 4.2.0[86] using the packages *tidyverse*[87], *janitor*[88], *sf*[89], *sp*[90], *rnaturalearth*[91] and *viridis*[92].

DATA AVAILABILITY

The datasets generated during the current study are available in the repository ccz_tuna available at https://github.com/jepa/ccz_tuna. Original tuna distribution data analysed in the current study can be found in the repository Tuna_Redistribution and can be accessed via this link https://osf.io/qa8w4/.

CODE AVAILABILITY

The underlying code for this study is available in the repository *ccz_tuna* and can be accessed via this link https://github.com/jepa/ccz_tuna.

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AUTHOR CONTRIBUTIONS

Conceptualization—D.J.A., J.P.A. Methodology—D.J.A., J.P.A., J.V.G. Formal analysis—D.J.A., J.P.A. Writing—original draft—D.J.A., J.P.A. Writing—review and editing—D.J.A., J.P.A., J.D., H.L., N.N., J.V.G., D.J.M.

COMPETING INTERESTS

All authors declare no competing interests.

ADDITIONAL INFORMATION

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