frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 25 July 2025
DOI 10.3389/fmars.2025.1420203

Check for updates

OPEN ACCESS

EDITED BY
Rolf Adriaan Groeneveld,
Wageningen University and Research,
Netherlands

REVIEWED BY
Kristy Wallmo,
NOAA Fisheries, United States
Maarten Punt,
Windesheim University of Applied Sciences,
Netherlands

*CORRESPONDENCE
Michael J. Weir
mweir@whoi.edu

RECEIVED 19 April 2024
ACCEPTED 30 June 2025
PUBLISHED 25 July 2025

CITATION
Weir MJ, Lozinsky M and Jin D (2025) Assessing public support for commercial fishing in the ocean twilight zone considering climate trade-offs and ocean literacy. *Front. Mar. Sci.* 12:1420203. doi: 10.3389/fmars.2025.1420203

Assessing public support for commercial fishing in the ocean twilight zone considering climate trade-offs and ocean literacy

Michael J. Weir[1]*, Maya Lozinsky[2] and Di Jin[1]

[1]Marine Policy Center, Woods Hole Oceanographic Institution, Woods Hole, MA, United States,
[2]Department of Politics and Department of Philosophy, Scripps College, Claremont, CA, United States

Biomass in the mesopelagic or twilight zone (OTZ) of the ocean is estimated to be 10–100 times that of current annual capture fishery production and plays a fundamental role in regulating global climate via both biological and physical processes. Recently, OTZ fisheries have gained commercial attention to support aquaculture feed production. However, scientific uncertainty remains about the OTZ's link to carbon cycling processes, making it difficult to craft a comprehensive policy to regulate human intervention and mitigate negative consequences. We distribute a choice experiment among U.S. residents to estimate the potential social benefit associated with expanding OTZ fisheries and whether ocean-literate individuals experience a different degree of benefits. We find that ocean-literate individuals are more likely to support positive levels of OTZ sourced seafood production relative to non-ocean-literate individuals. Average individual annual benefits range from $1.84 to $124.74 conditional on ocean literacy and harvest policy attributes. Ocean-literate individuals are estimated to experience benefits two to three times higher than those who are not ocean literate across all harvest policy scenarios, suggesting significant heterogeneity in the distribution of OTZ-derived benefits conditional on ocean literacy. While our results suggest significant social benefits to be gained from expanding OTZ fishery production, back-of-the-envelope calculations suggest that rapid development of OTZ fishing would likely induce social costs more than 10× that of any benefits experienced. As such, we recommend careful exercise of the precautionary principle in consideration of mesopelagic governance approaches and industry expansion.

KEYWORDS
choice experiment, mesopelagic, carbon capture, seafood, ocean literacy

1 Introduction

The mesopelagic or twilight zone (OTZ) of the open ocean is found at depths between 200 and 1,000 m (between 650 and 3,300 ft). While sunlight can no longer support photosynthesis at these depths, the OTZ is home to a large volume of biomass and variety of species. Recent estimates of mesopelagic biomass dwarf estimates of pelagic biomass by one to two orders of magnitude (Anderson et al., 2019; Proud et al., 2019; Irigoien et al., 2014; Kaartvedt et al., 2012). Although there remain many unanswered questions about the OTZ, it is known that mesopelagic species make what is considered to be the largest daily migration on earth as they move closer to the surface waters to feed at night and back down to the OTZ to avoid predators during the daytime, more formally referred to as diel vertical migration. Interesting in its own right, this vertical migration is a key mechanism that supports the biological carbon pump, cycling carbon from the surface waters toward the deeper ocean where it can be captured and stored for 100 or more years.

Given its estimated vastness, OTZ resources have gained commercial attention from the fishing industry as a new ingredient source for fishmeal and fish oil (Food and Agricultural Organization of the United Nations, 2016, 2018; Grimsmo et al., 2017; Tacon and Metian, 2008). Many initiatives across the world have begun to explore the additional commercial potential of OTZ species[1], ways they can be harvested, and what markets would be available (Kourantidou and Jin, 2022). There are select OTZ species already commercially harvested including the Orange Roughy (*Hoplostethus atlanticus*) and Hoki (*Macruronus novaezelandiae*) with some fisheries holding Marine Stewardship Council sustainability certification. While there is promising potential for the establishment of a larger commercial fishing sector to support the aquaculture development, significant uncertainty remains about the importance of OTZ species' contribution to ecosystem services, including carbon capture and climate regulation, and how commercial harvest of these species may disrupt the diel vertical migration and associated carbon cycle. As such, OTZ fishery resources remain largely unexploited (Grimsmo et al., 2017; Hidalgo and Browman, 2019; St. John et al., 2016). Crafting comprehensive policy to regulate human interaction and mitigate potential consequences is essential to responsibly utilizing OTZ resources, if at all, and its role in climate regulation. An understanding of the OTZ, and the ocean in general, is of critical importance in this effort (Schadeberg et al., 2023).

To date, few social science studies investigate the human dimensions of OTZ exploitation with most related literature focusing on the preservation of specific deep-sea resources (see Hilmi et al., 2023). Most related to our research are four stated preference studies that estimate the non-market benefits provided by deep-sea resources. Glenn et al. (2010), Aanesen et al. (2015), and Wattage et al. (2011) conduct discrete choice experiments to estimate willingness to pay for cold-water coral preservation. Jobstvogt et al. (2014) also implemented a discrete choice experiment to measure Scottish households' willingness to pay for additional deep-sea protected areas. Lastly, O'Connor et al. (2020) conduct a contingent valuation study and find positive willingness to pay for the restoration of deep-sea ecosystems in the Bay of Naples. Our study differs from the ones mentioned in that we are the first to use a stated preference approach to measure the social benefits of OTZ exploitation contributing to the growing literature on the human dimensions of deep-sea resources.

There are a select number of studies that take a stylized bioeconomic approach to assess the potential implications of OTZ exploitation. Kourantidou and Jin (2022); Groeneveld et al. (2024), and Oostdijk et al. (2024) show that the economic feasibility of mesopelagic fisheries is not straightforward to determine due to the lack of data on the biophysical processes of the OTZ. Groeneveld et al (2024) results further suggest that the social cost of climate impacts induced by harvesting mesopelagic fish is likely to dwarf the market price fishers could obtain. Taking an ecosystem services valuation approach, Prellezo et al. (2024) identify significant losses to ecosystem service values in the Bay of Biscay, on average, if harvesting mesopelagic fishes at levels producing maximum sustainable yield. Each of these studies has another commonality in their findings—point estimates of economic feasibility and changes in ecosystem service values contained within a large range of uncertainty. As identified by these social science findings and natural science research, studying the implications of OTZ exploitation is complicated by the paucity of data and limited understanding of linkages among and between OTZ biomass and carbon cycling. This uncertainty makes it challenging to estimate the non-market value of OTZ resources.

Because of the stochasticity of natural processes and their interaction with environmental policies, estimating precise policy outcomes is rarely possible (Pindyck, 2007). In the stated preference valuation literature, two main approaches are used to capture the influence of uncertainty on preferences for environmental policy and avoid biased welfare estimates (Johnston et al., 2017). The most observed method utilizes a split sample design in which one subsample of respondents is shown certain outcomes and another subsample is shown outcomes with some amount of uncertainty. In aggregate, this allows the researcher to separate the effects of outcome uncertainty on policy preferences. Lew et al. (2010) estimate willingness to pay for Stellar Sea Lion stock enhancement using three different versions of a discrete choice experiment that varied forecasted baseline stock changes, which had a significant influence on willingness to pay. Faccioli et al. (2019) find significant differences in preferences for conservation policies between their certain and uncertain treatment samples. An alternative to the split sample approach is to include uncertainty directly into the experimental design as a choice experiment attribute. Glenk and Colombo (2011) include a risk of failure attribute that probabilistically communicates the chance that a soil carbon program would fail to provide climate change mitigation benefits. Communicating uncertainty in the experimental design was shown to have significant influence on their respondents' preferences over public programs. As discussed

[1] OTZ project in the United States, EU horizon-funded projects (the MEESO, SUMMER, MESOPP, and PANDORA), and the Norwegian Mesopelagic Initiative.

above, outcome uncertainty for OTZ harvest policies is likely significant, which motivated our experimental design to follow the latter approach and include a likelihood variable to probabilistically communicate the chance a given OTZ harvest policy would result in a given combination of seafood production and carbon capture.

Anthropogenic climate change is by and large the biggest threat to the oceans, already contributing to a myriad of impacts, e.g., rising sea temperatures, ocean acidification, and rising sea levels, among many others (Halpern et al., 2007). Ocean citizens make informed choices to minimize impacts on ocean health and contribute to solutions for seemingly insurmountable global problems like climate change (Hawthorne and Alabaster, 1999; Fletcher and Potts, 2007). Ocean literacy is an important criterion of one being an ocean citizen. Previous studies found that enhancing ocean literacy is critical for increasing support for policies and measures that reduce negative impacts on the marine environment caused by anthropogenic activities (Schoedinger et al., 2005) and support for ocean-based solutions to climate change highlighted by the High Level Panel for a Sustainable Ocean Economy (Stuchtey et al., 2020). While many information campaigns exist to inform the public about the consequences of unhealthy oceans and how one can be a better steward of the ocean, there is no consistent evidence that more knowledge, education, and public awareness of the ocean directly leads to sustainable behavior (Stoll-Kleemann, 2019). Mixed evidence on interventions' efficacy in closing the pro-environmental attitude–behavior gap is observed in controlled experiments (Hagmann et al., 2019; Farjam et al., 2019), intervention studies (Lanzini and Thøgersen, 2014), and empirical studies (Keuschnigg and Kratz, 2017; Best and Kneip, 2011).

We make a novel contribution to both the marine policy and resource economics literatures by conducting the first stated preference study, to our knowledge, to elicit preferences for mesopelagic resource exploitation policies. We build on the limited body of social science literature by conducting a choice experiment that asks respondents to evaluate the trade-off between OTZ seafood production and carbon capture to measure the potential social benefit associated with establishment of an OTZ commercial fishery. Aside from the literature cited above, there is little information available to resource managers regarding preferences for OTZ fishing. Among the other complications related to expansion of the OTZ commercial fishing sector, this lack of information on public preferences, including estimates of social welfare, could lead managers to institute suboptimal policies. Responsible exploitation policies require a holistic view of both costs and benefits to society under varying assumptions. Our research contributes to clarifying the balance sheet managers and policymakers must evaluate before supporting protection of further exploitation of OTZ resources. Methodologically, our study contributes to the broader resource valuation literature by incorporating outcome uncertainty into our experimental design to reflect scientific uncertainty about OTZ biomass and carbon cycling. In addition, by explicitly incorporating uncertainty into our experimental design and empirical models, it is less likely that welfare estimates derived from our analysis are biased. Furthermore, we assess respondents' degree of ocean literacy using a subset of questions from a validated measure of ocean literacy (International Ocean Literacy Survey; Fauville et al., 2019) that we use as a proxy for degree of ocean citizenship. We investigate the extent to which ocean literacy moderates preferences for OTZ policy attributes and its effect on consumer welfare derived from an OTZ commercial fishery.

2 Materials and methods

2.1 Survey design

We designed our choice experiment to simulate a policy scenario that directly considers the trade-off between carbon sequestration and seafood production associated with the OTZ. We first developed a one-page summary about the OTZ for respondents to read prior to answering the choice questions. Our description was based on a summary originally prepared by researchers of the MEESO project in the European Union for inclusion in a stakeholder survey about the mesopelagic socio-ecological system and possible outcomes of fishing in the mesopelagic zone. We adapted the language and content from the MEESO description to avoid scientific jargon to be more approachable for a general audience. Providing information about the context considered in a stated preference study is critical to ensure survey respondents can make informed choices. This is important for our study given the public is likely unfamiliar with the OTZ. Our OTZ description and full survey content are included in the Supplementary Materials.

Attribute levels for the choice experiment were chosen based on recent academic literature related to the mesopelagic carbon pump and projected biomass and discussions with scientific experts. All choice questions included two policy alternatives and a status quo alternative. The order of each question in each block was randomized for each respondent. To capture preferences for exploiting OTZ biomass for food production, respondents were presented with the percentage of global seafood demand that might be met by establishing OTZ fisheries (19%, 48%, and 96%). Since biomass and the biological carbon pump are linked, we incorporated a carbon sequestration attribute summarizing how much carbon is captured and stored by OTZ processes. For salience, we expressed this in terms of the percentage of U.S. motor vehicle emissions sequestered by OTZ processes (100%, 92%, and 85%). While the use of varying scales may be a point of confusion for respondents, i.e., global seafood demand and U.S. vehicle emissions, we needed to present the attributes in an interpretable fashion. For example, if we presented seafood consumption at the U.S. level, harvesting 10% of OTZ biomass would translate to approximately 17,000% of U.S. seafood consumption being met. This amount is difficult to interpret and would certainly lead to invalid measures of welfare. Additional details on the definition of the carbon sequestration and seafood production attributes can be found in the Supplementary Materials. A crucial component of the experimental design is the likelihood attribute that we designed to incorporate the large degree of scientific uncertainty regarding interactions between mesopelagic biomass and carbon capture. This attribute was included to communicate the joint outcome probability of emissions captured and global seafood demand met. The cost attribute levels were defined based on annual expenditure for U.S. fisheries management covered by federal income tax. Back-of-the-envelope estimates show that the median taxpayer in the United States contributes less than 10 cents annually to fisheries management in the form of income tax. As such, we defined five cost levels ranging from $5 to $25 in even increments to reflect the small amount contributed by taxpayers to fishery management while also attempting to mitigate the potential inconsequentiality of the cost attribute. In sum, the attributes and levels included in the design are as follows:

Likelihood (%): 20, 50, and 80
Seafood production (%): 19, 48, and 96
Carbon sequestration (%): 92, 85, and 100
Annual cost (US dollars): 5, 10, 15, 20, and 25

We used a D-efficiency criterion to select the best experimental design. Our optimal design had a D-efficiency of 95% and was composed of 45 total choice questions divided into nine blocks each containing five choice questions. Respondents were randomly assigned to one choice question block to answer. An example choice menu is presented in Figure 1.

In addition to the choice experiment, respondents self-reported demographic information, climate change beliefs, environmental preferences, perceptions of social norms, and self-assessed risk preferences. The other primary component of the survey was the ocean literacy assessment. The assessment consisted of 14 questions taken from the most recent version of the International Ocean Literacy Survey (IOLS; Chen et al., 2020). The IOLS was designed to cover seven essential principles of ocean science that were agreed upon during a decade-long effort by scientists and educators to formalize a framework that outlined the core tenants that comprised an ocean-literate individual (Figure 2). This framework was designed to be incorporated into K-12 science education classes to bolster young peoples' working knowledge of the ocean. While our sample of interest is not K-12 students, the IOLS can serve as a validated assessment of ocean literacy to be adapted for use in other populations. Since this assessment was to be incorporated into a larger survey, we wanted to avoid unnecessary cognitive burden for our respondents while still capturing meaningful, engaged responses. The full IOLS assessment consists of 52 multiple choice and true/false responses covering each of the seven essential principles of ocean sciences summarized in Figure 2. For our use case, we separated each question into its respective essential principle and randomly selected two questions covering each of the

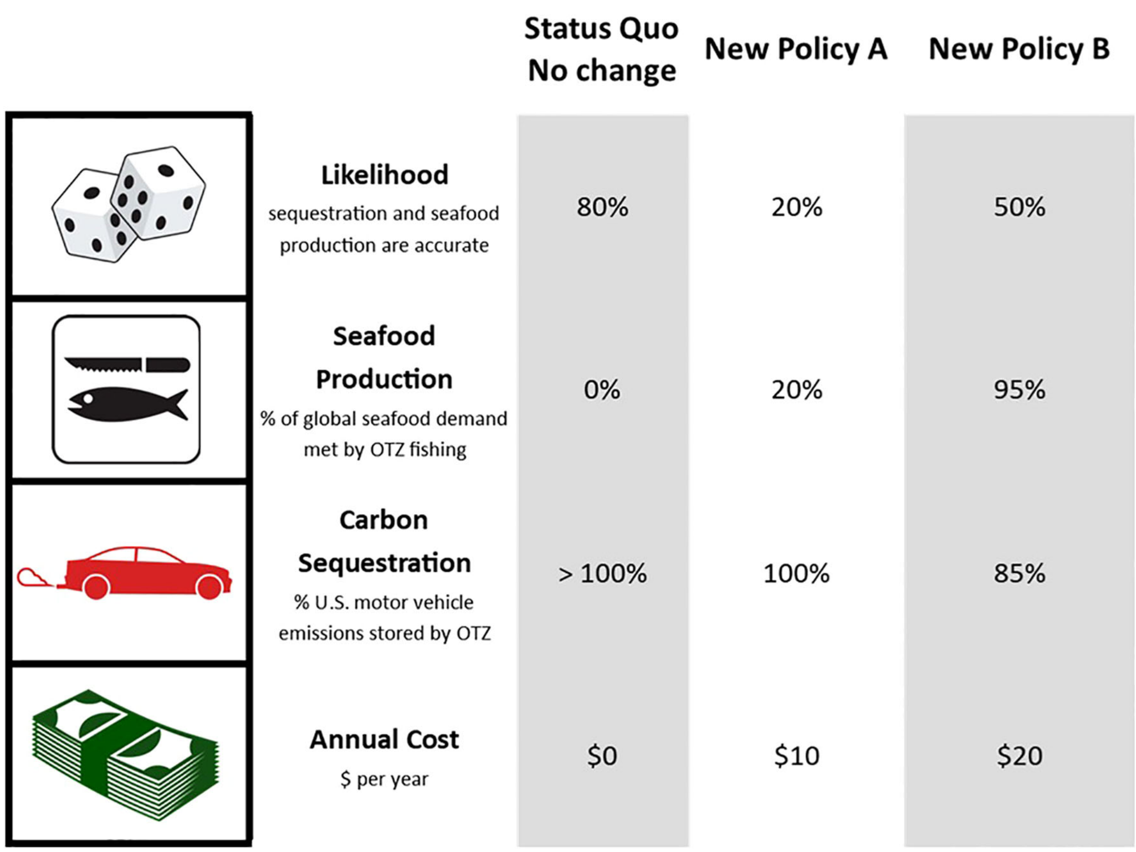

FIGURE 1
Example choice experiment menu.

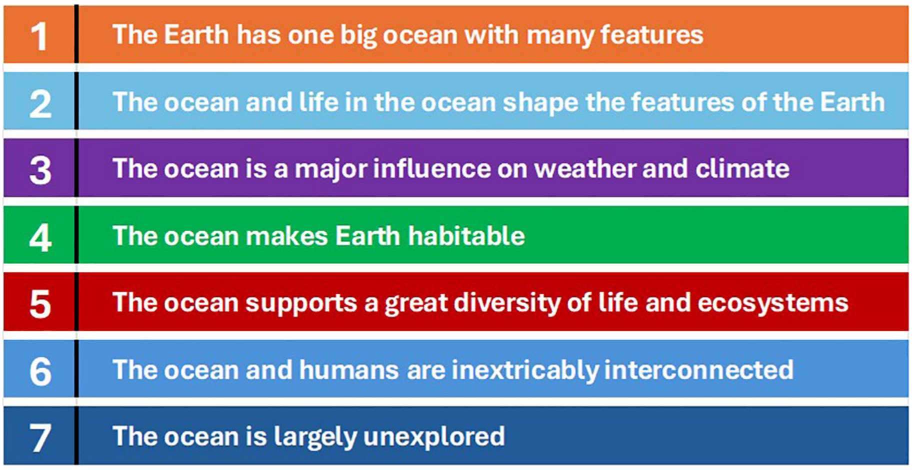

FIGURE 2
The seven essential principles of ocean sciences reproduced from Fauville et al. (2019).

seven essential principles. Thus, our assessment included 14 total questions. Each of the 14 questions and their summary scores are shown in Table 1.

2.2 Survey distribution

Prior to distribution of the survey, the final survey design was distributed among a small group of representatives from the marine policy and marine science fields and members of the public to ensure survey content was communicated effectively, particularly the choice experiment attributes and levels included in the experimental design. After receiving approval of our human subjects protocol from the Woods Hole Oceanographic Institution's Office of the Deputy Director and Vice President for Research (Approval # IRB-006), we distributed our survey in Spring 2023 among U.S. residents aged 18 years or older. Respondents were recruited from an opt-in panel managed by the survey platform Alchemer. Recruitment was census balanced by gender.

We collected a total of 1,625 survey responses. We removed responses that completed the full survey in less than one-third the median completion time for the sample. We also dropped incomplete responses to the choice questions. This filtering procedure left a final sample of 5,947 choices made by 1,196 unique individuals for analysis.

2.3 Random parameter logit specification

We use a random utility framework to analyze our data and assume individual i makes choices between J alternatives in T choice situations by considering all available alternatives and chooses the alternative with the highest utility. The expression, $U_{ijt} = V_{ijt} + \varepsilon_{ijt}$, characterizes the indirect utility associated with alternative j for individual i in choice situation t, where $V_{ijt} = \beta_i x_{ijt}$ is the deterministic portion of utility with x the vector of attributes and β the individual parameter vectors assumed to be drawn from a population distribution, $g(\beta|\theta)$, where θ is a vector of the parameter of the distribution, and the error term ε_{ijt} is independent and identically distributed extreme value type 1. Since each participant answered more than one choice question, we account for the panel structure of our data in the choice probability as discussed in Train (2009).

We estimate a random parameter logit ("RPL") model to capture the marginal change in utility given the different OTZ harvest scenario attributes. We use maximum-likelihood methods to numerically evaluate the choice probability integral using 5,000 Sobol draws. Our specification for the empirical model captures preferences for the expected value of a scenario outcome as determined by the corresponding likelihood level for a given alternative. This specification is grounded in expected utility theory, which assumes that utility from a particular outcome is multiplied by the probability of that outcome (e.g., Roberts et al., 2008)[2]. Furthermore, preferences over uncertainty itself are not theoretically justified in this framework, which limits its value for estimating welfare. Thus, our empirical model is specified as follows:

$$v_{ijt} = \alpha_i^{SQ} + \beta_{i\ cost} cost + \beta_{i\ seafood} \mu_{seafood} + \beta_{i\ OL,seafood} \cdot OL_i \mu_{seafood} + \beta_{i\ carbon} \mu_{carbon} + \beta_{i\ OL,\ carbon} \cdot OL_i \mu_{seafood}, \quad (1)$$

where for a given likelihood, π, $\mu_{seafood} = \pi \cdot x_{seafood} + (1-\pi) \cdot x_{seafood}^{SQ}$, $\mu_{carbon} = \pi \cdot x_{carbon} + (1-\pi) \cdot x_{carbon}^{SQ}$, α_i^{SQ} is the alternative specific constant for status quo that captures utility respondents associated with current OTZ harvest policy as described in the experimental design and OL_i is an indicator

[2] We ultimately selected this specification by first estimating conditional logit models as a parsimonious representation of our model of consumer preferences. These are parsimonious in the sense that they do not rely on distributional assumptions of the researcher as in a mixed logit. We present results for two conditional logit models in the Supplementary Materials to support our decision of Equation 1 being our preferred model specification.

TABLE 1 IOLS question summary and average respondent scores.

Ocean literacy principle	IOLS question and correct answer (bold)	Mean score
Principle 1	Rivers can transport ______ to the ocean.	0.62
	Nutrients; sand; rocks; pollutants	
	Changes to sea level are caused by ______.	0.52
	Movement of the continental plates; Melting and growing of ice caps on land; Warming and cooling of ocean water	
Principle 2	Which statement describes the main process that shapes the features of the land and the ocean floor?	0.5276
	Both the land and the ocean floor are shaped by movement of the earth's crust	
	Sand on the shoreline is:	0.63
	Continually transported by waves and currents	
Principle 3	The ocean affects climate change by absorbing, storing, and moving:	0.40
	Carbon and heat	
	What happens in an El Niño year?	0.52
	There are large but temporary changes in global weather patterns	
Principle 4	Where did most of the oxygen in the atmosphere originally come from?	0.18
	Released during photosynthesis by marine organisms	
	Fossil evidence shows that life most likely first evolved:	0.66
	In the ocean	
Principle 5	Which of the following most influences the depth at which organisms live in the open ocean (away from the shoreline)?	0.29
	Light levels	
	Most living material (biomass) in the ocean is found in:	0.56
	Plankton (jellyfish, krill, diatoms, etc.)	
Principle 6	Humans depend on the ocean for ______.	0.60
	Food and medicine; mineral and energy resources; transportation and jobs; benefits to our economy	
	Which statement is the best explanation of ocean acidification?	0.43
	Burning fossil fuels adds carbon dioxide to the atmosphere, which is then absorbed by the ocean and increases its acidity.	
Principle 7	Which of the following is true concerning the exploration of the ocean?	0.55
	Most of the ocean is still unexplored despite improvements in technology in the last 50 years.	
	The use of satellites, buoys, and remotely operated vehicles improve our understanding of the ocean because the new technologies:	0.39
	Collect much more data than scientists on ships can.	

Bold text indicates the correct answer to the preceding IOLS question in the table.

variable equal to one if a respondent scored at least 60% on the ocean literacy assessment. The likelihood level, π, is the level of scientific uncertainty presented in each choice menu. The variables $x_{seafood}$ and x_{carbon} indicate the level of seafood production and carbon sequestration in each choice menu, while $x^{SQ}_{seafood}$ and x^{SQ}_{carbon} are held constant at the status quo level of seafood production and carbon sequestration, respectively. Aside from the cost coefficient, each coefficient is assumed to follow a normal distribution that allows us to account for unobserved individual heterogeneity without imposing undue restrictions on the population distribution for any given parameter. We modeled the cost coefficient as a negative log-normal distribution. This assumption guarantees that the sign of the cost coefficient, β_{cost}, is consistent with economic theory and that welfare estimates have finite

TABLE 2 Summary of respondent characteristics, median (SD); %.

Characteristic	N = 1,196	2023 ACS 5-year estimates
Age (years)	45.01 (16.43)	39.2
Gender (%)		
Male	47.74	49.0
Female	52.09	51.0
Gender-variant/Non-conforming	0.08	–
Prefer not to answer	0.08	–
Education (%)		
Did not complete high school	1.59	11.6
High school graduate or GED	10.62	28.8
Trade/technical school	2.59	–
Some college, no degree	11.04	17.0
College degree (2-year, 4-year, or advanced)	74.17	42.6
Income (%)		
Less than $25,000	9.78	15.1
$25,000 to $34,999	7.86	6.8
$35,000 to $49,999	6.19	10.4
$50,000 to $74,999	9.78	15.7
$75,000 to $99,999	8.03	12.7
$100,000 or more	58.36	39.3
Race (%)		
Asian	1.17	5.8
Black or African American	4.77	12.0
White	87.79	58.2
Hispanic or Latino	2.09	19.0
American Indian or Alaska Native	0.84	.5
Other	0.25	.5
Two or more races	3.09	3.9
Ocean literacy score (out of 14)	6.50 (2.32) (Mean = 6.87)	
Risk tolerance (out of 10)	8.00 (2.53) (Mean = 7.21)	
Climate change cause beliefs (%)		
Human activity	64.46	
Natural patterns	25.25	
No evidence Earth is warming	7.44	
None of the above	2.84	

ACS, American Community Survey.

moments (Ray et al., 2023; Weir et al., 2021; Carson and Czajkowski, 2019). Both $\beta_{seafood}$ and β_{carbon} are expected to be positive given the commodity characteristics of (sea)food and public good provided by capturing more carbon. Given the mixed evidence on the efficacy of ocean literacy to promote ocean stewardship, it is less straightforward to make confident predictions about the signs of $\beta_{OL,\ seafood}$ and $\beta_{OL,\ carbon}$. However, if we assume ocean citizens in our sample consider sustainable

10.3389/fmars.2025.1420203

behavior to be less harvest of wild fish, then we might expect $\beta_{OL,\ seafood} < 0$ and $\beta_{OL,\ carbon} > 0$.

To generate individual welfare estimates, *CS*, for different policy scenarios we follow Hanemann (1984):

$$CS = \frac{1}{\exp(\mu_{cost} + \sigma_{cost} \cdot \zeta_{cost})} [\ln\sum_n \exp v_n^s - \ln\sum_n \exp v_n^{SQ}] \quad (2)$$

where μ_{cost} is the mean of the cost coefficient distribution, σ_{cost} is the standard deviation, and ζ_{cost} is a standard normal random disturbance. We must exponentiate the cost parameter expression for welfare calculations because β_{cost} is assumed to follow a log-normal distribution. The distributions of the other random parameters are simulated in the same manner to calculate the indirect utility, v_n^s, for each policy scenario, *s*, considered below. The indirect utility for each scenario is calculated by substituting the estimate coefficients into a function of the same specification as Equation 1 and the level of each attribute of interest. The baseline scenario used in all welfare calculations uses the following attribute levels: 80% likelihood, 107% U.S. auto emissions, 0% seafood production, and $0 cost. As shown in the second part of Equation 2, the difference between indirect utility from scenario *s* and the status quo scenario, v_n^{SQ}, are differenced to calculate the change in utility by implementing a scenario other than the status quo. Scaling this difference by the cost parameter expression in the first half of Equation 2 translates the unitless indirect utility calculation into monetary term. Further discussion on attribute level definition and status quo attribute levels is in the Supplementary Materials for this manuscript.

3 Results

3.1 Respondent characteristics

Summary statistics for the final sample are presented in Table 2. Overall, our sample is diverse and represents a distribution of individuals similar to the makeup of the United States within age and gender. Similar to other online convenience samples, such as Amazon Mechanical Turk, our respondents are more educated, have a higher income, and represent a larger white population by about 30% when compared to the general population.

The overall ocean literacy of our sample hovers near the midpoint with a median score of 6.5 out of 14 total points, consistent with previous findings of low ocean literacy among Americans (Steel et al., 2005). Respondents received a full point for a correct answer and a half point if selecting at least one but not all correct responses for a select all that apply question type. Since each question in our subset of the IOLS was a multiple choice, it is unlikely that respondents would achieve this median score by simply guessing. Relatedly, if respondents were dishonest and searching for correct answers online or other sources, we would expect a higher median score. In fact, the highest score recorded was 13.5, which, taken together with the other observations, suggests that the summary scores accurately reflect the degree of ocean literacy of respondents.

Based on the concept of distance decay, we assumed that respondents from areas with higher concentration of coastal

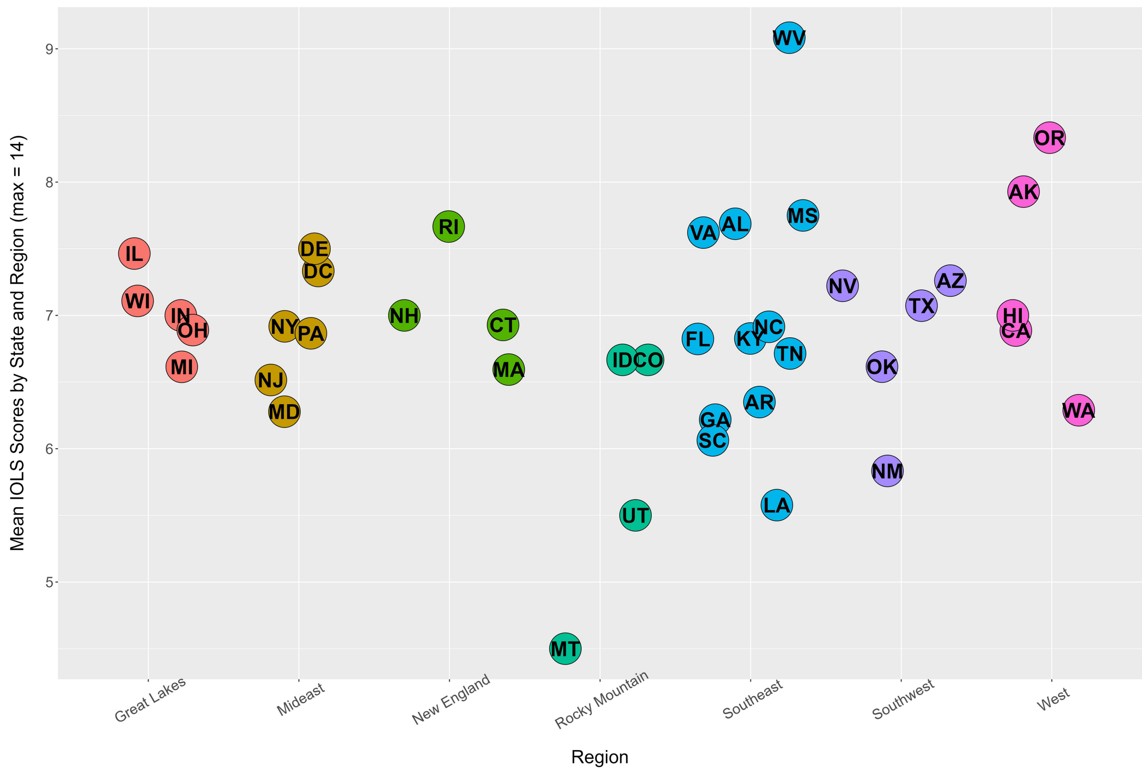

FIGURE 3
Summary of IOLS scores by state and US bureau of economic analysis region.

TABLE 3 Association between utility and policy attributes.

Parameter	Estimate (robust SE)
ASC-Status Quo	−1.1563 (0.1231) ***
Cost	−5.6865 (0.8553) ***
Seafood Production	0.0033 (0.0012) ***
Emissions capture	0 (0.0047)
OL × Seafood production	0.0076 (0.0024) ***
OL × Emissions capture	−0.0067 (0.0086)
Standard deviations of random parameters	
ASC-Status Quo	−2.9627 (0.1503) ***
Cost	−0.0166 (0.4465)
Seafood production	−0.0059 (0.0036)
Emissions capture	−0.0002 (0.0003)
OL × Seafood production	−0.0143 (0.0039) ***
OL × Emissions capture	0.0193 (0.0348)
Model fit	
LL(0)	−6,533
LL(final)	−5,615
Adjusted McFadden's R^2	0.139
AIC	11,255
BIC	11,335

*** indicates significance at the 1% level.

states, like the Northeast, might exhibit a higher degree of ocean literacy while those regions further away from the ocean would have lower ocean literacy. Surprisingly, average ocean literacy score by region did not differ significantly. Notably, regions with a high concentration of coastal states (New England, Southeast and West) did not outperform land-locked regions in terms of average ocean literacy scores (Figure 3). Based on our definition of earning a minimum 60% or 8.5 out of 14 points on the IOLS subset, approximately 30% of our sample qualifies as ocean literate.

3.2 Model results

Table 3 reports RPL results in preference space. The cost parameter is negative and statistically different from zero. Those that are not ocean literate in our sample are more likely to accept a policy with higher expected OTZ seafood production relative to the status quo. This result suggests that for every 1% increase in OTZ seafood production, the odds of supporting a policy increase by 1.003. At the median level of OTZ seafood production (48% of global seafood demand met), this would suggest an odds increase of approximately 16% in support of a given policy relative to the status quo. RPL results also suggest that increasing emissions captured reduces the odds of accepting a policy relative to the status quo, but this coefficient is not statistically different from zero. In other words, respondents are not responsive to changing levels of emissions capture, on average.

We see similar qualitative findings for the ocean-literate individuals in our sample. There is a statistically significant, positive effect on support for increasing OTZ seafood production equivalent to an increase in policy support of 37% at the median OTZ seafood production level. Considering the 16% increase in policy support among the comparison group, this suggests a 53% total increase in support of an OTZ harvest policy among ocean-literate individuals in our sample relative to the status quo. We again observe no statistical effect on policy support from higher levels of emissions capture. The results for emissions capture are counterintuitive as we would expect, at a minimum, a positive sign regardless of one's degree of ocean literacy given that emissions captured are a public good. There are a few possibilities for why we observe these effects that we discuss below. The results for seafood production follow our intuition. We further identify significant preference heterogeneity for the status quo alternative and seafood production for ocean-literate individuals based on the statistically significant standard deviations of the RPL parameters. This indicates that there are factors influencing preferences to preserve the status quo among our full sample and expected seafood production among ocean-literate individuals that are not captured by our model specification that would be interesting to explore in future work.

3.3 Welfare estimates

We estimate individual-level consumer surplus, *CS*, for a suite of potential policy outcomes following Hanemann (1984). Consumer surplus represents the additional social benefit experienced by a representative consumer if a policy is enacted that is different from the status quo. Confidence intervals were estimated using the Krinsky–Robb method (Krinsky and Robb, 1986) with 10,000 draws from estimated parameter distributions. The surplus estimates presented in Table 4 are all relative to the status quo alternative. For each level of certainty presented in the choice experiment, we present consumer surplus estimates for both ocean-literate and non-ocean-literate individuals to be consistent with our mixed logit specification. Individual-level welfare estimates are shown in Table 4.

First, scenarios a, d, and g consider the minimum expected seafood production assuming a harvest policy is enacted (19%) while maintaining enough carbon capture equivalent to 100% of annual U.S. auto emissions or 1.4 PgC (referred to as maximum emission capture scenarios). All surplus estimates considered in this suite of scenarios are statistically different from zero. Furthermore, each is statistically different from the maximum seafood scenarios (c, f, and i). Specifically, each of these surplus estimates is positive but smaller than their respective maximum seafood counterpart by roughly a factor of five. Among non-ocean-literate individuals in our sample, surplus estimates range from \$1.84 to \$7.43, which are roughly one-third of the surplus estimates for those that are ocean literate in our sample, which range from \$5.00 to \$21.08.

TABLE 4 Individual-level consumer surplus conditional on ocean literacy.

Scenario	Non-ocean literate		Ocean literate	
	Surplus ($)	95% Confidence interval	Surplus ($)	95% Confidence interval
80% likelihood				
a. 19% global seafood demand, 100% U.S. auto emissions captured	7.43	(5.9, 8.86)	21.08	(17.76, 24.05)
b. 48% global seafood demand, 92% U.S. auto emissions captured	19.15	(17.93, 20.27)	56.93	(54.74, 58.82)
c. 96% global seafood demand, 85% U.S. auto emissions captured	39.48	(38.82, 40.07)	124.74	(124.58, 124.76)
50% likelihood				
d. 19% global seafood demand, 100% U.S. auto emissions captured	4.62	(3.02, 6.12)	12.84	(9.26, 16.06)
e. 48% global seafood demand, 92% U.S. auto emissions captured	11.83	(10.42, 13.14)	33.53	(30.6, 36.12)
f. 96% global seafood demand, 85% U.S. auto emissions captured	24.13	(23.05, 25.12)	70.22	(68.45, 71.71)
20% likelihood				
g. 19% global seafood demand, 100% U.S. auto emissions captured	1.84	(1.19, 8.46)	5.00	(1.17, 8.45)
h. 48% global seafood demand, 92% U.S. auto emissions captured	4.67	(9.04, 15.84)	12.60	(9.02, 15.83)
i. 96% global seafood demand, 85% U.S. auto emissions captured	9.43	(21.9, 27.94)	25.07	(21.88, 27.92)

Scenarios b, e, and h all represent the median attribute level scenarios for the respective likelihood. In this case, nearly half of global seafood demand is met while the amount of carbon captured by the OTZ would be equivalent to 92% of annual U.S. auto emissions or roughly 1.3 PgC. For those in our sample that are not ocean literate, average surplus ranges from $4.67 to $19.15 per person per year. Each of these surplus estimates is statistically significant. In the subsample of those that are ocean literate, as defined herein, welfare values are approximately three times larger and all statistically different from zero ranging from $12.60 to $56.93.

In scenarios c, f, and I, we consider maximizing expected seafood production and minimizing emissions captured by the OTZ (referred to as maximum seafood scenarios). Based on the experimental design, this implies that 96% of global seafood demand is met and the equivalent of 85% of U.S. auto emissions are captured (1.2 PgC). Surplus estimates for non-ocean-literate individuals more than double compared to the median attribute scenarios ranging from $9.43 to $39.48 in annual benefits per person. For those that are ocean literate, surplus further increases, ranging now from $25.07 to $124.74 in annual benefits per person. All surplus estimates are statistically significant from zero.

Our results indicate that significant societal benefits could be derived under different OTZ harvest scenarios ranging from $1.84 to $124.74 per person conditional on ocean literacy and harvest policy attributes. To estimate potential social welfare gains, we assume a U.S. population over 18 years of age equal to 258.3 million. We also assume that our observed distribution of 30% ocean literacy holds on average such that that 77.5 million individuals are ocean literate and 180.8 million are not ocean literate in the United States. Table 5 summarizes the social welfare estimates for these two sub-populations. Social welfare for non-ocean-literate individuals ranges from $332.67 million to $7.13 billion while estimates for those that are ocean literate range from $387.50 million to $9.67 billion. For a frame of reference, U.S. commercial fishery landings revenues were $5.9 billion in 2022. Since revenues only reflect market prices, they do not capture the non-market value of resources that our methodology is designed to measure. This, in part, can explain why our high-end estimates of social welfare eclipse the market value of fishery landings. While our estimates suggest the non-market value of carbon capture may not be high within our sample, we could be detecting a second-order interpretation of the seafood attribute as conservation of traditional stocks that support seafood demand, which is known to be associated with positive WTP and social surplus (e.g. Ojea and Loureiro, 2010).

While these high-level estimates might suggest that both groups experience similar social welfare under a given policy, it is important to keep in mind that this aggregation masks the fact that individual benefits are much smaller for non-ocean-literate individuals as discussed above. Another crucial note for interpretation of these findings is that while these values represent net benefits from the perspective of welfare economics, these gains do not explicitly incorporate societal costs due to potentially lost carbon capture, for example. In fact, the results of several recent studies suggest that the rapid development of OTZ fishing could lead to a significantly higher social cost of climate change (Groeneveld et al., 2024; Oostdijk et al., 2024; Prellezo et al., 2024). To gain initial insight into this dimension, we use the climate damage estimate of $343/ton of OTZ harvest from Groeneveld et al (2024). As an example, the minimum seafood scenario implies an upper-bound OTZ harvest of 240 MMT based on our assumptions described in the Supplementary Materials. At this harvest level and damage value assumption, climate damages would cost society approximately $82 billion, which, by and far, eclipses even our high-end social welfare estimates by nearly 10-fold. While the

TABLE 5 Aggregate social welfare estimates conditional on degree of ocean literacy in US dollars.

Scenario	Non-ocean literate (180.8 million people)	Ocean literate (77.5 million people)
80% likelihood		
a. 19% global seafood demand, 100% U.S. auto emissions captured	1.34 billion	1.63 billion
b. 48% global seafood demand, 92% U.S. auto emissions captured	3.46 billion	4.41 billion
c. 96% global seafood demand, 85% U.S. auto emissions captured	7.14 billion	9.67 billion
50% likelihood		
d. 19% global seafood demand, 100% U.S. auto emissions captured	835.30 million	995.10 million
e. 48% global seafood demand, 92% U.S. auto emissions captured	2.14 billion	2.60 billion
f. 96% global seafood demand, 85% U.S. auto emissions captured	4.36 billion	5.44 billion
20% likelihood		
g. 19% global seafood demand, 100% U.S. auto emissions captured	332.67 million	387.50 million
h. 48% global seafood demand, 92% U.S. auto emissions captured	844.34 million	976.50 million
i. 96% global seafood demand, 85% U.S. auto emissions captured	1.71 billion	1.96 billion

benefit estimates presented herein are only applicable for interpretation within the United States, we have reasonable doubt that OTZ fisheries are worth developing.

4 Discussion

A consistent finding across all consumer surplus estimates is that the maximum seafood production scenarios are always valued higher than the maximum emission capture scenarios. This raises a question as to what is driving our respondents' preferences in this manner. The first consideration might be that respondents could more easily evaluate the trade-offs for seafood production given seafood is a tangible good and food, more generally, is a necessity. As such, this attribute might have been more salient to our respondents. In comparison, emissions capture, the social cost of not capturing emissions, and potential costs of alternative carbon removal technologies are unverifiable or credence attributes of OTZ harvest for the public that could have made it difficult to evaluate the presented trade-offs.

To explore this hypothesis, we looked to answers to individual questions of the IOLS from the survey. Specifically, one question asked The ocean affects climate change by absorbing, storing, and moving: with the correct answer being carbon and heat. Thirty-nine percent of our sample answered this question correctly. The second most popular answer choice was carbon and salt, which 25% of the sample selected. Thus, nearly two-thirds of our sample have some degree of understanding about the ocean's relationship to carbon. We interpret this as partial evidence to refute the hypothesis that our sample is unfamiliar with carbon emissions capture. With that in mind, the context in which we asked respondents to evaluate trade-offs regarding carbon capture may be the dimension that is lacking saliency rather than the attribute itself. While we did collect feedback on saliency of the context and attribute description prior to distributing the survey, there is still a possibility that this could drive the result.

In addition to the interesting relationship between seafood production and emissions capture, our results suggest that ocean-literate individuals might experience higher surplus gains assuming some positive quantity of OTZ harvest relative to the status quo. All of the surplus estimates for non-ocean-literate and ocean-literate individuals are statistically different from one another, indicating significant heterogeneity in the distribution of benefits. The distributional differences we observe in our results could be exacerbated by potential lost carbon capture and associated shifts in climate patterns, which is known to have its own distributional impacts (Mumtaz and Theophilopoulou, 2024). Relatedly, while previously successful ocean literacy and awareness campaigns (e.g., Zoological Society of London's Project Ocean or Monterey Bay Aquarium's Seafood Watch) suggest that improving public awareness and literacy related to the ocean and its processes could provide societal benefits, we caution the interpretation of our findings that increasing ocean literacy would necessarily increase societal benefits derived from implementing an OTZ harvest policy. Our study design did not address this hypothesis. Previous research exploring this topic found that more knowledge does not necessarily translate into more informed and/or correct choices as evidenced by recent studies. For example, Lackner et al. (2023) identify significant overconfidence exhibited by individuals with intermediate scientific knowledge when asked about general science topics. Specifically, these individuals chose incorrect answers on a science assessment rather than selecting the offered I don't know option on topics they were unfamiliar with. In a study on perceptions of deep-sea mining, Kaikkonen and Putten (2021) find that self-assessed knowledge of the deep sea does not directly correlate with how much individuals care about the deep sea. What we intend to highlight is a need to consider ways to promote understanding of topics rather than simply familiarity with a topic.

As mentioned above, an alternate interpretation of the estimated differences in surplus gains might be that respondents in our survey interpreted the OTZ seafood production attribute to imply that exploitation of traditional stocks would be halted, leading to conservation and stock rebuilding. While not explicitly communicated as an attribute, it is a reasonable conjecture that respondents could make this second-order connection. Though we cannot be certain that respondents of our survey would interpret the seafood attribute in this manner and no one in our survey would pre-test the provided commentary on this point, it would be interesting to understand how seafood consumers, and the public more generally, would interpret the co-benefit of OTZ fishery development. Regardless of how the public might interpret these co-benefits, the large uncertainties and impacts on oceanic carbon sequestration of rapid mesopelagic fisheries development warrant a precautionary approach (Groeneveld et al., 2024; Oostdijk et al., 2024; Prellezo et al., 2024). This is particularly true given the fact that any social benefits derived from development of an OTZ seafood supply chain are likely to be eclipsed by the social costs of weakening oceanic carbon sequestration as discussed above.

4.1 Limitations and extensions

Given the nascent state of knowledge about the OTZ and related social preferences, there are some limitations to our work that could serve as important extensions for future researchers. One important dimension our study does not incorporate is the external cost of lost carbon capture and sequestration by removing biomass from the OTZ. The results presented in our work only capture social benefits to the public from different OTZ harvest scenarios. Incorporating the external cost of lost carbon capture and sequestration into the experimental design would allow for more complete estimation of net benefits to society, which could be more informative for policy design. Of course, appropriately incorporating these costs into a stated preference design is conditional on more work in the natural sciences to refine estimates of OTZ-related carbon capture and how the biological carbon pump would interact with the harvest of OTZ species. However, credible estimates from the literature are a useful starting point and seem to suggest that OTZ exploitation is unlikely to offer net positive benefits to society as a whole.

Another important extension to this work would be expanding the population sampled to be more diverse along lines of geography and roles in society. Our sample focused only on U.S. residents. Given the OTZ is part of the global ocean and the geographic diversity of commercial interests in the OTZ, distributing the survey among residents in other countries would provide more generalizable estimates of social preferences for OTZ resources. In this vein, including perspectives of policymakers, fishery managers, and industry representatives is an invaluable extension for considering the costs and benefits of establishing OTZ fisheries. This extension would add a valuable contribution to research on social license and societal engagement in deep-sea governance, which is an ongoing challenge for management of resources outside national jurisdictions.

5 Conclusions

While there is a growing volume of scientific discovery about the OTZ in the natural sciences, further work in the social sciences should be pursued to develop responsible policy alternatives regarding exploitation of OTZ resources. Our study joins this growing literature as a first step towards estimating the social benefits derived from OTZ fisheries and deep-sea resources more broadly. We find that on average, those that are ocean literate experience benefits two to three times higher than those that are not ocean literate across all harvest policy scenarios, suggesting significant heterogeneity in the distribution of OTZ-derived benefits. This finding alone can be interpreted to show that the public would likely support OTZ fisheries if they are presented with a similar description to the one in our choice experiment. The troubling dimension of this observation is that it also implies supporting reduction in the ocean's ability to capture and sequester carbon. Given the initial evidence of substantial social costs from OTZ harvest, this presents an opportunity for scientists and policymakers to carefully present the balance sheet of impacts in a clear manner among themselves and the public for discussion regarding OTZ fishery development.

As we note, much more work is required across disciplines to fully consider the potential implications of exploiting OTZ resources though, and the current body of evidence in conjunction with the current study leads us to echo previous literature by recommending a precautionary approach when considering the exploitation of OTZ fishery resources. As Schadeberg et al (2023). acknowledge, mesopelagic science serves a *de facto* governing role in the absence of traditional state-led, legally binding forms of mesopelagic governance, thus holding a significant portion of power when it comes to decision-making about exploitation of the OTZ. It is a responsibility of the scientific community to refine our knowledge about the societal costs and benefits of OTZ exploitation to inform confident recommendations on governance approaches and industry expansion.

Data availability statement

The raw data supporting the conclusions of this article are made available by authors via open access repository. Data may be accessed using the following link: https://hdl.handle.net/1912/71435.

Ethics statement

The studies involving humans were approved by Woods Hole Oceanographic Institution Office of the Deputy Director and Vice President for Research. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

MW: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing. ML: Investigation, Visualization, Writing – original draft. DJ: Conceptualization, Supervision, Writing – original draft.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This study was supported by Woods Hole Oceanographic Institution's Ocean Twilight Zone program, which is part of the Audacious Project, a collaborative endeavor, housed at TED.

Acknowledgments

We appreciate the feedback from our colleagues during the 2023 OTZ Symposium and the 2023 North American Association of Fisheries Economists Annual Forum.

Conflict of interest

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

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2025.1420203/full#supplementary-material

References

Aanesen, M., Armstrong, C., Czajkowski, Mj, Falk-Petersen, J., Hanley, N., and Navrud, S. (2015). Willingness to pay for unfamiliar public goods: preserving cold-water coral in Norway. *Ecol. Economics* 112, 53–67. doi: 10.1016/j.ecolecon.2015.02.007

Anderson, T. R., Martin, A. P., Lampitt, R. S., Trueman, C. N., Henson, S. A., and Mayor, D. J. (2019). Quantifying carbon fluxes from primary production to mesopelagic fish using a simple food web model. Edited by jason link. *ICES J. Mar. Sci.* 76, 690–701. doi: 10.1093/icesjms/fsx234

Best, H., and Kneip, T. (2011). The impact of attitudes and behavioral costs on environmental behavior: A natural experiment on household waste recycling. *Soc. Sci. Res.* 40, 917–930. doi: 10.1016/j.ssresearch.2010.12.001

Carson, R. T., and Czajkowski, M. (2019). A new baseline model for estimating willingness to pay from discrete choice models. *J. Environ. Economics Manage.* 95, 57–61. doi: 10.1016/j.jeem.2019.03.003

Chen, Y.-F., Cannady, M. A., Fauville, G., and Strang, C. (2020). *Working toward an international assessment of ocean literacy: validating instrument with rasch measurement model* (San francisco, CA: American Educational Research Association (AERA) annual meeting).

Faccioli, M., Kuhfuss, L., and Czajkowski, M. (2019). Stated Preferences for Conservation Policies Under Uncertainty: Insights on the Effect of Individuals' Risk Attitudes in the Environmental Domain. *Environ. Resour. Econ.* 73 (2), 627–659. doi: 10.1007/s10640-018-0276-2

Farjam, M., Nikolaychuk, O., and Bravo, G. (2019). Experimental evidence of an environmental attitude-behavior gap in high-cost situations. *Ecol. Economics* 166, 106434. doi: 10.1016/j.ecolecon.2019.106434

Fauville, G., Strang, C., Cannady, M. A., and Chen, Y.-F. (2019). Development of the international ocean literacy survey: measuring knowledge across the world. *Environ. Educ. Res.* 25, 238–263. doi: 10.1080/13504622.2018.1440381

Fletcher, S., and Potts, J. (2007). Ocean citizenship: an emergent geographical concept. *Coast. Manage.* 35, 511–524. doi: 10.1080/08920750701525818

Food and Agricultural Organization of the United Nations. (2016). *State of world fisheries and aquaculture 2016-contributing to food security and nutrition for all* (Rome). Available online at: http://www.fao.org/3/a-i5555e.pdf.

Food and Agricultural Organization of the United Nations. (2018). *State of world fisheries and aquaculture 2018-meeting the sustainable development goals* (Rome). Available online at: http://www.fao.org/3/i9540en/i9540en.pdf.

Glenk, K., and Colombo, S. (2011). How sure can you be? A framework for considering delivery uncertainty in benefit assessments based on stated preference methods. *J. Agric. Economics* 62, 25–46. doi: 10.1111/j.1477-9552.2010.00278.x

Glenn, H., Wattage, P., Mardle, S., Van Rensburg, T., Grehan, A., and Foley, N. (2010). "Marine protected areas—substantiating their worth," *Mar. Policy.* 34 (3), 421–430. doi: 10.1016/j.marpol.2009.09.007

Grimsmo, L., Almas, K. A., and Hognes, E. S. (2017). "Industriell Utvikling Av et Mesopelagisk Fiske-Miljøeffekter. Industrial Development of a Mesopelagic Fishery-Environmental Effects," in *SINTEF ocean;OC2017 A-196* (Trondheim, Norway: SINTEF Ocean). Available online at: https://sintef.brage.unit.no/sintef-xmlui/handle/11250/2457166 (Accessed January 22, 2024).

Groeneveld, R. A., Richter, A., and Sen, S. (2024). Climate damage from fishing the mesopelagic zone exceeds its economic benefits. Edited by sean pascoe. *ICES J. Mar. Sci.* 81, 1620–1631. doi: 10.1093/icesjms/fsae108

Hagmann, D., Ho, E. H., and Loewenstein, G. (2019). Nudging out support for a carbon tax. *Nat. Climate Change* 9, 484–489. doi: 10.1038/s41558-019-0474-0

Halpern, B. S., Selkoe, K. A., Micheli, F., and Kappel, C. V. (2007). Evaluating and ranking the vulnerability of global marine ecosystems to anthropogenic threats. *Conserv. Biol.* 21, 1301–1315. doi: 10.1111/j.1523-1739.2007.00752.x

Hanemann, W.M. (1984). Welfare evaluations in contingent valuation experiments with discrete responses. *Am. J. Agric. Economics* 66, 332–341. doi: 10.2307/1240800

Hawthorne, M., and Alabaster, T. (1999). Citizen 2000: development of a model of environmental citizenship. *Global Environ. Change* 9, 25–43. doi: 10.1016/S0959-3780(98)00022-3

Hidalgo, M., and Browman, H. I. (2019). Developing the knowledge base needed to sustainably manage mesopelagic resources. *ICES J. Mar. Sci.* 76, 609–615. doi: 10.1093/icesjms/fsz067

Hilmi, N., Sutherland, M., Farahmand, S., Haraldsson, G., Doorn, E. V., Ernst, E., et al. (2023). Deep sea nature-based solutions to climate change. *Front. Climate* 5. doi: 10.3389/fclim.2023.1169665

Irigoien, X., Klevjer, T. A., Røstad, A., Martinez, U., Boyra, G., Acuña, J. L., et al. (2014). Large mesopelagic fishes biomass and trophic efficiency in the open ocean. *Nat. Commun.* 5, 3271. doi: 10.1038/ncomms4271

Jobstvogt, N., Hanley, N., Hynes, S., Kenter, J., and Witte, U. (2014). Twenty thousand sterling under the sea: estimating the value of protecting deep-sea biodiversity. *Ecol. Economics* 97, 10–19. doi: 10.1016/j.ecolecon.2013.10.019

Johnston, R. J., Boyle, K. J., Adamowicz, W. (., Bennett, J., Brouwer, R., Cameron, T. A., et al. (2017). Contemporary guidance for stated preference studies. *J. Assoc. Environ. Resource Economists* 4, 319–405. doi: 10.1086/691697

Kaartvedt, S., Staby, A., and Aksnes, D. (2012). Efficient trawl avoidance by mesopelagic fishes causes large underestimation of their biomass. *Mar. Ecol. Prog. Ser.* 456, 1–6. doi: 10.3354/meps09785

Kaikkonen, L., and Putten, I. V. (2021). We May Not Know Much about the Deep Sea, but Do We Care about Mining It? *People Nat.* 3, 843–860. doi: 10.1002/pan3.10224

Keuschnigg, M., and Kratz, F. (2017). Thou shalt recycle: how social norms of environmental protection narrow the scope of the low-cost hypothesis. *Environ. Behav.* 50, 1059–1091. doi: 10.1177/0013916517726569

Krinsky, I., and Leslie Robb, A. (1986). On Approximating the Statistical Properties of Elasticities. *Rev. Econ. Stat.* 68 (4), 715–719. doi: 10.2307/1924536

Kourantidou, M., and Jin, D. (2022). Mesopelagic–epipelagic fish nexus in viability and feasibility of commercial-scale mesopelagic fisheries. *Natural Resource Modeling* 35, e12350. doi: 10.1111/nrm.12350

Lackner, S., Francisco, F., Mendonça, C., Mata, A., and Gonçalves-Sá, J. (2023). Intermediate levels of scientific knowledge are associated with overconfidence and negative attitudes towards science. *Nat. Hum. Behav.* 7, 1490–1501. doi: 10.1038/s41562-023-01677-8

Lanzini, P., and Thøgersen, J. (2014). Behavioural Spillover in the Environmental Domain: An Intervention Study. *J. Environ. Psychol.* 40, 381–390. doi: 10.1016/j.jenvp.2014.09.006

Lew, D. K., Layton, D. F., and Rowe, R. D. (2010). Valuing Enhancements to Endangered Species Protection under Alternative Baseline Futures: The Case of the Steller Sea Lion. *Mar. Resour. Econ.* 25 (2), 133–154. doi: 10.5950/0738-1360-25.2.133

Mumtaz, H., and Theophilopoulou, A. (2024). The distributional effects of climate change. *Empirical Analysis. Eur. Economic Rev.* 169, 104828. doi: 10.1016/j.euroecorev.2024.104828

O'Connor, E., Hynes, S., and Chen, W. (2020). Estimating the non-market benefit value of deep-sea ecosystem restoration: evidence from a contingent valuation study of the dohrn canyon in the bay of naples. *J. Environ. Manage.* 275, 111180. doi: 10.1016/j.jenvman.2020.111180

Ojea, E., and Loureiro, M. L. (2010). Valuing the recovery of overexploited fish stocks in the context of existence and option values. *Mar. Policy* 34, 514–521. doi: 10.1016/j.marpol.2009.10.007

Oostdijk, M., Elsler, L. G., Deelen, J. V., Willem, L.A., Kwakkel, J., Schadeberg, A., et al. (2024). Modeling fisheries and carbon sequestration ecosystem services under deep uncertainty in the ocean twilight zone. *Ambio* 53, 1632–1648. doi: 10.1007/s13280-024-02044-1

Pindyck, R. S. (2007). Uncertainty in environmental economics. *Rev. Environ. Economics Policy* 1, 45–65. doi: 10.1093/reep/rem002

Prellezo, R., Corrales, X., Andonegi, E., Bald, C., Fernandes-Salvador, J. A., Iñarra, B., et al. (2024). Economic trade-Offs of harvesting the ocean twilight zone: an ecosystem services approach. *Ecosystem Serv.* 67, 101633. doi: 10.1016/j.ecoser.2024.101633

Proud, R., Handegard, N. O., Kloser, R. J., Cox, M. J., and Brierley, A. S. (2019). From siphonophores to deep scattering layers: uncertainty ranges for the estimation of global mesopelagic fish biomass. Edited by david demer. *ICES J. Mar. Sci.* 76, 718–733. doi: 10.1093/icesjms/fsy037

Ray, K. D., Lew, D. K., and Kosaka, R. (2023). A random coefficients model of seafood demand: implications for consumer preferences and substitution patterns. *Mar. Resource Economics* 38, 113–133. doi: 10.1086/723730

Roberts, D. C., Boyer, T. A., and Lusk, J. L. (2008). Preferences for environmental quality under uncertainty. *Ecol. Economics* 66, 584–593. doi: 10.1016/j.ecolecon.2008.05.010

Schadeberg, A., Kraan, M., Groeneveld, R., Trilling, D., and Bush, S. (2023). Science governs the future of the mesopelagic zone. *NPJ Ocean Sustainability* 2, 2. doi: 10.1038/s44183-023-00008-8

Schoedinger, S., Cava, F., Strang, C., and Tuddenham, P. (2005). "Ocean literacy through science standards," in *Proceedings of OCEANS 2005 MTS/IEEE* (IEEE, Washington, DC, USA), 1–5. doi: 10.1109/OCEANS.2005.1639840

St. John, M. A., Borja, A., Chust, G., Heath, M., Grigorov, I., Mariani, P., et al. (2016). A dark hole in our understanding of marine ecosystems and their services: perspectives from the mesopelagic community. *Front. Mar. Sci.* 3. doi: 10.3389/fmars.2016.00031

Steel, B. S., Smith, S., Opsommer, L., Curiel, S., and Warner-Steel, R. (2005). Public Ocean Literacy in the United States. *Ocean Coast. Manag.* 48 (2), 97–114. doi: 10.1016/j.ocecoaman.2005.01.002

Stoll-Kleemann, S. (2019). Feasible options for behavior change toward more effective ocean literacy: A systematic review. *Front. Mar. Sci.* 6. doi: 10.3389/fmars.2019.00273

Stuchtey, M. R., Vincent, A., Merkl, A., Bucher, M., Haugan, P. M., Lubchenco, J., et al. (2020). *Ocean solutions that benefit people, nature and the economy* (Washington, D.C: World Resources Institute). Available online at: http://www.oceanpanel.org/ocean-solutions (Accessed November 1, 2021).

Tacon, A. G. J., and Metian, M. (2008). Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: trends and future prospects. *Aquaculture* 285, 146–158. doi: 10.1016/j.aquaculture.2008.08.015

Train, K. (2009). *Discrete choice methods with simulation. 2nd ed* (Cambridge ; New York: Cambridge University Press).

Wattage, P., Glenn, H., Mardle, S., Van Rensburg, T., Grehan, A., and Foley, N. (2011). Economic value of conserving deep-sea corals in irish waters: A choice experiment study on marine protected areas. *Fisheries Res.* 107, 59–67. doi: 10.1016/j.fishres.2010.10.007

Weir, M. J., Uchida, H., and Vadiveloo, M. (2021). Quantifying the effect of market information on demand for genetically modified salmon. *Aquaculture Economics Manage.* 25, 1–26. doi: 10.1080/13657305.2020.1803447