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Publication Date

2024-09-01

DOI

10.1016/j.ecolecon.2024.108228

Ecological Economics xxx (xxxx) xxx

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Understanding and valuing human connections to deep-sea methane seeps off Costa Rica

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A R T I C L E I N F O

Keywords:
Choice modelling
Deep sea
Ecosystem services
Existence value
Methane seeps

A B S T R A C T

Methane seeps are highly productive ecosystems that provide carbon sequestration services, host diverse communities including endemic species, and serve as habitats for commercial fisheries. Little is known about the economic value the public places on them. Discrete Choice Experiments (DCEs) are administered to a sample of Costa Rican taxpayers to evaluate their willingness to pay (WTP) in monetary terms using tradeoffs made in a survey context involving three of the main attributes of methane seep ecosystems to provide insights for future conservation and management efforts. Extensive effort is devoted to understanding how Costa Ricans view different aspects of the deep sea. We find that they associate it with strange animals, natural resources, the unknown, and being far from reach. Perhaps surprisingly, they underestimate how much they know about the deep sea. We find that WTP for methane seep protection is the highest for programs that protect seeps with endemic species, followed by seeps with high climate change mitigation potential and commercial fishing habitat. Higher-income groups and women are more likely to prefer options that increase the current level of protection. We discuss how science communication and community engagement contribute to care expressed toward the deep sea.

1. Introduction

Although there is an increasing interest in deep-sea resources there is still a critical knowledge gap in understanding how people value such resources. Values include direct and indirect use values, non-use values, and option values (Folkersen et al., 2018), as well as the value of the associated ecosystem services, i.e., the contributions to human well-being from ecosystems. Deep-sea environments are critical to nutrient cycling, carbon absorption and sequestration, and contain genetic and biological assets that are unique to these ecosystems (Thurber et al., 2014). They also hold cultural and spiritual significance and have inspired literature, film, art, dance, and education (Levin et al., 2016; Turner et al., 2019; Armstrong et al., 2022). Among the many deep-sea ecosystems that have been discovered since Western exploration began are chemosynthetic ecosystems, including methane seeps, that rely on chemical energy rather than photosynthesis (Ramirez-Llodra et al., 2010). Methane seeps are common on continental margins globally, where fluid enriched in reducing gas (mainly methane and hydrogen sulfide) ascends from the seafloor due to tectonic activity (Ritt et al., 2010). Microorganisms consume the methane and reduced compounds in the seeping fluids and synthesize organic matter fueling a diverse, chemosynthetic community (see Orphan et al., 2001; Ritt et al., 2010; Marlow et al., 2014; Ashford et al., 2021). Methane seeps are known to provide important climate services such as carbon cycling and carbon sequestration (indirect use value), host diverse specialized animal communities including endemic species (with potential option value and non-use values), and serve as nursery and feeding habitats for important fisheries species (see Marlow et al., 2014; Levin et al., 2015, 2016; Le et al., 2017, 2022; Seabrook et al., 2019). Seeps may also be important potential systems for genetic and biopharmaceutical studies and were considered a promising alternative energy source (Desbruyères et al., 2007; Liu et al., 2019).

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https://doi.org/10.1016/j.ecolecon.2024.108228
Received 1 December 2023; Received in revised form 26 April 2024; Accepted 3 May 2024

In spite of many possible reasons why the public values protecting deep-sea ecosystems, relatively little work exists evaluating economic willingness to pay (WTP) for preservation of these systems. We fill this gap by conducting a discrete choice experiment (DCE)[1] to investigate (i) perceptions about the deep sea and methane seeps, (ii) what aspects of the deep sea people most value, and (iii) how much people are willing to pay for methane seep protection in Costa Rica. Our goal is to provide insights and recommendations for future management and conservation efforts; the DCE allows us to separate the importance of several different attributes of deep-sea ecosystems. The relative novelty of deep-sea ecosystem services, defined here as contributions to human well-being including supporting services, provisioning services, regulating services, and cultural services (Millennium Ecosystem Assessment, 2005, see Le et al., 2017), complicates their economic valuation (Le et al., 2017). An important reason is that many of these services represent non-use values; They involve benefits derived from the existence of the ecosystem (for example the desire to preserve a resource for its own sake) but not from direct use.

While few deep-sea ecosystems have been studied in an economic valuation context, deep-water coral reefs are an important exception: Glenn et al. (2010) estimate WTP of the public for the conservation of cold-water corals and find strong public support for banning trawling. They observe that lower scientific knowledge on the part of respondents reduces WTP. Jobstvogt et al. (2014) also consider cold-water corals and find that preferences for cold-water coral conservation are linked to the non-use value of preserving particular species like deep-sea fish, starfish, lobsters, anemones, and sponges. Injuries to deep-sea corals are a component of the economic damage assessment conducted for the BP oil spill (Bishop et al., 2017). More recently, Xuan et al. (2021) investigate WTP in Norway, Scotland, and Canada for policy to protect ecosystems in the North Atlantic. We observe that most deep-sea economic valuation studies have been conducted in Europe and that very few estimates (either marine or terrestrial) are available from Latin America. Our study is among the first to gather data and develop WTP estimates for marine ecosystems in Latin America. We are also the first to consider WTP related to methane seeps or any chemosynthetic ecosystem.

Finally, a range of questions in the conservation literature revolve around the idea of care (Armstrong et al., 2022) and whether knowledge, for example of the deep sea, strengthens care.[2] Jamieson et al. (2020), Armstrong et al. (2022), and Jamieson et al. (2022) debate whether perceptions and care toward the 'deep' are primarily associated with fear. Given this background, we also incorporate questions in our survey about perceptions, examining initial reactions to the deep sea (before we work to strengthen understanding and conduct the DCE itself). Using these initial reactions we also offer additional interpretation and evidence in the discussion of care and human motivation toward conservation generally.

2. Study area and methods

2.1. Costa Rican methane seeps

Costa Rica is one of the 20 most biodiverse countries in the world due to its geographic location; it experiences tropical weather, is surrounded by the Pacific and Atlantic Ocean, and includes the oceanic Cocos Island (Alvarado et al., 2012). With 92% of its total territory being marine area, Costa Rica possesses a great variety of marine ecosystems, including gulfs, bays, rocky shores, beaches, islands, and deep-sea ecosystems (e.g., seamounts, methane seeps, and mesophotic corals) hosting high marine richness (Alvarado et al., 2012; Levin et al., 2015; Cortés, 2019; Maestro et al., 2022). The country also stands out for its commitment to conservation and has recently expanded its marine protected area to ~30% of the country's marine territory (MINAE, 2022). Although public participation in management efforts has been increasing in recent years (Maestro et al., 2022), the lack of adequate stakeholder participation, limited coordination among governmental agencies, and a shortage of economic resources are the main threats to marine management in the country (Alvarado et al., 2012).

In deep waters, methane seeps are common features along the Pacific margin of Costa Rica (Fig. 1). This is a convergent margin characterized by subduction erosion, where >100 fluid seeps have been discovered, corresponding to a seep site every 4 km along the continental slope. These seeps show diverse structures, associated with landslide scars, seamounts, fractures, mounds, and faults, at depths from 400 to 2200 m and occur <100 km away from the Costa Rican shoreline (Sahling et al., 2008). Since the discovery of Costa Rica's methane seeps, research has been conducted describing the chemosynthetic communities associated with these methane-rich environments (see Sahling et al., 2008; Levin et al., 2012, 2015; Goffredi et al., 2014, 2020; Ashford et al., 2021; Pereira et al., 2021, 2022; Azofeifa-Solano et al., 2022). Costa Rican seeps support 3 to 30 times higher hardground faunal densities than seeps in the northeast Pacific off California and in the Mediterranean Sea (Levin et al., 2015). However, the intense oxygen minimum zone (OMZ) off Costa Rica between ~200–500 m deep, where oxygen concentration is lower than 22 μmol/L, yields much lower diversity in comparison to seep sites below the OMZ (Levin et al., 2015). The megafauna (larger animals) at these seeps varies among sites, but is mainly dominated by bathymodiolin mussels, the Costa Rican yeti crab *Kiwa puravida*, siboglinid polychaetes *Lamellibrachia barhamia* and *Escarpia spicata*, as well as lepetodrilid and neolepetopsid limpets and provannid snails (Levin et al., 2015; Pereira et al., 2021). Recently, new species have been described, including the new deep-sea eelpout fish *Pyrolycus jaco* nestling within the tubeworms (Frable et al., 2023), nine new ribbon worm species (Sagorny et al., 2022), five new species of scale worms (Lindgren et al., 2019; Hatch et al., 2020), and a new deep-sea coral species (Breedy et al., 2019). Many more remain to be described (G.W. Rouse, personal communication).

2.2. Survey

The survey was conducted in Spanish and the complete version can be found in Supplementary File 1, along with a translation into English. It consisted of background questions to evaluate perceptions and prior knowledge about the deep sea, a two-minute long informative video about methane seeps (Supplementary File 2, in Spanish), six choice sets (see section below), and demographic questions. If participants chose a "no conservation" option for any of the six cards they were also asked the reason why they picked that option. Prior to the final design of the survey, a focus group provided feedback on the questions, selection of attributes, and accompanying options.

Participants for the main survey were recruited by Qualtrics (www.qualtrics.com), a major online panel provider, where the sampling frame was specified as current Costa Rican taxpayers who were 18 years and older. As is standard practice, participants received a small compensation payment from Qualtrics. A sample of 502 respondents was obtained.

2.3. Discrete choice experiment

The survey respondents were given a discrete choice experiment. This offered three options per choice set: A status quo option where seeps were not explicitly protected which involved zero new costs and

[1] DCEs can be used to investigate direct economic use and non-use values connected to ecosystem existence (Glenn et al., 2010). DCEs aim to estimate the structure of an individual's preferences by establishing the relative importance of different attributes as incorporated within a set of alternatives presented in a survey questionnaire format (Adamowicz et al., 1994; Carson and Czajkowski, 2014; Johnston et al., 2017).

[2] In the economic literature on non-market valuation, this notion of care would be categorized as a stewardship motivation for the class of economic benefits related to the resource's existence (Mitchell and Carson, 1989).

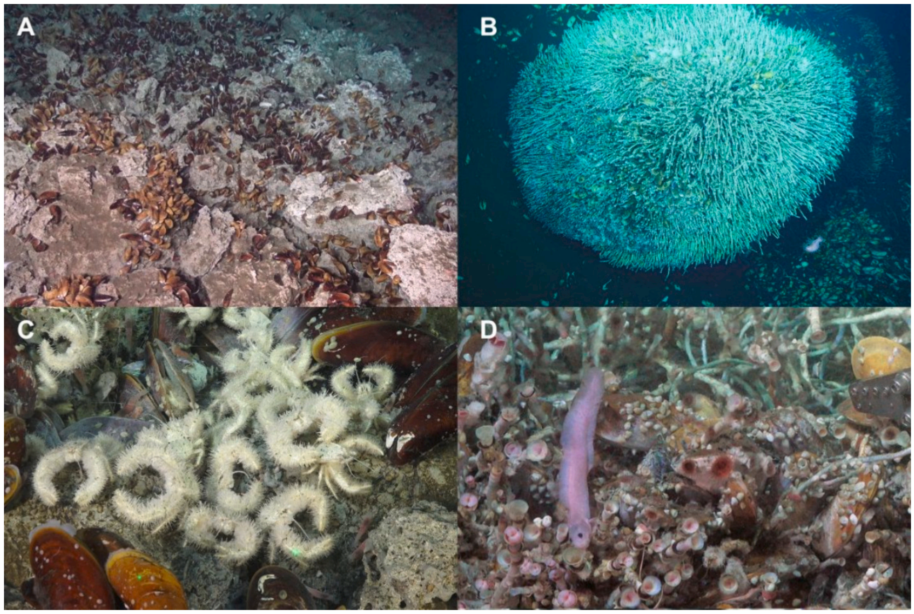

Fig. 1. Methane seeps off the Costa Rican Pacific margin and some of their endemic species. (A) Mussel bed at Mound 12 at 1000 m deep, (B) Tubeworms at Jaco Scar at 1800 m deep, (C) *Kiwa puravida*, yeti crab from Mound 12, (D) *Pyrolycus jaco*, eelpout from Jaco Scar, within *Lamellibrachia barhamia* and *Escarpia spicata* tubeworms (from Frable et al., 2023).

two options that would increase the level of protection in different ways and incur a specified increase in cost. The questionnaire reminded participants to account for budget constraints and to consider their other expenses to avoid hypothetical bias from people ignoring their budget constraints (Jobstvogt et al., 2014).

The increased protection options described to participants on the choice cards (see Fig. 2) were built around existing science describing ecosystem services offered by methane seeps and, more specifically, by methane seeps on the Costa Rican margin. The attributes and accompanying options are described in Table 1.

The zero-cost option was described as a scenario where the seep offers basic ecosystem services (i.e., there are no unique species, no special benefits to commercial fisheries, and little potential for climate regulation), and no conservation policy would be implemented. The cost attribute for the other options was chosen from six levels in the local currency, the Costa Rican colón (₡ 685 = US$ 1 at the time of the survey). Magnitudes were chosen considering local annual income, tax rates, and bill denominations. The question frames the amount in the form of an annual payment. The cost levels were: ₡500, ₡1000, ₡2000, ₡5000, ₡7000, and ₡10,000 ($0.73 to $14.64 at the time the survey was conducted).

There was a total of 36 choice sets, each with three options 1, 2, and 3 (see Supplementary File 3 for all cards in Spanish). Option 1 was the status quo option, and it was kept the same for all choice sets to ensure that the respondent could always afford one of the options. An example choice set is provided in Fig. 2 (card 17 in Supplementary File 3). The order of the 36 choice sets was randomized so there was no methodical structure, and they were divided into blocks of 6 choice sets. Each block of choice sets was randomly assigned to an equal number of respondents. A more in-depth explanation of the DCE methodology can be found in Supplementary File 4.

2.4. *Surveying prior background knowledge and affiliation with the marine sector*

To understand respondent prior knowledge about the deep sea we provided a list of statements (all of which are considered scientifically correct) and asked if the respondent agreed or disagreed. This allowed us to categorize knowledge of the deep sea. For each statement where a respondent selected "Completely agree" we assigned 1 point, 0.75 point for "Agree", 0.5 point for "Neutral", 0.25 point for "Disagree" and 0 points for "Completely disagree". There were 10 statements for a total of 10 points allowing us to create a calculated index of knowledge categories (CalcKnow). We did the same with a series of statements asking for level of agreement with conservation actions (CalcConserv), allowing us to see how this connected with respondent's knowledge and WTP.[3]

We also included a dummy variable based on the respondents' affiliation with the marine sector (Sector), including but not limited to tourism, fishing industry, marine shipping, other marine resources (oil, gas), education (student or professor), non-governmental organizations (NGOs), and governmental institutions.

2.5. *Data synthesis and statistical analyses*

Our main analysis used conditional and mixed (random parameters) logit models (Train, 2009) of the DCE results and were estimated using STATA 17. Our random parameter's models included both mean and standard deviation parameters on the three ecosystem attributes (*Endemic species*, *Fisheries*, and *Climate change*) experimentally assigned by the DCE. The cost parameter following Train and Weeks (2005) is specified as fixed in order to ensure that the WTP ratio is well-behaved. We provide estimates for the sample itself and the sample weighted to make the median age, percent male and percent college educated match the 2021 Costa Rican Census (INEC, 2021). Results for our preferred model without weights and after weighing are shown in Table 2 which uses an alternative specific constant (ASC) attached to the status quo option. The ASC captures respondents' preference for a zero cost, business as usual outcome relative to any conservation option. We explore interactions between the ASC and each of the demographic variables in Table 2. In the mixed logit model, we specify the parameters on attributes and ASC as random. WTP estimates are similar across the fixed and random parameters models. We note a likelihood ratio test prefers the random parameters model and so refer to those results in what follows (fixed-coefficient model results can be found in Supplementary File 5).

[3] CalcConserv ranges from 0 to 5 based on a series of 5 statements.

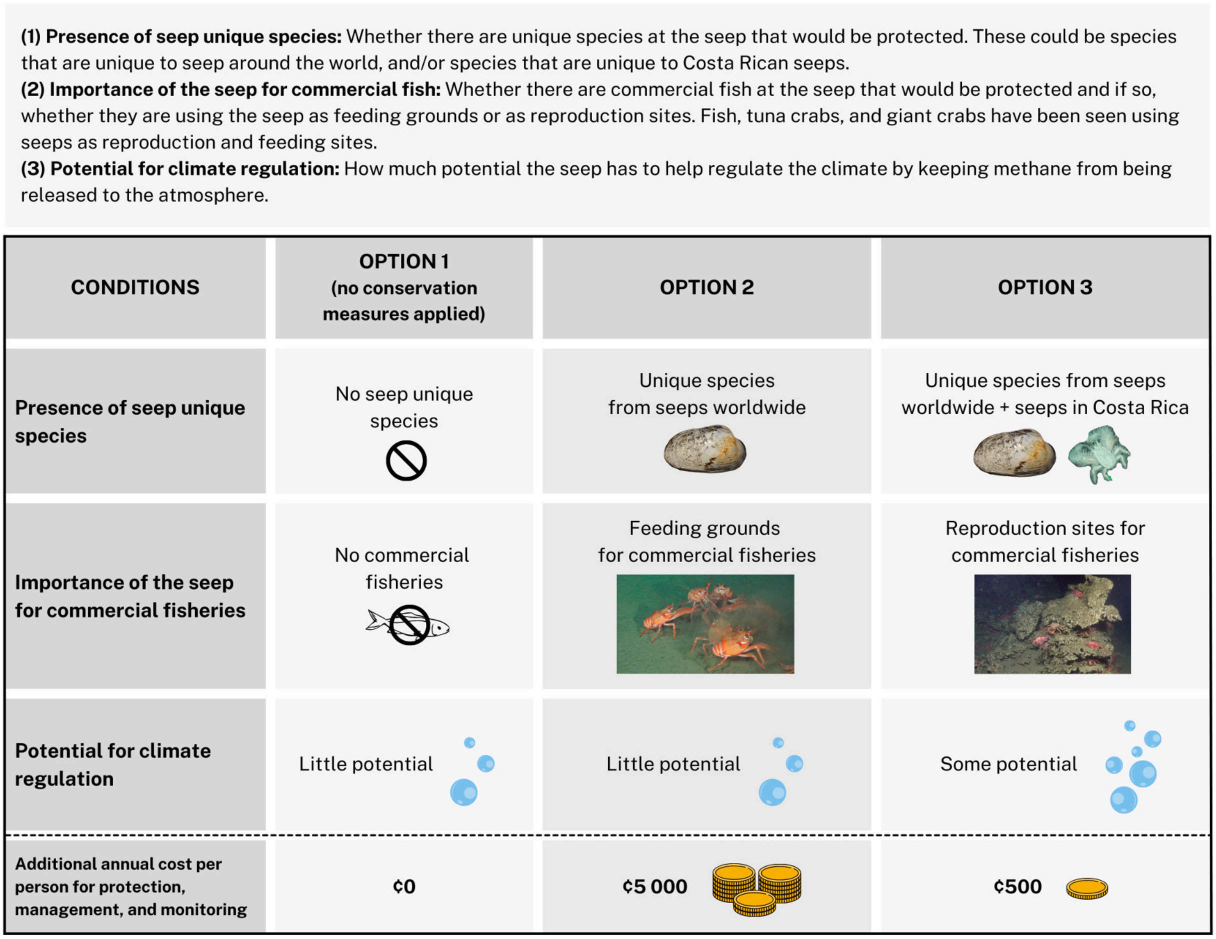

Fig. 2. Choice card example in English. All choice cards can be found in Supplementary File 3 in Spanish.

WTP values are expressed in US$/per unit increase in the attribute throughout, and we also calculated WTP as a fraction of average annual income for reference.

Linear regression models were estimated to evaluate whether there is a correlation between knowledge and level of agreement with conservation actions. Answers to the open-ended question of what people think of when they hear the words "deep sea" were coded into a set of categorical variables.

Finally, we compare our results to other economic valuation studies of deep-sea ecosystems. We used exchange rates and average annual income[4] at the time the studies were conducted to provide the most meaningful comparisons.

3. Results

3.1. Socio-demographics characteristics of survey respondents

The sociodemographic characteristics of our survey respondents were compared to their population characteristics as reported by the Instituto Nacional de Estadistica y Censos Costa Rica (INEC, 2021). Our sample was reasonably representative along some dimensions, but had the divergences common to many internet panels. It is younger (sample = 59% under median age, INEC = 26%), had a higher proportion of males (sample = 57%, INEC = 46%), and better educated (sample = 39% university degree, INEC = 10%). For the choice models estimated below, we provide estimates using the unweighted sample and a weighted sample where the inverse probability weights result in our sample matching INEC on the eight cells defined by these three variables. If younger, female, and college graduate are positively related to willingness to pay, applying the weights should result in lower estimate and that is the observed result below.

Most income brackets were well represented in the sample, except for people earning less than US$ 5600 annually who, not unexpectedly, were underrepresented (sample = 29%, INEC = 60–70%).[5] The same pattern was observed in employment status, where 77% of the sample was employed (INEC = 49%). Considering respondents with dependents, the most common number of dependents (2–4) in the sample was similar to the Costa Rican population (sample = 37.8%, INEC = 34.3% based on number of people in a household), but there were fewer respondents with no dependents in the sample than in the population (sample = 27.3%, INEC = 39.3%). 79% of respondents said they are not associated with the marine sector, and of the 21% who are, they work mainly in tourism (56% of respondents associated with the marine sector), followed by the fishing industry (15% of respondents associated with the marine sector) and academia/research (12.5% of respondents associated with the marine sector). We interacted these sociodemographic variables with the ASC in our conditional logit models and explored subsamples of the data restricted to particular income and education groups. See Supplementary File 5 for more complete characterization of the socio-demographic data.

[4] Average annual income data from Organization for Economic Co-operation and Development via Statista.

[5] Weighting directly on income in not typically done due its strong relationship with the other three variables, which temporally precede.

Table 1
Attributes and accompanying levels used in the discrete choice experiment.

Attribute	Attribute description	Levels
Presence of seep unique species	This attribute assesses whether there are unique species (i.e., endemic, however we used the term "unique" to keep the survey in non-scientific language) at the seep that would be protected. These could be species that are unique to seep ecosystems and occur at seeps around the world (worldwide seep unique species) and/or species that are unique to Costa Rican seeps (Costa Rican seep unique species). For example, the giant clams *Calyptogena* occur globally at seeps, but the yeti crab *Kiwa puravida* is only found in Costa Rica.	1. No unique species (status quo) 2. Worldwide seep unique species 3. Worldwide and Costa Rican seep unique species
Importance of seep for commercial fish	This attribute assesses whether there are commercial fish at the seep and if so, whether they are using the seep as feeding grounds or as reproduction areas. Fish, tuna crabs, and giant crabs have been seen using seeps as reproduction and feeding sites.	1. No commercial fish (status quo) 2. Commercial fish use the seep as feeding grounds 3. Commercial fish use the seep as reproduction sites
Climate regulation potential	This attribute assesses how much potential the seep has to help regulate the climate by keeping methane from being released to the atmosphere.	1. Little potential (status quo) 2. Some potential 3. Great potential

Table 2
Variables and levels used in conditional and mixed logit models.

Attribute	Levels
Endemic species	Presence of endemic species (0 = No endemic species, 1 = Worldwide seep endemic species, 2 = Worldwide and Costa Rican seep endemic species).
Fisheries	Relevance for fisheries (0 = No commercial fisheries, 1 = Feeding grounds to commercial fisheries, 2 = Reproductive sites for commercial fisheries).
Climate change	Climate mitigation potential (0 = Little potential, 1 = Some potential, 2 = Great potential).
Cost	Cost attribute (₡500, ₡1000, ₡2000, ₡5000, ₡7000, and ₡10,000).
STR	Respondent's identification number and question number (specific to each response of each individual).
Card	Choice set number
Gender	0 = Prefer not to say, 1 = Woman, 2 = Men, 3 = Transgender, 4 = Non-binary.
Income*	0 = Prefer not to say, 1 = Up to US$5600, 2 = More than US$ 5600 and less than US$ 8400, 3 = More than US$ 8400 and less than US$ 13,900, 4 = More than US$13,900 and less than US$ 28,000, 5 = More than US$ 28,000.
Education	0 = Prefer not to say, 1 = Pre-school, 2 = Sixth grade, 3 = High school, 4 = College, 5 = Masters, 6 = PhD, 7 = Technical degree.
Work	0 = Prefer not to say, 1 = Part-time worker, 2 = Full time worker, 3 = Student, 4 = Independent, 5 = Looking for a job, 6 = Retired, 7 = Other.
Marine sector	Whether the respondent works in the marine sector (1 = yes).
Deep sea knowledge	Respondent's own perception of their knowledge about the deep sea (1 = Little knowledge to 5 = Excellent knowledge).
Conservation index	Category of level of agreement with conservation actions based on a point system (1 = Little knowledge to 5 = Excellent knowledge).

* ₡ 685 = US$ 1 at the time of the survey; US$ rounded to hundreds.

3.2. Background knowledge about the deep sea

In an open-ended question asking people about the first thing they think of when they hear the words 'deep sea', people associated the deep sea with biodiversity, marine resources, science, environmental characteristics, specific ecosystems, and emotions (Fig. 3). Some interesting patterns emerged when analyzing these answers by sociodemographic characteristics; biodiversity terms were mentioned more often by lower income people, emotion terms were mentioned more with lower education level, while environmental aspects were mentioned more by those with higher education level (Supplementary File 5). More than 50% of the respondents put "habitat for unique animals" as the first or second most important connection they have to the deep sea, and >50% and >75% of the respondents ranked "provision of mineral resources" and "biomedical potential", respectively, as the least important connections they have to the deep sea. "Provision of food" and "climate regulation" were ranked second and third (Fig. 4).

Respondents were asked whether they agreed or not with statements that are considered scientifically correct (Fig. 5). Overall, respondents agreed or totally agreed with most of the scientific statements regarding general aspects of the deep sea. But they tended to be more neutral toward statements regarding the specifics of methane seeps and the role of the deep sea in climate mitigation, suggesting most respondents are less informed prior to the survey on these issues. We also compared respondents' self-assessment of knowledge about the deep sea to calculations based on their responses to these scientific statements: 10% vs 4% (self-assessment vs calculated) had no knowledge about the deep sea, 49% vs 50% had little knowledge, 35% vs 5% had some knowledge, 4% vs 4% had good knowledge, and 2% vs 37% had excellent knowledge.

3.3. Willingness to pay for methane seep protection

Table 3 reports coefficient estimates from the mixed logit models we fit for the sample both unweighted and weighted, as well as the corresponding estimates of willingness to pay (WTP) for conservation for a one-unit improvements in three attributes: Endemic species, fisheries, and climate change mitigation. For the weighted sample, appropriate when estimates for Costa Rican taxpayers are desired, increasing the importance of the endemic species attribute in the specified manner (Table 2) one level raises WTP to protect methane seeps by US$ 22.86/year. Increasing the importance of seeps for commercial fisheries raise WTP by US$ 9.25/year. And finally increasing the importance of climate regulation provided by seeps increases WTP for their protection by US$ 15.10/year. All three WTP values were significantly different from zero at the 1% level.

With respect to the parameters on the random components, there is considerable preference heterogeneity with respect to endemic species and climate change but not fisheries. The random component on the ASC, itself, is also insignificant suggesting that variation here is adequately captured by the ASC interaction terms. Interactions between the ASC and social demographic characteristics were generally not strongly statistically significant. This is not an uncommon phenomenon in a DCE; without interaction with the ASC they fall out of the model as the demographic factor is held constant across choices. Perhaps more important here though is that there were non-trivial correlations between them. For instance, education and income have the expected positive correlation. The point estimates for income and gender suggest that women and higher income groups were less likely to choose the status quo, instead favoring one of the other options, although the point estimates are individual. The major reason for inclusion of these variables is to absorb some of the sources of unobserved heterogeneity. It is

Fig. 3. Responses when asked about the first thing respondents think of when they hear the words deep sea. Responses to this open-ended question were categorized for analysis and this visual representation. Numbers and shading represent the number of times each word or phrase was mentioned.

also worth noting that, as expected, WTP decreases between unweighted sample and the sampled weighted to match Costa Rica's INEC with respect to median age, gender, and college graduate. With the down weighting of the younger, male, and college graduates, we find that for individual attributes WTP declines by a fairly small (6%) to moderate (22%) degree. Estimates of the magnitudes of the random components generally increase by a small to moderate amount and all become insignificant due to noisier estimates of standard deviation parameters.

3.4. Attitudes toward conservation

Respondent's attitudes toward conservation actions were positive overall (Fig. 6), and they tended to become more favorable with greater knowledge (Fig. 7). Respondents mostly agreed that deep-sea ecosystems should be protected (63% agreed that the government should do more to protect them), but were more negative when it came to conservation actions justified through the provision of fish habitat and climate change mitigation (only 21% agreed that the deep sea should be protected for providing such services). Interestingly, respondents seemed to value the deep sea mostly for its existence and bequest values: 52% would like to have the option to use deep-sea ecosystems in the future, 77% agreed that they provide benefits for their children and future generations, and 85% valued the uniqueness and fragility of deep-sea ecosystems even though they don't intend to use them.

In spite of these generally positive attitudes, we also found that nearly half of respondents (226) were not willing to pay (i.e., chose the zero-cost status quo option) in at least one choice set. The main reason given for this, when asked in a follow-up question, was that they believe the Costa Rican government should pay out of its existing budget (39%), a common response of those in surveys who are happy to have the good

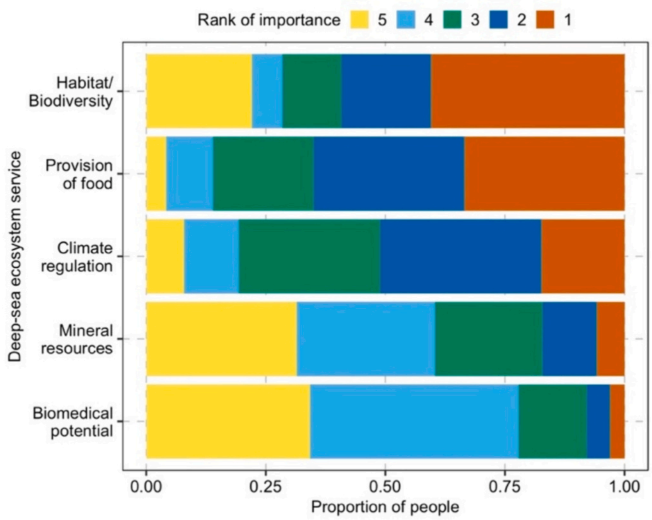

Fig. 4. Ranked importance of deep-sea ecosystem services by respondents.

provided at no direct cost to them. Other common reasons provided were that resource users should pay (18%), an inability to afford payments (14%), or they would rather pay into a conservation trust fund rather than directly pay a tax (13%) (see Supplementary File 4 for details).

4. Discussion

4.1. Willingness to pay for methane seep protection

We first compare the magnitudes of our WTP results with related studies conducted in other countries and settings (Table 4). Our estimated WTP for methane seep conservation in Costa Rica is lower than WTP for deep-sea ecosystems in Norway (LaRiviere et al., 2014; Aanesen et al., 2015; Xuan et al., 2021), Canada (Xuan et al., 2021), and Italy (O'Connor et al., 2020). It exceeds that for a marine ecosystem (cold-water corals) in Ireland (Glenn et al., 2010) and for certain terrestrial ecosystems in Chile (Cerda et al., 2013). However, Costa Rica also has lower average income than countries in nearly all prior studies. When we consider WTP as a fraction of average annual income we find that WTP in our setting is comparable to related studies in Table 4. This supports the idea that environmental concerns as measured by WTP may be fairly high in some middle-income countries (Vincent et al., 2014). Our results here are consistent with Costa Rica's emergence as the leader among developing Latin American countries in environmental conservation (Steinberg, 2001) and it is well-known for its attention to tropical forest (Biénabe and Hearne, 2006). Costa Rica was one of the first countries to voice concerns about deep-seabed mining when it did so in 2022.[6]

In several related studies of deep-sea ecosystems, attributes associated with existence value had the highest WTP, including protection of species living there (Jobsvogt et al. 2014), protection of habitat (LaRiviere et al., 2014; Aanesen et al., 2015), and existence of endemic species (Cerda et al., 2013, this study). In our study, respondents were

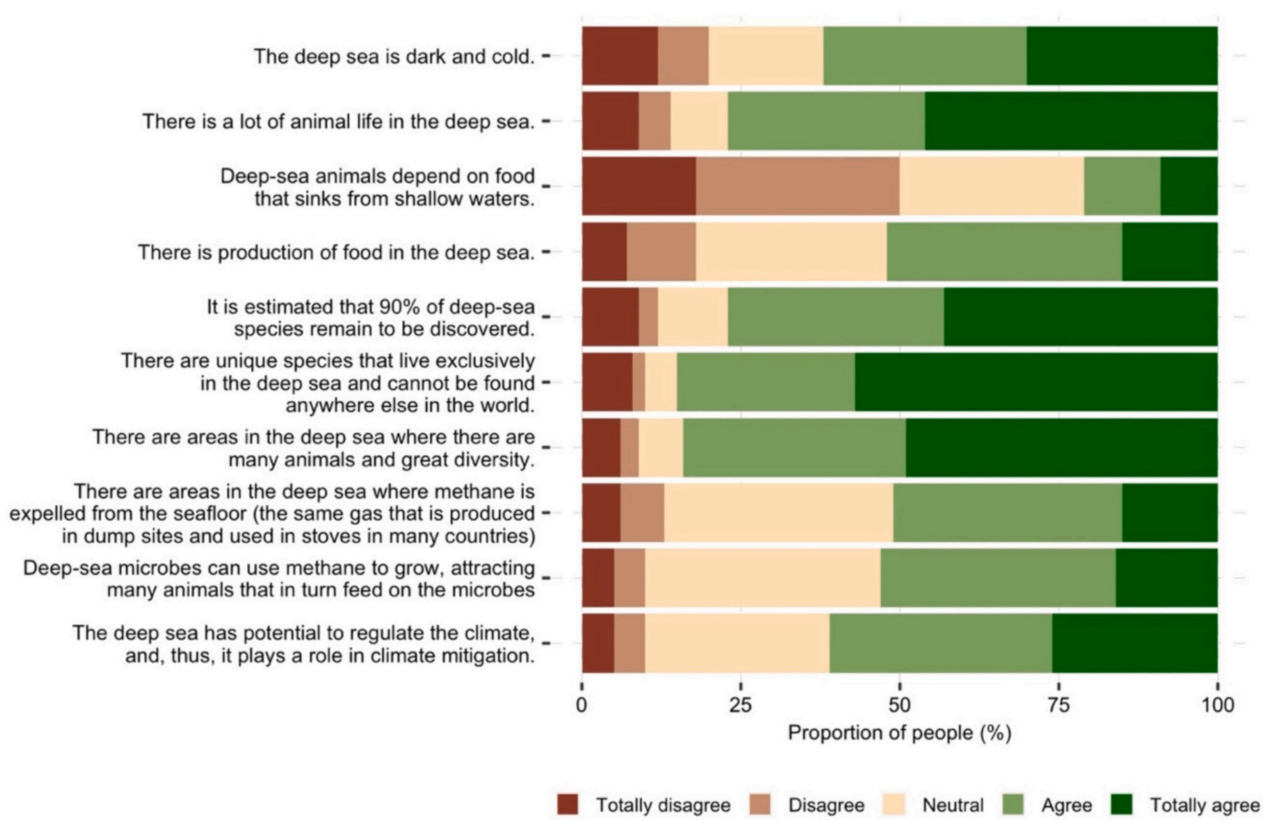

Fig. 5. Respondents' level of agreement (%) on deep-sea science questions. Data are available in Supplementary File 5.

[6] https://savethehighseas.org/voices-calling-for-a-moratorium-governments-and-parliamentarians/

Table 3
Attribute coefficients and WTP estimates for methane seep conservation for the mixed logit models without weighting the data and after weighting the data to make the sample statistically equivalent to the population considering gender, age, and education.

	Without weights		With weights	
Random parameters				
	Mean of coefficient	**WTP (US$)**	**Mean of coefficient**	**WTP (US$)**
ASC	−0.664 (1.070)	–	−0.459 (0.953)	–
Endemic species	0.470 (0.089)***	24.30	0.609 (0.147)***	22.86
Fisheries	0.228 (0.059)***	11.80	0.246 (0.077)***	9.25
Climate change	0.309 (0.069)***	16.00	0.402 (0.125)***	15.10
	SD of coefficient		**SD of coefficient**	
ASC	0.926 (2.524)		1.390 (2.104)	
Endemic species	0.841 (0.271)***		1.066 (0.512)	
Fisheries	0.090 (0.669)		0.065 (0.236)	
Climate change	0.797 (0.296)***		0.867 (0.381)	
Non-random parameters				
	Mean of coefficient		**Mean of coefficient**	
Cost	−0.019 (0.007)***		−0.027 (0.010)**	
ASC x Income group	−0.217 (0.193)		−0385 (0.299)	
ASC x Education group	0.545 (0.327)*		0.476 (0.342)	
ASC x Female	−0.291 (0.194)		−0.036 (0.215)	
ASC x Full-time worker	−0.003 (0.145)		−0.126 (0.243)	
ASC x Marine sector	0.018 (0.167)		−0.594 (0.404)	
ASC x Knowledge of deep sea	−0.074 (0.097)		0.144 (0.166)	
ASC x Conservation index	−0.013 (0.062)		−0.117 (0.118)	

Standard errors in parentheses. Significance levels are indicated as ***, **, and * for 1%, 5%, and 10%, respectively. A negative ASC interaction coefficient indicates preference for one of the improvement options over the status quo option. Choice sets: 6 per $N = 502$ respondents.

willing to pay the most for protection of endemic species and the least for protection of commercial fish habitat. The fish habitat attribute contains both an existence motivation (as with the endemic species attribute) and a value from the direct consumption of commercial fish (Aanesen et al., 2015). Expectations might have been that in a low-income country there would be a greater emphasis on direct fisheries value; it is interesting to see here that the global climate mitigation value, along with protection of endemic seep species, dominates over those associated with commercial fishing.

4.2. Limitations of surveys and DCEs

Some common limitations associated with DCEs and valuation surveys more generally include the need for the survey to present the material in such a way as to enable almost all respondents including those

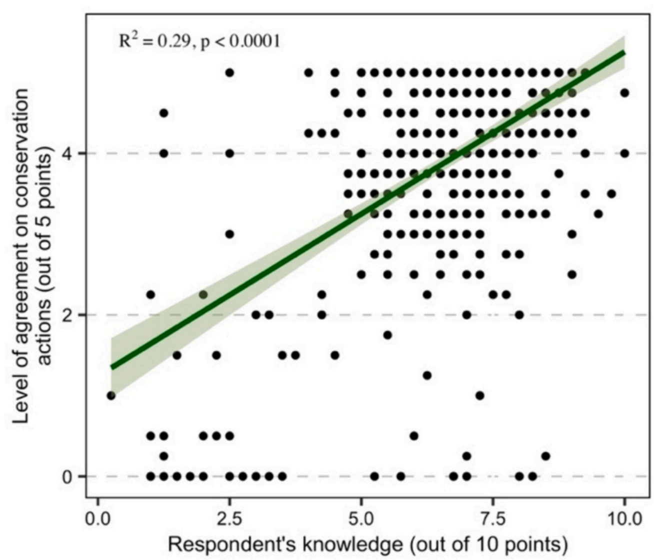

Fig. 7. Linear regression between respondent's knowledge and level of agreement on conservation actions.

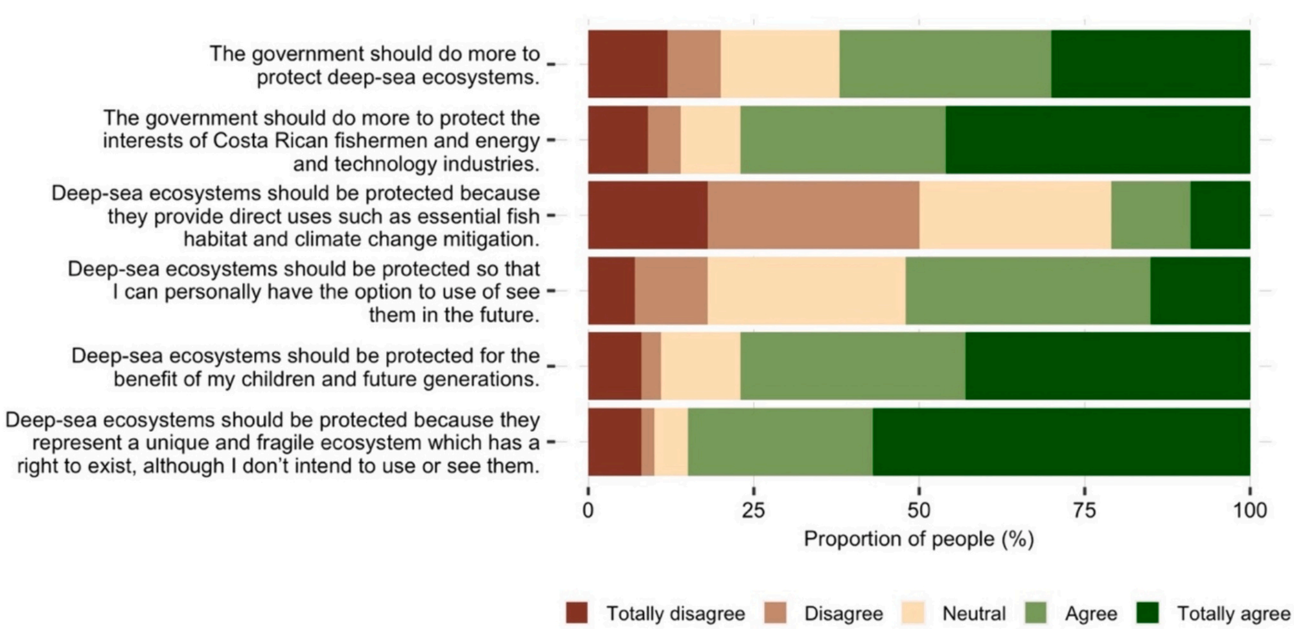

Fig. 6. Respondents' level of agreement (%) on conservation actions. Data are available on Supplementary File 4.

Table 4
Comparison of willingness to pay (WTP) for protection or restoration of deep-sea ecosystems around the world and other ecosystems in Latin America: WTP in US$ per year, and as a percentage of the country's average annual income. Currency converted to US$ with exchange rates at the time the study was conducted. Average annual income at the time the study was conducted.

Country	Goal of the study	Attribute	WTP (US $/year)	WTP (% of average annual income)	Reference
Costa Rica	Conservation of methane seeps	Protect seeps with endemic species	22.86	0.19	This study
		Protect seeps with potential for climate regulation	15.10	0.12	
		Protect seeps that are habitat and/or nursery for economically important fisheries	9.25	0.07	
		High potential for medicinal products from deep-sea organisms	62.19	0.14	
United Kingdom	Protection of deep-sea biodiversity				Jobstvogt et al. (2014)
		High level of species protection	47.28	0.11	
		Intermediate level of species protection	43.29	0.10	
		Ban trawling in all coral areas	0	0	
Ireland	Protection of cold-water corals				Glenn et al. (2010)
		Ban trawling in all known coral areas	12.27	0.02	
		Ban all fishing in all coral areas	1.33	<0.001	
		Protect areas that are habitat/nursery for many fish species	267.16	0.45	
Norway	Extension of current MPAs with the goal of including cold-water corals				LaRiviere et al. (2014)
		Protect areas attractive for the fish industry	41.23	0.07	
		Increase total protected area to 10,000 km^2	41.10	0.07	
		Protect areas attractive for oil and gas industry	22.02	0.04	
		Protect areas that are important habitat for fish	187.58	0.40	
Norway	Protection of cold-water coral				Aanesen et al. (2015)
		Protect areas attractive for the fish industry	44.07	0.09	
		Protect areas attractive for the oil industry	18.08	0.04	
		Extend protected area to 5,000 km^2	59.89	0.13	
		Extend protected area to 10,000 km^2	74.58	0.16	
Italy	Restoration of a deep-water canyon		39.62	0.11	O'Connor et al. (2020)
		Reduction in marine litter density	35.04–52.51	0.05–0.07	
Norway	Protection of high-seas ecosystems in the North Atlantic				Xuan et al. (2021)
		Improvement of health of fish stock	30.33-72.29	0.04-0.05	
		Increase in protected area	3.30-28.32	0.004-0.04	
		Number of marine economy jobs created	14.28-18.41	0.02-0.03	
		Reduction in marine litter density	83.19–128.27	0.20–0.30	
Scotland	Protection of high-seas ecosystems in the North Atlantic				Xuan et al. (2021)
		Improvement of health of fish stock	50.86-86.97	0.10-0.20	
		Increase in protected area	25.13-50.62	0.07-0.14	
		Number of marine economy jobs created	26.67-44.72	0.07-0.12	
		Reduction in marine litter density	38.59–57.23	0.05–0.08	
Canada	Protection of high-seas ecosystems in the North Atlantic				Xuan et al. (2021)
		Improvement of health of fish stock	38.94-50.62	0.06-0.07	
		Increase in protected area	22.54-25.02	0.03-0.04	
		Number of marine economy jobs created	20.18-31.03	0.03-0.05	
		Availability of drinkable water	6.60–8.90	0.04–0.06	
Chile	Valuation of environmental benefits provided by a terrestrial reserve				Cerda et al. (2013)
		Existence of endemic amphibians in the reserve	6.70-8.20	0.04-0.05	
		Observe animals in a visit to the reserve	4.40-4.70	0.02-0.03	
		Existence of endemic orchids in the reserve	1.70-3.00	0.01-0.02	
Costa Rica	Public preferences for biodiversity conservation and scenic beauty	Increased protection of biodiversity in relatively remote areas	3.98	0.08	Biénabe and Hearne (2006)
		Improved protection of scenic beauty in relatively accessible forest areas	3.00	0.06	

not originally that familiar with the ecosystem and the changes of interest to it to understand the choice task they are being asked about. Further, they need to do so in a manner that makes the survey consequential in the sense that they are providing information about the tradeoffs they are willing to make and that policymakers may take the public's preferences into account in making decisions concerning the ecosystem. Since directly assessing understanding via surveys can often be challenging (Aanesen et al., 2015), we undertook several initial focus groups and in-depth interviews where we gathered feedback in-person with respect to specific issues. This allowed us to closely tailor the final survey, with detailed instructions especially for the DCE component.

Although respondents showed more knowledge about the deep sea than we originally expected, they were substantially less familiar with methane seeps, and in particular with the role of the deep sea in climate mitigation. However, previous studies show that even though respondents may not have pre-existing preferences on a subject they are unfamiliar with, they are still able to build preferences within the survey if the information they need for making an informed decision is provided (Jobstvogt et al., 2014). A related issue is whether respondents perceive the information provided in the survey to be accurate as this can influence (typically in a negative direction) both preferences and WTP (LaRiviere et al., 2014). Our finding that WTP for improvements in the protection of methane seeps despite the relative unfamiliarity with these ecosystems compared to the other two experimentally assigned attributes (i.e., fisheries and climate) is suggestive evidence that the survey presentation with respect to endemic seep species was largely successful.

Another potential challenge related to the information provided in our survey is that we cannot compare results to alternative approaches (for example, to a survey where no information is provided at all). However, based on our analyses using the calculated deep-sea knowledge index, it seems that this does affect WTP (see discussion below). In addition, a prior study observed that when respondents were informed of how well they scored on background knowledge questions, their WTP for an extension of current marine protected areas in Norway was 1.5× higher (LaRiviere et al., 2014). Thus, we recommend that future studies further consider how background knowledge questions may impact responses within a DCE.

Protest votes from respondents who reject some aspect of the survey's scenario in DCEs can be identified, to some extent, by adding background and follow-up questions to understand the reasoning behind their choice. Often, protest voters believe that others should bear the costs of a policy and so vote 'no' even when they like the policy itself (Mariel et al., 2021). In our study, the set of potential protesters were initially identified by looking at the set of respondents who choose the zero-cost status quo option in all six choice sets and gave a reason for doing so other than being unable to afford payment (5 respondents out of 502). We also looked at two patterns of choices that may be reflective of quickly going through the DCE without paying much attention to the attribute levels – picking all of their options from the second column (2 respondents out of 502) or picking all of their options from the third column (4 respondents out of 502). Here random assignment of attribute levels to options makes it likely that only a very small fraction of respondents finds this pattern of choices optimal. We also looked at what fraction of respondents disagreed with all of the conservation actions statements (19 out of 502 respondents), but none of these respondents chose the status quo option in all six choice sets nor disagreed with all of the deep-sea science statements, which both seems plausible and suggestive that these were not necessarily protest voters.

4.3. *Management application to methane seeps, the deep sea, and in Costa Rica*

Global protection of methane seeps is limited, especially in deep waters, and at present is mostly based on area-based management tools (ABMTs, also known as spatial management strategies). These include twenty-seven marine protected areas (MPAs) that have been designated in European shallow waters (< 200 m) for methane seeps, known as Special Areas of Conservation (SACs) (Noble-James et al., 2019). Methane-derived authigenic carbonates associated with methane seepage are termed 'submarine structures made by leaking gases' and together with their biological communities are considered 'habitats of community importance' under the EC Habitats Directive (European Commission, 2013). These SACs are located within the EEZs of the UK, Ireland, Denmark, France, Romania, Greece, and Spain (Noble-James et al., 2019). Outside of Europe, the uThukela Banks MPA off the east coast of South Africa was designated to protect coastal, shelf, and slope ecosystems (e.g., sand, gravel, reefs, and submarine canyons) spanning an area of 4094 km^2, and recently gas (likely methane) leakage at depths of <100 m was mapped for the first time in the region (Green et al., 2022). Within deep waters, Canada recently established the Tang.ɢ̱wan–ḥačx^{w}iqak–Tsig̱is MPA, a 133,000 km^2 area off the west coast of Vancouver Island featuring methane seeps, hydrothermal vents, and >40 seamounts at depths of up to 2250 m (Times Colonist, 2023). The region of the Finike Seamount (880–1000 m) in the Mediterranean Sea has been identified as a fragile and unique ecosystem with a distinct methane seep community where trawling should be banned or controlled (Öztürk, 2009). ABMTs have also been proposed for deep-sea ecosystems in the vicinity of oil and gas industrial activity, including methane seeps, where protected areas would be established around ecologically or biologically significant areas (EBSAs) of representative communities with a buffer zone at least 2 km away from the protected area (Cordes et al., 2016). The Pacific Fishery Management Council also recognized methane seeps and associated biological communities as essential fish habitat due to trophic and reproductive support and incorporated seeps into fisheries management (NOAA, 2020).

Other types of ABMTs consider fundamental ecological characteristics of the ecosystem, such as those we describe in the policy attributes for our DCE. Intergovernmental organizations may develop criteria to identify vulnerable, sensitive, and ecologically or biologically significant ecosystems in need of protection (Gollner et al., 2021). These alternative types of ABMT include (i) Vulnerable Marine Ecosystems (VMEs), developed in the context of deep-sea fishing by Regional Fisheries Management Organizations within the Food and Agriculture Organization (FAO), (ii) Ecologically and Biologically Significant Areas (EBSAs), developed in the context of the Convention on Biological Diversity (CBD), and (iii) Particularly Sensitive Sea Areas (PSSAs), developed in the context of international shipping activities by the International Maritime Organization. These three tools use similar criteria to those we study, making more precise the concepts of uniqueness/rarity, vulnerability, biological diversity, structural complexity, importance for threatened, endangered or declining species, and others (Blanchard and Gollner, 2022). Regarding deep-sea ecosystems, hydrothermal vents are considered VMEs by FAO, four have been described as EBSAs, and seven additional vents should also be considered for inclusion (see Gollner et al., 2021). Cold-water corals ecosystems have also been recognized as VMEs (FAO, 2009). Although methane seeps have not yet been officially recognized by such tools, they have been considered for several possible VMEs (FAO, 2009), and studies show their potential to fit these criteria (FAO, 2018).

Notably, among these three tools, PSSAs are the only one to have social, cultural, and economic criteria (Gollner et al., 2021), mentioning the use of living marine resources of social or economic importance and cultural and historical importance (IMO, 2005). Gollner et al. (2021) deemed these not relevant for hydrothermal vents and suggested an ecosystem service criterion instead to identify hydrothermal ecosystems in need of protection, considering provisioning (e.g., genetic resources), regulating and supporting (e.g., carbon sequestration), and cultural services (inspiration for arts, science, and technology), as well as importance for scientific research. However, these are all mainly direct or indirect use values since contribution to art through inspiration is potentially monetizable and is not necessarily connected to existence or bequest motivations for non-use value (Chan et al., 2011). Perhaps, more importantly, it is the public who will ultimately be asked to pay for any protection effort in a world of competing demands and limited resources. Thus, management tools still need to incorporate non-use values for marine management programs to be successful (O'Connor et al., 2021). Including non-use values in management tools increases the overall value of ecosystems and their services (Xuan et al., 2021) and better measures welfare losses arising from damages (see Bastian-Olvera and Moore, 2021).

In general, in Costa Rica, MPA management tends to be adaptive with high public participation (Maestro et al., 2022), and the existence value of biodiversity given by Costa Ricans in our survey is reflected in the country's position toward marine conservation. Costa Rica recently expanded the Cocos Island National Park and the Bicentennial Marine Management Area from 2.7% to ~30% of the country's marine territory (MINAE, 2022), achieving for Costa Rican waters the global goal of protecting 30% of the world's ocean by 2030. The expanded protected area is centered around Cocos Island and includes deep seamounts located south of the island.

However, offshore MPAs are difficult to keep and patrol due to logistics and cost, especially when they are large and do not have easily identifiable boundaries (e.g., in the case of Cocos MPA, the boundaries are represented by territorial sea). In addition, enforcement can be quite expensive, and other tools such as social norms and inclusion of all stakeholders can help with compliance and, consequently, the success of the MPA (Arias et al., 2014). The incorporation of local communities into protected area management is emerging in Costa Rica (Maestro et al., 2022). Marine Areas for Responsible Fishing (AMPR) were recognized in 2009 as a new model for participatory management of small-scale fisheries in the country, and, although its effectiveness remains to be determined, collaborations with NGOs and the government have strengthened the participation of small-scale fishers (Lozano and Heinen, 2016). The Santa Rosa National Park (northwest coast of Costa Rica) has a strong local component based on education and awareness-raising, following a bottom-up approach with the inclusion of the population at all stages (Maestro et al., 2022).

The inclusion of stakeholder consultation in conservation strategic planning processes through ecotourism provides dual benefits for conservation and local communities (Hunt and Vargas, 2018). In addition, tourism activities can be sources of income for conservation efforts in the form of entrance fees to protected areas and national park stamps, for example (Maestro et al., 2022). Tourism is one of the main sources of foreign income in Costa Rica (Biénabe and Hearne, 2006), and it is estimated that up to 80% of tourists visit the country for ecotourism activities. A previous study by Biénabe and Hearne (2006) reported that foreign tourists were willing to pay a one-time fee of $6.77 in the form of an airport tax, as well as voluntary contributions at hotels, for improved biodiversity conservation of Costa Rican tropical forests. Similarly, governmental institutions and NGOs could propose an additional fee to the national income tax paid by Costa Rican citizens paired with voluntary contribution scheme to fund offshore, deep-sea management efforts[7]. However, it is important to consider people's preferences when developing such projects to ensure public awareness and support (O'Connor et al., 2021). Here, we observed that people in Costa Rica tend to care the most about the biodiversity value of deep-sea ecosystems. This is important because while the value of a seep as a commercial fisheries habitat might be estimable by a production function approach, as might be the value of the seep in terms of mitigating carbon, an analysis that fails to consider existence value defined in terms of endemic species, omits the biggest of these three factors expressed in monetary terms. Our more qualitative work helps illustrate that respondents perceived the good they would get if the protection policy was implemented: a fascination with or the wonderment of the strange creatures of the dark, deep sea and the thought that society should also be willing to give up something monetarily to help ensure they continued to thrive offshore in Costa Rica. Specific wordings by respondents and information about the knowledge held by different segments of the population can be helpful in developing programs concerning methane seeps, and effectively communicating with those segments of the public.

Finally, WTP values can be used as inputs in cost-benefit analyses associated with policies affecting marine biodiversity and resources. The cost-benefit framework informs trade-offs between the costs of an activity and the benefits to the public given different levels of protection (Lew, 2015). For example, a study estimated that the costs and time required to restore the habitat and fauna associated with deep-seabed mining of polymetallic nodules would result in a significant reduction in profitability (Sumaila et al., 2023).[8] The benefits of such restoration, however, could also be large and would be informed by the WTP values estimated here. Related, WTP values of the type we provide also play a key role in natural resource damage assessment, where restoration action needs to provide services of the same type, quality, and value of those lost (NOAA, 1996).

4.4. People do care about the deep sea, and the importance of science communication

Although WTP studies help us understand whether (and how much) people are willing to pay for deep-sea conservation, it is unclear how they contribute to people's perception of the deep sea (Jamieson et al., 2022) and to what degree WTP is largely motived by the notion of care advanced by some researchers looking at deep-sea protection issues (Armstrong et al., 2022). To try to elucidate these aspects, we incorporated other sets of questions in our survey. First, we followed a common survey practice for qualitative exploratory analysis by asking respondents for the first thing they thought about when they hear the words "deep sea" before we had provided respondents with any specific information about the deep sea. Jamieson et al. (2020) argues that the deep sea is often associated with feelings of thalassophobia, "deepest darkest fears", monsters, the unknown, and that there is an anthropocentric disconnect. Indeed, these were concepts mentioned by respondents as their first thoughts of the deep sea, including "dangerous waters" [*agua peligrosa*] and "fear" [*miedo*]. However, these were in the minority ($n = 10$), and the answers regarding mysteries and the unknown ($n = 31$) were rather positive, e.g., "a very respected place in the world due to its mysteries" [*un lugar del mundo muy respectable debido a su enorme misterio*], "a world to be discovered" [*un mundo por descubrir*], "an adventure with many mysteries" [*una aventura con muchos misterioso*], and "habitat for many species that remain to be discovered" [*habitat de muchas especies por conocer*]. The anthropocentric disconnect was also present but rather as a place that is distant ("away from the coast" [*más adentro que de la costa*], "into the ocean" [*el mar adentro*]), deep ("very deep" [*muy hondo, gran profundidad*], "below the waves" [*debajo de las olas*]), and dark ("where you cannot see" [*no se ve nada*], [*oscuro*]), which are not wrong in their essence. Some even recognized the need for specialized equipment to reach the deep ocean ("where it is hard to get to" [*donde es difícil llegar*], "where humans can't reach under their own means" [*donde el ser humano no es capaz de llegar bajo sus proprios medios*]). A lack of intimacy, relatability, and common ground that people tend to feel toward deep-sea animals (Jamieson et al., 2020) also proved not to be the case with our respondents. Animals mentioned included sharks, crabs, tuna, and whales, which are more familiar than

[7] In practice, done through executive/legislative actions that sets agency budgets and mandate actions.

[8] The restoration costs here were based on shallow-water ecosystem restoration and on the costs to develop and deploy artificial nodules; there is no evidence that such restoration would be successful. https://planet-tracker.org/the-sky-high-cost-of-deep-sea-mining/

some other deep-sea species examples portrayed in the media. Lastly, it seems that the idea that the deep sea is to be feared might be fading, and people are seeing it for its "beauties" [*belleza, incredible, hermoso*], "valuable assets" [*son nuestras riquezas marinas*], "diversity and natural richness" [*diversidad y riquezas naturales*], as an "exciting adventure" [*aventura emocionante*], "peaceful" [*paz*], and in a respondent's own words, "each sense that it [the deep sea] captures is a door of well-being, but it is imperative that the sea becomes that infinite balm for our mind" [*cada sentido que lo capta es una puerta de bienestar pero se impone que el mar se convierte en ese bálsamo infinito para nuestra mente*].

From these responses, it is clear that perceptions about the deep sea are not necessarily negative. This impression is later supported by the results from our DCE tradeoff analysis reported above which shows that most respondents are willing to pay non-trivial amounts for helping to ensure deep-sea conservation. But is this the same thing as "care"? The definition of "care" in the Oxford dictionary is "the provision of what is necessary for the health, welfare, maintenance, and protection of someone, or something", "feel concern or interest; attach importance to something", and "look after and provide for the needs of". In the economics/environmental philosophy literature, "care" has been used to define "environmental stewardship":

> The actions taken by individuals, groups, or networks of actors, with various motivations and levels of capacity, to protect, care for or responsibly use the environment in pursuit of environmental and/or social outcomes in diverse social-ecological contexts (Bennett et al., 2018).

Stewardship actions can operate directly (e.g., establishment of protected areas) or indirectly (e.g., environmental education) and happen at different scales, from individual species to entire ecosystems (Bennett et al., 2018). Motivation for stewardship actions has been increasingly connected to relationships between human and non-human life, or "relational values". These refer to a sense of connection, kinship, and identity that people develop to other living things and the desire to look after something (West et al., 2018). Respondents in our survey ranked provision of habitat and biodiversity as their most important connection to the deep sea, and the majority (> 80%) agreed with statements that deep-sea ecosystems should be protected so they can personally have the option to use or see them in the future, for the benefit of their children and future generations, and because they represent a unique and fragile ecosystem that has a right to exist. What is valuing the protection of an ecosystem and attaching importance and a connection to it if not care and stewardship?

The question that remains open is whether "knowledge of the deep sea encourages care, or at least reduces fear" (Armstrong et al., 2022). Fear of the deep sea and lack of care may be attributed to lack of knowledge. At the same time, fear can be a barrier for effective deep-sea science communication (Jamieson et al., 2022). Our survey results indicate that people tend to be more prone to conservation actions and have a higher WTP when they have more knowledge, but interestingly, also that their self-perception of their own knowledge might be underestimated. Jamieson et al. (2020) introduces an interesting discussion of how deep-sea scientists tend to diminish how much we know about the deep sea. It is understandable then that people would also think that they do not know much about the deep sea, especially when science is traditionally communicated through peer-reviewed publications written in technical language and not always with free access (Mea et al., 2016).

Science communication, outreach efforts, community engagement and incorporation of traditional knowledge can help scientists amplify the impact of the research, reach key audiences, improve access to science, and increase literacy (Shanley and López, 2009; Escobar-Briones and Álvarez-Sánchez, 2023). Engagement of the public in deep-sea research can also contribute to informed citizen input to policy, have a positive effect on generating support for deep-sea conservation, and can influence economic decisions (LaRiviere et al., 2014; O'Connor et al., 2021; Escobar-Briones and Álvarez-Sánchez, 2023). In past years, there has been a general increased interest in communication efforts from the academic community (Rose et al., 2020). Within the deep-sea science community, scientists are also changing how they communicate, highlighting the importance, values, and fascinating aspects of the deep sea, and encouraging people to create a connection to the deep sea (Jamieson et al., 2020; Jamieson et al., 2022).

Recent advancements in technology allow for deep-sea scientists to engage with the public in real-time exploration of the deep sea through livestream of remotely operated vehicle video (e.g., telepresence by NOAA Ocean Exploration Trust and Schmidt Ocean Institute) (Gallaudet et al., 2020), and for the public to interact with live deep-sea animals in aquariums (e.g., Monterey Bay Aquarium "Into the Deep: Exploring Our Undiscovered Ocean" exhibition that opened in 2022). Virtual reality, ocean digital twins, and virtual representations of the environments have also been evolving as tools that can be used in deep-sea science communication (see Burke and Crocker, 2020; Hruby et al., 2020). Finally, deep-sea scientists and institutions are also engaging more with social media and featuring art exhibitions showcasing the deep sea including a photographic exhibition in metro stations in Bilbao, Spain, in 2023, and the exhibition "Painting the Deep" by the artist Lily Simonson at the Harvard Museum of Natural History in 2019. These virtual and in-person forms of communication are effective to improve feelings of thalassophobia, perspectivism, and phenomenology described by Jamieson et al. (2020), and to create relatability and help develop personal connections to the deep sea.

5. Conclusion

Our study is the first to estimate Costa Rican's WTP for protection of a marine ecosystem. It is also the first WTP study, globally, for a methane seep or for any chemosynthetic ecosystem. A key demonstration here is the possibility of designing effective valuation surveys for novel marine ecosystems that have thus far been neglected. For future studies in countries where very little prior research exists, we recommend that the survey and DCE include other ecosystems that may be more well-studied, and more relatable to respondents, as a means for additional comparison.

The work reported here shows Costa Ricans support protection of methane seeps off their coast. Strikingly, our respondents had the highest willingness to pay for programs that protect endemic seep species. Changes that enhanced climate change mitigation and commercial fishing habitat were also associated with substantial economic value, although notably smaller than that for protecting endemic seep species. Respondent willingness to pay increases with prior knowledge about the deep sea, suggesting a key role for science education in driving public willingness to monetarily support government actions to protect key ecosystem services in Costa Rica. Current management tools used for deep-sea ecosystems such as EBSAs and VMEs still need to incorporate non-use values as a criterion. Our approach can be seen as one way to rigorously demonstrate the value of a cultural resource in the deep-sea environment. Moreover, continued science communication and outreach efforts from the deep-sea science community can contribute to a more engaged and informed population that will in turn provide further input to policy. Our results indicate that both policymakers and scientists should put new weight on the role of deep-sea literacy and existence values, which together underpin economic willingness to pay and the potential success of deep-sea management programs.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2024.108228.

Funding sources

This work was supported by the Ferguson Family Award 2021/2022 and the Friends of the International Center Fellowship 2022 awarded to OSP. OSP received additional support from the Program for Interdisciplinary Environmental Research PhD fellowship during survey development and implementation. NSF OCE 2048720 supported OSP and LAL during manuscript preparation. Foundational Research on Costa Rican methane seeps was provided by NSF OCE 0939557 and OCE 1634172.

CRediT authorship contribution statement

Olívia S. Pereira: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mark Jacobsen:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Richard Carson:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Data curation. **Jorge Cortés:** Writing – review & editing, Validation, Resources. **Lisa A. Levin:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

We thank E. Brazier for the help with survey design, J.C. Azofeifa-Solano and M. Guraieb for the help with translating the survey to Spanish, and S. Cambronero and D. González for the help with setting the price levels. Special thanks to D. Vlach, J. Gonzalez, A. Pezner, S. Matthews, K. Mullane, A. Munro, C. Robles, S. Cook, R. Darling, I. Soares, and G. Pereira for providing feedback on the survey prior to the final design. We also thank the Office of IRB Administration at UC San Diego for the help with the IRB application. Photos in the choice cards were provided by ROV SuBastian/Schmidt Ocean Institute (FK190106/ Chief Scientist Eric Cordes), and Ocean Exploration Trust, NAO066). We thank the anonymous reviewers for their comments that helped us improve our manuscript.

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