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REVIEW AND SYNTHESIS

Disentangling global market drivers for cephalopods to foster transformations towards sustainable seafood systems

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Abstract

1. Aquatic food systems are important contributors to global food security to satisfy an intensifying demand for protein-based diets, but global economic growth threatens marine systems. Cephalopod (octopus, squid and cuttlefish) fisheries can contribute to food security; however, their sustainable exploitation requires understanding connections between nature's contributions to people (NCP), food system policies and human wellbeing.
2. Our global literature review methodology examined what is known about cephalopod food systems, value chains and supply chains, and associated market drivers. For analysis, we followed the IPBES conceptual framework to build a map of the links between cephalopod market drivers, NCP and good quality of life (GQL). Then we mapped cephalopod food system dynamics onto IPBES (in)direct drivers of change relating to catch, trade and consumption.
3. This research contributes knowledge about key factors relating to cephalopods that can support transitions towards increased food security: the value of new aquatic food species; food safety and authenticity systems; place-based innovations and empowerment of communities; and consumer behaviour, lifestyle and motivations for better health and environmental sustainability along the food value chain. We outline requirements for a sustainable, equitable cephalopod food system policy landscape that values nature's contributions to people, considers UN Sustainable Development Goals and emphasises the role of seven overlapping IPBES (in)direct drivers of change: Economic, Governance, Sociocultural and Socio-psychological, Technological, Direct Exploitation, Natural Processes and Pollution. We present a novel market-based adaptation of the IPBES conceptual

framework—our 'cephalopod food system framework', to represent how the cephalopod food system functions and how it can inform processes to improve sustainability and equity of the cephalopod food system.

4. This synthesised knowledge provides the basis for diagnosing opportunities (e.g. high demand for products) and constraints (e.g. lack of data about how supply chain drivers link to cephalopod NCP) to be considered regarding the role of cephalopods in transformations towards a resilient and more diversified seafood production system. This social–ecological systems approach could apply to other wild harvest commodities with implications for diverse marine species and ecosystems and can inform those working to deliver marine and terrestrial food security while preserving biodiversity.

KEYWORDS
diet, metasynthesis, nature's contributions to people, policy, seafood, trade

1 | INTRODUCTION

Achieving food security and biodiversity conservation are interconnected challenges operating across international pathways (Crenna et al., 2019; Fischer et al., 2017). Food and nutrition connect most of the United Nations Sustainable Development Goals (SDGs) (Grosso et al., 2020; Rockström & Sukhdev, 2016) and the aims of eliminating hunger, achieving food security and improving the health, nutrition and wellbeing of the world's population (SDG 2, 3) are linked to natural resource use (e.g. SDG 12, 14) (UN, 2015; UNEP, 2016). Equally, reversing biodiversity loss depends on transformative action towards sustainable value chains and food systems (CBD, 2021). Achieving these aims requires a globally coordinated, evidence-based and transformative governance approach to future-proof nutrition security via sustainable and accessible food systems (EC, 2021; EEA, 2016). We define food systems here following HLPE (2017) as the collection of activities linking production to consumption across the food supply chain.

Transformative food system studies have typically focused on the agricultural sector (FAO, UNDP and UNEP, 2021). However, the fisheries and aquaculture sectors must also be considered, as they are essential to satisfy an intensifying demand for fish-based diets (SCAR-FISH, 2019), can improve opportunities for availability, access, utilisation and stability of food resources (FAO, 2022) and can have lower carbon footprints than other food systems (Bianchi et al., 2022; Gephart et al., 2021).

Critical reasons for transforming marine food systems include that world production of fish has risen dramatically in recent decades to meet increasing consumption demands (World Bank, 2013) while around 92.7% of global fish stocks are already maximally sustainably fished or overfished (FAO, 2022). Meanwhile, modern neoliberal policies of capitalism and associated development in 162 nations across the globe comprising the majority of the world's population threaten marine systems as nations' fisheries footprints and seafood consumption increase (Clark et al., 2018).

Food systems and their outcomes can be measured by indicators relating to ecosystem health, social wellbeing and food security (HLPE, 2014). Many existing food systems are linked to poor health and environmental degradation (Willett et al., 2019). Transformation, an inherently political process, aims to fundamentally improve the structure, functions and actor relations within a social–ecological system (Hebinck et al., 2018; Villasante, Tubío, Gianelli, et al., 2021).

Pathways for transformation include building a shared understanding of food systems and their outcomes and building on efforts to develop and operationalise the 'nature's contributions to people' (NCP) approach as a common language between ecosystems and human benefits (EEA, 2016). Such relationships are increasingly being interpreted through lenses such as the IPBES conceptual framework which conceptualises ecosystem services as NCP (IPBES, 2019).

Consumption of cephalopods (octopus, squid and cuttlefish) has historical and cultural importance across the world and cephalopod fisheries are globally distributed and locally exploited resources that can contribute to food security. World-wide, cephalopod fisheries have rapidly expanded over the last 50 years, from approximately 99,100 tonnes in 1970 to 374,200 tonnes in 2020 (FishStatJ, 2020), and have moved into new fishing areas to match growing market demand (Arkhipkin et al., 2015; Jereb et al., 2011). The global network for cephalopod trade involves around 220 countries, dominated by eight countries in Asia (China, India, Republic of Korea, Thailand, Vietnam), Europe (Netherlands, Spain) and the United States (Ospina-Alvarez et al., 2022).

Cephalopods are targeted by large- and small-scale fisheries and caught as by-catch (Rodhouse et al., 2014), while recreational fishing is also significant (ICES, 2020). However, cephalopods are understudied compared to other commercially valuable species, and fisheries tend to be minimally managed (Arkhipkin et al., 2020; Markaida & Gilly, 2016; Pierce & Portela, 2014). This is likely related to unique life-history characteristics along with inadequate fisheries data, infrastructure and resources to conduct routine stock assessments which challenge sustainable management (Arkhipkin et al., 2020; Pierce & Portela, 2014). A short life cycle implies nonoverlapping generations which offers no buffer if recruitment fails or recruits are fished out, there is high year-to-year variability in abundance and probably also in distribution, reflecting sensitivity to changes in environmental conditions (Arkhipkin et al., 2020). There have been marked fluctuations in population abundance with no general upward trend during the last decade (Doubleday et al., 2016). Importantly, total annual landings are highly sensitive to the status of several squid stocks, notably those of *Dosidicus gigas* and *Illex argentinus* (Villasante et al., 2014), which experienced sharp declines in 2016 and have subsequently increased again (FAO, 2020b). Fluctuations in Chinese coastal cephalopod populations have been associated with environmental variations linked to marine ecosystem regime shift and/or climate change (Pang et al., 2018). Sustainable exploitation of cephalopod fisheries requires understanding connections between NCP food system policies and human wellbeing.

Ecosystem-based fisheries management (EBFM) (e.g. the reformed Common Fisheries Policy [CFP]) necessitates consideration of trade-offs among services provided by the oceans and prioritises the wellbeing of ecosystems over economic and social objectives (Baudron et al., 2019). Since cephalopods provide both provisioning (e.g. commodity) and supporting (e.g. keystone predator and prey species) services, caution is required regarding their removal (Essington & Munch, 2014; Hunsicker et al., 2010; Pierce & Portela, 2014), and ecosystems where cephalopods are targeted require further evaluation to prevent the unsustainable development of fisheries within them and potential conflicts among cephalopod and finfish fisheries (Hunsicker et al., 2010). Fishing for cephalopods could contribute more towards sustainable seafood systems if drivers (the major forces) influencing the catch, trade and consumption of cephalopods were better understood and successfully managed in the context of the NCP they provide. Many previous studies of cephalopods have focused on their role in the ecosystem or as human commodities but to the best of our knowledge no studies have examined which drivers affect cephalopod markets or how supply chain drivers link to cephalopod NCP.

Our global literature review of prevailing research interests addresses this major knowledge gap by examining what is known about cephalopod food systems, value and supply chains, and associated market drivers. We collected evidence to build a map of the links between cephalopod market drivers, NCP and good quality of life (GQL), applying the IPBES conceptual framework. We believe this synthesised knowledge can provide the basis for diagnosing opportunities and constraints to be considered in the transformation towards a resilient and more diversified seafood production system. The approach and findings will be helpful for policy actors, practitioners, researchers and professionals working on marine and terrestrial food security as well as seafood and marine environmental sustainability.

2 | METHODS

We conducted a global review of scientific literature published in English relating to cephalopod market drivers. Drivers were explained by indicators that influenced market dynamics in positive, negative, neutral or ambivalent directions with respect to different market actors (e.g. relating to market growth/consumer acceptance for a given species or product). Our social science methodology followed an inductive analytical approach whereby we interpreted and drew insight from themes emerging from the literature to develop a theory as opposed to using a predefined hypothesis that was then tested through the observations collected.

We developed our conceptual system based on the existing IPBES conceptual framework and applied it to identify objectives for a sustainable cephalopod food system. The IPBES framework consists of six interlinked elements of society and nature operating at various spatial and temporal scales which aim to link people and nature (Figure 1). Principal features of this approach include: centralising institutions as key drivers of change; considering different knowledge systems; coproducing NCP; and including plural values and interests (IPBES, 2019). GQL comprises human wellbeing and other analogous concepts and consists of various material and non-material dimensions linked to nature and NCP (Díaz et al., 2015).

2.1 | Data collection

The literature selection criteria aimed to ensure that peer-reviewed publications (e.g. scientific articles, reports, book chapters) were about cephalopods, and their catch, trade or consumption. We developed a preliminary search string of terms relevant to cephalopods, markets and anticipated drivers, which we trialled and adjusted to retrieve the maximum number of relevant records. We then developed a customised, a priori protocol (Appendix S1) based on Arton et al. (2020), which we used to agree on the review scope, research questions and protocol and to define our search terms, eligibility criteria, data analysis parameters, etc.

We conducted two literature searches on topics (title + abstract + keywords) in Web of Science Core Collection (1985–2020; English) and Scopus databases. The first search (November 2019) employed the following search terms: (cephalopod* OR octopus* OR squid* OR cuttlefish*) AND (market*) AND (driver* OR institution* OR regulation* OR manage* OR social-ecological OR socialecological OR socio-ecological OR socioecological OR social-environmental OR socialenvironmental OR socio-environmental OR socioenvironmental OR socio-economic OR socioeconomic OR social-economic OR socialeconomic OR technolog* OR cultur* OR govern* OR climate OR pollution OR invasive* OR bycatch* OR by-catch* OR discard* OR catch* OR caught OR consum* OR trad* OR import* OR export* OR demand* OR supply* OR sustainab*).

We based our second search (August 2020) on the SPIDER tool (Cooke et al., 2012) to capture studies missed by the first search, especially qualitative social science research which can be inconsistently indexed by literature databases. We included the search terms above which equated to sample (S) and phenomenon of interest (PI) in the SPIDER format, with new terms for study design (D) (e.g. questionnaire), evaluation (E) (e.g. attitude) and type of research (R) (e.g.

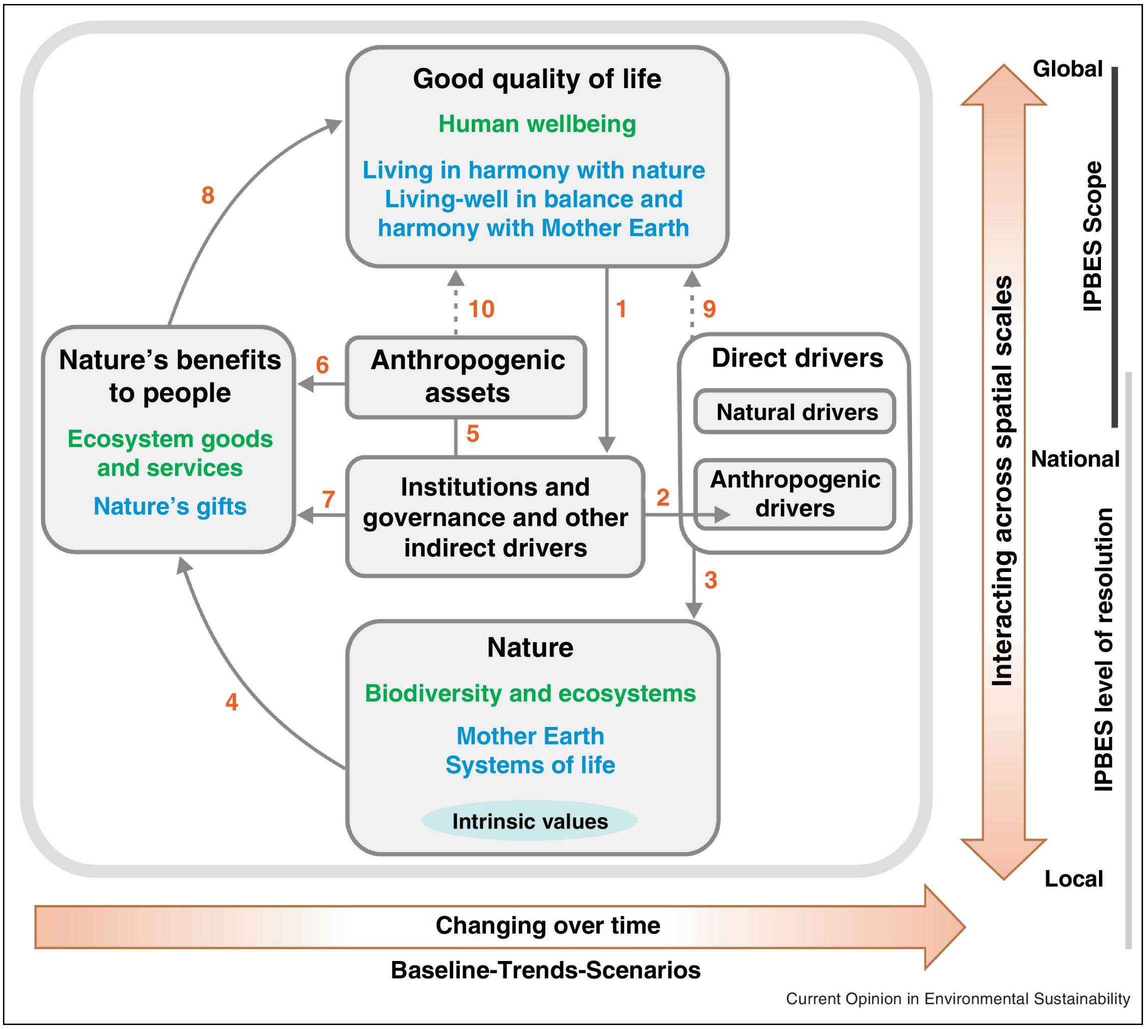

FIGURE 1 IPBES conceptual framework (IPBES, 2019). Boxes and arrows in the central panel denote the elements of nature and society that are the main focus of the Platform. In each box, the headlines in black are inclusive categories that embrace western science (in green) and equivalent or similar categories according to other knowledge systems (in blue). Solid arrows in the main panel denote influence between elements; the dotted arrows denote links that are acknowledged as important but are not the main focus of the Platform.

qualitative) (Appendix S1). We trialled the string suggested by Cooke et al. (2012) ('S AND PI AND D OR E OR R') but 'S AND PI **OR** D OR E OR R' was most effective.

2.2 | Data analysis

We followed PRISMA guidelines regarding record screening, eligibility and inclusion (Moher et al., 2009). The analysis was complicated by literature deriving from numerous disciplinary epistemologies with studies broaching the topic from sometimes oblique perspectives (i.e. investigating cephalopods or their markets was not always the primary objective of the research). We created an online, multi-user data extraction form to systematically capture, compare, code and analyse qualitative and quantitative data from records based on a form developed by Wolf et al. (2017).

To pilot the data extraction process, we chose two records from different research disciplines which all reviewers coded to assess consistency among reviewers regarding interpretation of the data extraction process, compare coding results and test the extraction form. This revealed important variations in data extraction between studies and reviewers.

We adjusted the form and agreed on the data extraction process then distributed eligible records among reviewers according to broad thematic categories and areas of expertise. Most records were analysed by a single reviewer, except in the case of doubts when the lead author assisted.

Qualitative data were directly copied from records into the form (e.g. for specific drivers investigated). These data were analysed qualitatively to identify common themes, emerging patterns and outlying themes of interest.

For quantitative analysis, reviewers coded study data to identify methodological characteristics of the articles studied (Figure 2). Next, we coded the data using 51 indicators we created inductively based on our collective knowledge of the subject matter, preliminary reading of literature and piloting. Indicators were categorised as

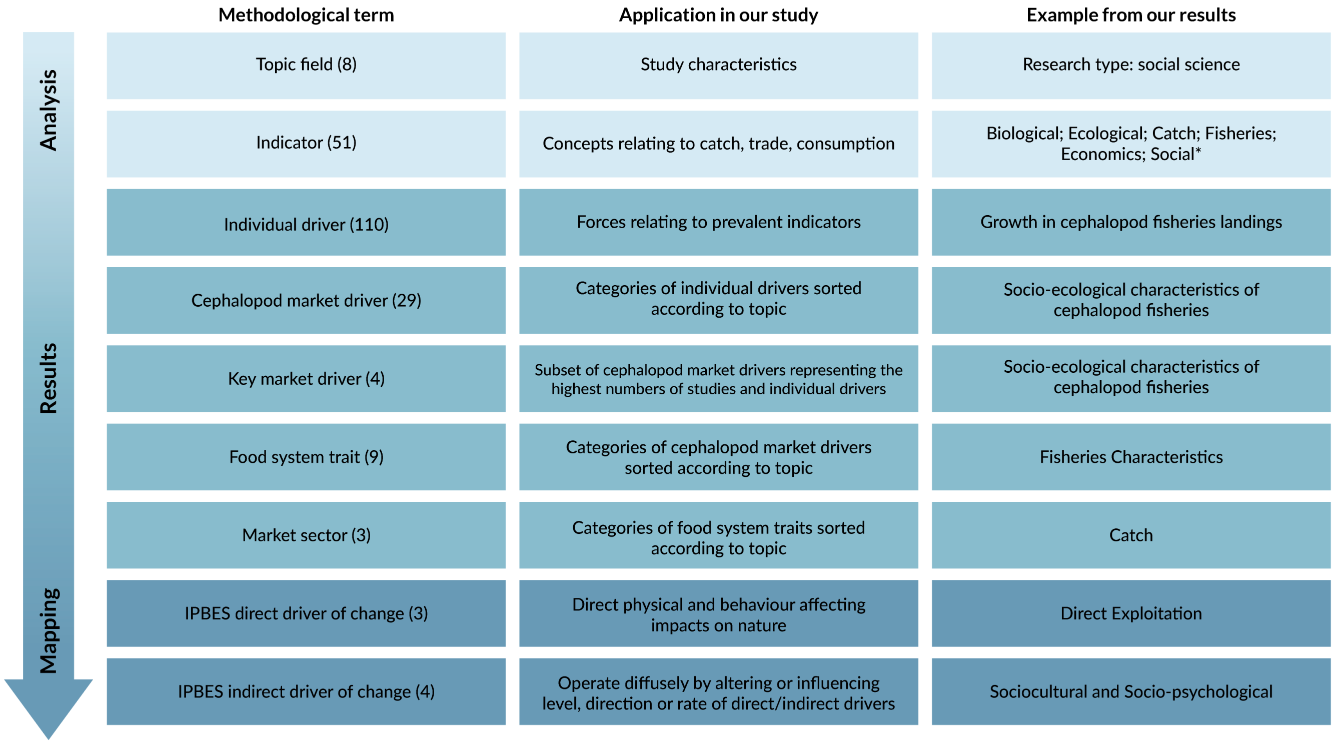

FIGURE 2 Flowchart of the methodological terms and steps applied in the study. *Full list of indicators includes: Biological (distribution/abundance); Ecological (environmental conditions, geographic layout of fishing grounds); Harvest (by-catch, cephalopod species, fishing effort, gear type, landings, noncephalopod species, stock assessment); Fisheries (fishing tactics, fishing traditions, fishery type); Economics (demand, domestic trade, exports, imports, international trade, supply, volume); Social (markets).

follows: Biological (5 indicators), Harvest (8), Climatic (2), Ecological (5), Economics (9), Environmental Contaminants (2), Fisheries (3), Governance (3), Food Health and Safety (7), Food Quality (1), Social (5) (Figure 2; Appendix S1). To address the strength of evidence regarding presence of indicators, reviewers coded data as: 0 = topic not mentioned; 1 = mentioned; 2 = alluded to. Where an indicator for a driver was coded as 1, we calculated what percentage of the overall coding these 1s accounted for, within that indicator and driver, using this scale: 0%–35% = weak evidence; 36%–70% = medium; 71%–100% = high. We highlight in brackets any occurrences of 'weak' or 'medium' evidence.

Next, we examined study objectives to identify individual drivers discussed, which were then sorted by theme into 'cephalopod market drivers' and analysed qualitatively (Figure 2). Market drivers were sorted into generic groups called 'food system traits' which were further sorted into market sectors (Section 3.2.1). We quantitatively calculated the proportion of individual drivers mentioning a supply chain element/value chain actor within each food system trait (Section 3.2.2). 'Key market drivers' (Figure 2) representing the highest numbers of studies and individual drivers were analysed by calculating which individual indicators were reported most frequently (i.e. indicators were reported in 50% or more of the studies included within a key market driver) and comparing these with the most frequently reported indicators for all cephalopod market drivers combined (Section 3.2.3). Unless otherwise stated, percentages cited refer to the percentage of individual drivers.

2.3 | Mapping data to the IPBES conceptual framework

To interpret our results we conducted various steps whereby we mapped our findings onto elements of the IPBES conceptual framework (Figure 3; see also Figure 8). To better understand relationships between cephalopod market drivers, NCP and GQL, we mapped key findings onto elements of the framework by associating common themes (e.g. we associated our indicator categories with a corresponding IPBES (in)direct driver of change) (IPBES, 2019, Chapter 1 Supplementary materials) (Section 3.3). To better understand the cephalopod food system and situate our findings within a socio-ecological system, we explored broad associations in meaning and content within market sectors between our indicator categories, food system traits and market drivers, and linked these with relevant IPBES (in)direct drivers of change. To fine-tune our understanding of the socio-ecological dynamics of the cephalopod food system, we mapped the most frequently reported indicators for the key market drivers by topic to the IPBES (in)direct drivers of change. To highlight similarities and differences in how the key drivers were operationalised, we calculated what proportion of individual drivers each indicator category

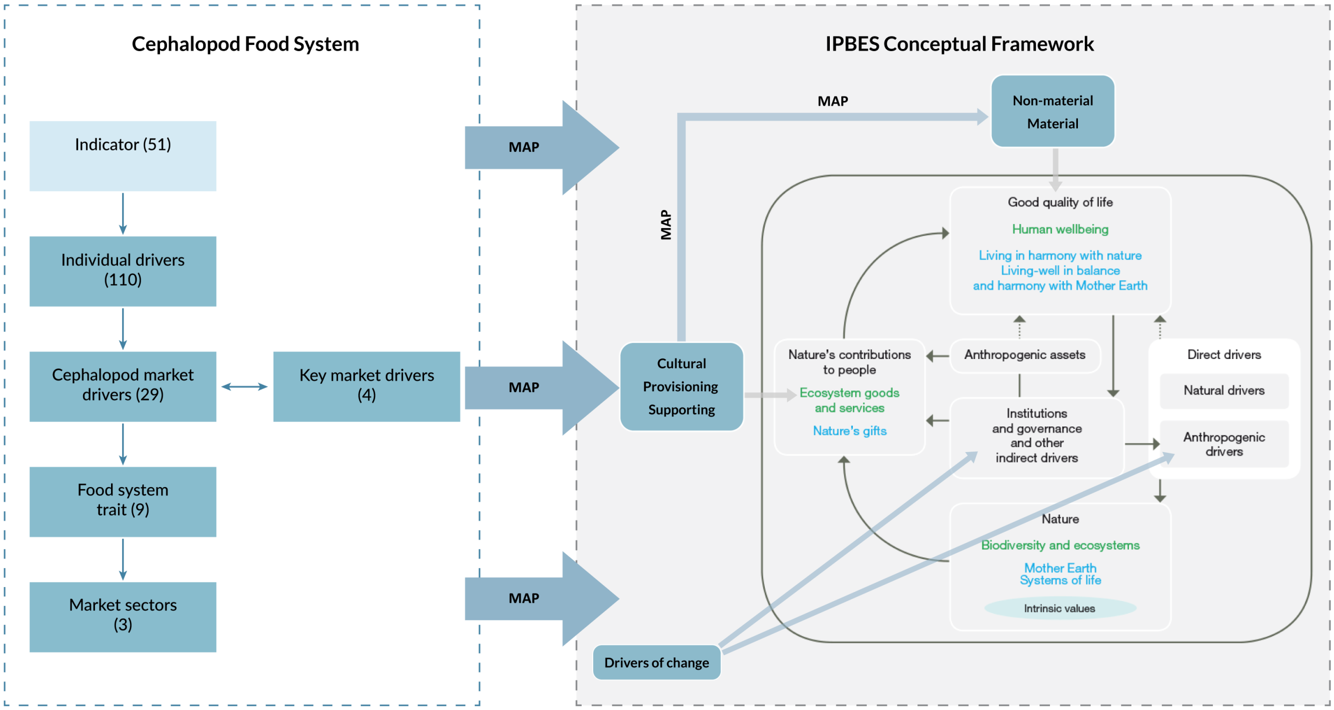

FIGURE 3 Diagram representing the process used to interpret this study's key findings by mapping data from the cephalopod food system onto elements of the IPBES conceptual framework. The arrow between 'Cultural, Supporting, Provisioning' and 'Material, Nonmaterial' indicates that we conducted an additional mapping step to identify which specific dimensions of GQL were applicable to the NCP provided by cephalopods.

represented for each key driver and grouped these according to their associated IPBES (in)direct driver of change (Section 3.4).

2.4 | Study limitations and methodological issues

Where possible, we addressed known problems of literature reviews such as bias (Haddaway et al., 2020; McKinnon et al., 2015). However, it is likely we did not capture all relevant records, partly due to the way that studies are indexed in the two databases we searched. Also, we elected not to include grey literature in the formal review, nor did we include literature in languages other than English, both of which are potentially rich sources of further information but beyond the scope of our study and likely resulted in a geographic skew of studies synthesised. The number of publications on different topics reflects the outcome of interactions between researcher interests, availability of funding and journal policies.

It was evident that many papers referred only tangentially to markets and in several cases (e.g. the papers on contaminants in cephalopods mentioning markets) are a subset of a larger body of similar work. Thus, where market drivers have been identified in these papers it should be borne in mind that the literature on these drivers is considerably broader. Further work could involve using these drivers as the starting point (the search terms) for a follow-up review.

Other considerations include the limits of current knowledge on abundance and fluctuation in the availability of cephalopods, and emerging issues like climate change. Additional study limitations, methodological issues, knowledge gaps and research needs which may inform future similar studies are described in Appendix S2 (see Section 'Data Sources' below for all S2 references).

3 | RESULTS

3.1 | Search results and study characteristics

Search 1 and 2 captured 1119 records (Appendix S3). We screened titles and abstracts and removed duplicates and ineligible records (i.e. from unrelated disciplines, did not refer to key terms in our definition of drivers or full texts were not published in English). Neither search revealed an existing metasynthesis of relevant literature.

The 101 studies coded and analysed were published between 1979 and 2020 (50% since 2013). They featured 27 countries, most frequently: the United States (18 studies), Italy (14), Spain (10), Portugal (6), South Korea (6) and Greece (4), and three ocean areas: North-east Atlantic, Mid-Atlantic and Eastern Pacific. More studies were regional (37%) in scope, than international (22%), local (18%) or national (14%), while five were global, and one was EU-wide. Most studies included empirical data (76%) and involved food science and technology (44%) (e.g. molecular, microbiological or chemical analyses), social science (42%) (e.g. socio-ecological analyses of fisheries, socio-economic analyses of markets) or fisheries science (14%) (e.g. aquaculture/capture fishery biology, ecology, technology). The studies represented diverse research disciplines, methodologies and topics ranging from ecology of cephalopods to market characteristics and together represent available knowledge published in English about the cephalopod food system.

Squid were studied most frequently (70%), followed by octopus (49%), cuttlefish (32%) and 'undetermined' (10%). Overall, cephalopods were more often studied fresh (68%) rather than processed (38%) or frozen (34%), but preparation type varied by cephalopod groups.

3.2 | The cephalopod food system

3.2.1 | Market sectors, food system traits and market drivers

Among the 101 studies analysed (Table 1), we identified three overarching market sectors—catch, trade and consumption, into which we grouped our indicators, along with nine corresponding food system traits identified in the study: Bacterial Contamination/Parasitic Infestation; Biology and Ecology of Stocks; Catch and Landings; Environmental Contamination; Fisheries Characteristics; Fisheries Governance; Food Control, Nutrition and Quality; Market Characteristics; and Product Traceability. We identified 110 individual drivers among study objectives which we grouped by topic into 29 'cephalopod market drivers' (henceforth 'market drivers') (Figure 2; Ainsworth et al., 2023) (e.g. 'volume, value and landings of cephalopod catches'). The review captured more studies and market drivers relating to the catch and consumption sectors than the trade sector. The food system trait Environmental Contamination included most studies overall. The most and least frequently reported indicators overall are shown in Figure 3. Geographic differences existed in research interests among the 29 market drivers (Ainsworth et al., 2023).

Figure 4 demonstrates that the five most frequently reported indicators were: regulations, laws and norms (56%) (Governance); fishery type (50%) (Fisheries); distribution/abundance (49%) (Biological); supply (48%); and demand (45%) (Economics). The least frequently reported indicators were: acidification (0%); climate change (6%) (Climatic); parasites (5%); hygiene (8%) (Food Health and Safety); and role in the value chain (7%) (Social).

3.2.2 | Cephalopod supply and value chains

The cephalopod food system comprised nine principal supply chain components (Table 1; Figure 5). Studies discussed different supply chain components according to the focus of market drivers within each food system trait. Overall, production, consumption, purchasing, processing and stock were prioritised while least attention was paid to distribution, retail, brokerage and ecosystems.

The food system comprised 10 principal types of value chain actors (Table 1; Figure 6). The types of value chain actors discussed varied by food system trait. Most attention was paid to consumers; industrial and small-scale fisheries; processors; fish markets and first buyers. Least attention was paid to brokers, distributors, retailers and aquaculture fisheries. Several 'other' actors as well as regulations and policy documents were also mentioned (Figure 7).

Only three studies conducted value chain analysis, and these were within three food system traits: Market Characteristics (Wamukota et al., 2014); Fisheries Governance (Diedhiou et al., 2019) and Fisheries Characteristics (Coronado et al., 2020).

TABLE 1 Cephalopod market sectors, indicators, food system traits, market drivers, supply chain components and value chain actors studied by literature captured in the review

Market sector	Indicators	Food system trait	No. of cephalopod market drivers (no. of studies)	Supply chain component (% of drivers)	Value chain actor (% of drivers)
Catch	Biological; Ecological; Harvest; Climatic; Fisheries; Governance	Biology and Ecology of Stocks	1 (2)	Ecosystem (11%) Stock (28%) Production (54%)	Small-scale fishery (39%) Industrial fishery (41%) Aquaculture producer (9%)
		Catch and Landings	4 (21)		
		Fisheries Characteristics	4 (13)		
		Fisheries Governance	2 (6)		
Trade	Economics; Social	Market Characteristics	6 (12)	Purchasing (32%) Brokerage (11%; medium) Processing (31%) Distribution (20%) Retail (20%)	First buyer (25%; medium) Fish market (30%; medium) Broker (23%; medium) Processor (32%) Distributor (20%; medium) Retailer (20%)
	Food Health and Safety; Food Quality	Product Traceability	2 (4)		
Consumption	Environmental Contaminants	Bacterial Contamination/ Parasitic Infestation	2 (11)	Consumption (54%)	Consumer (50%)
		Environmental Contamination	4 (22)		
	Food Health and Safety; Food Quality	Food Control, Nutrition and Quality	4 (10)		

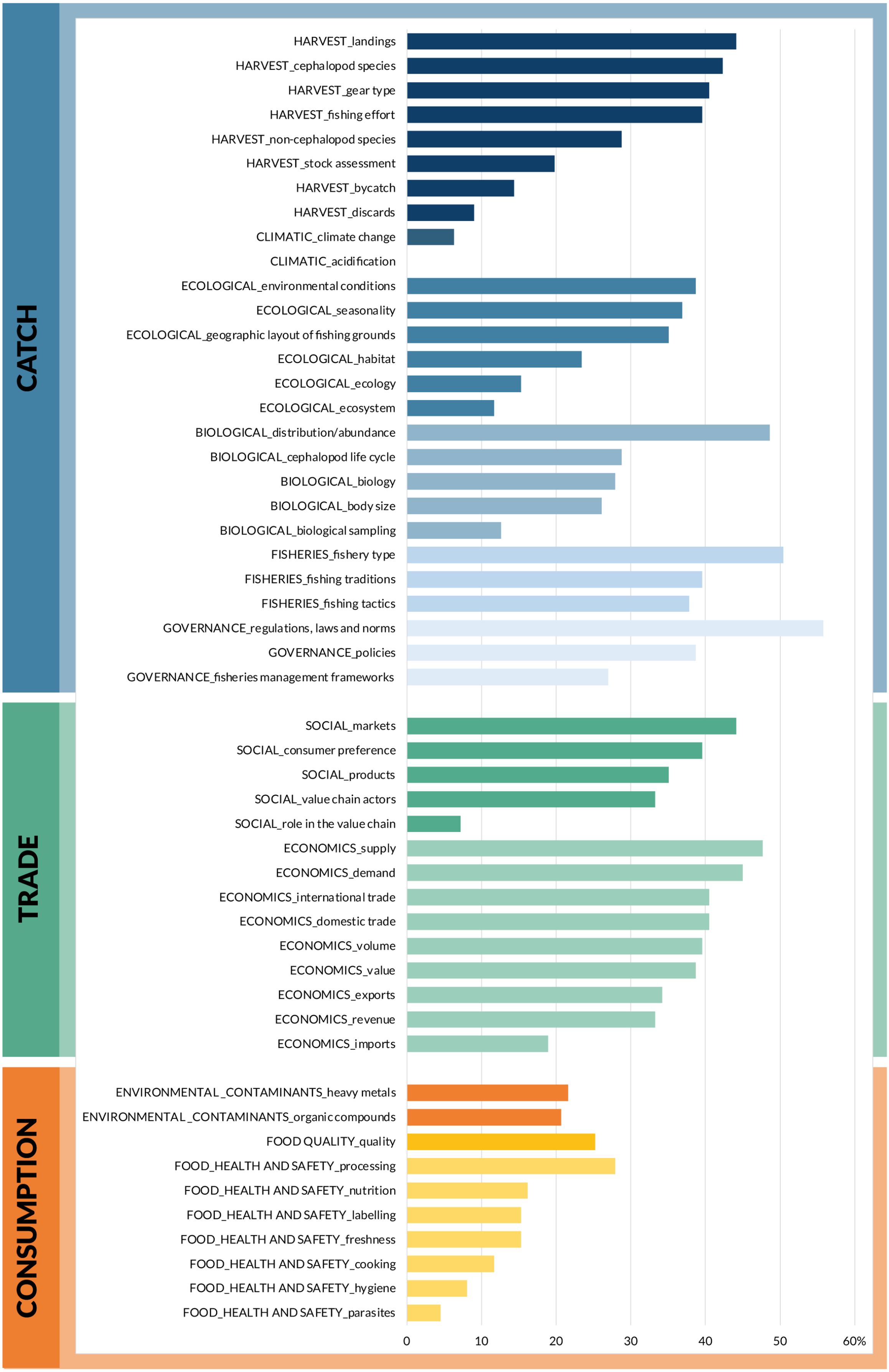

FIGURE 4 Frequency with which the 51 indicators were reported in the literature (blue bars = catch sector-related data, green = trade, orange = consumption).

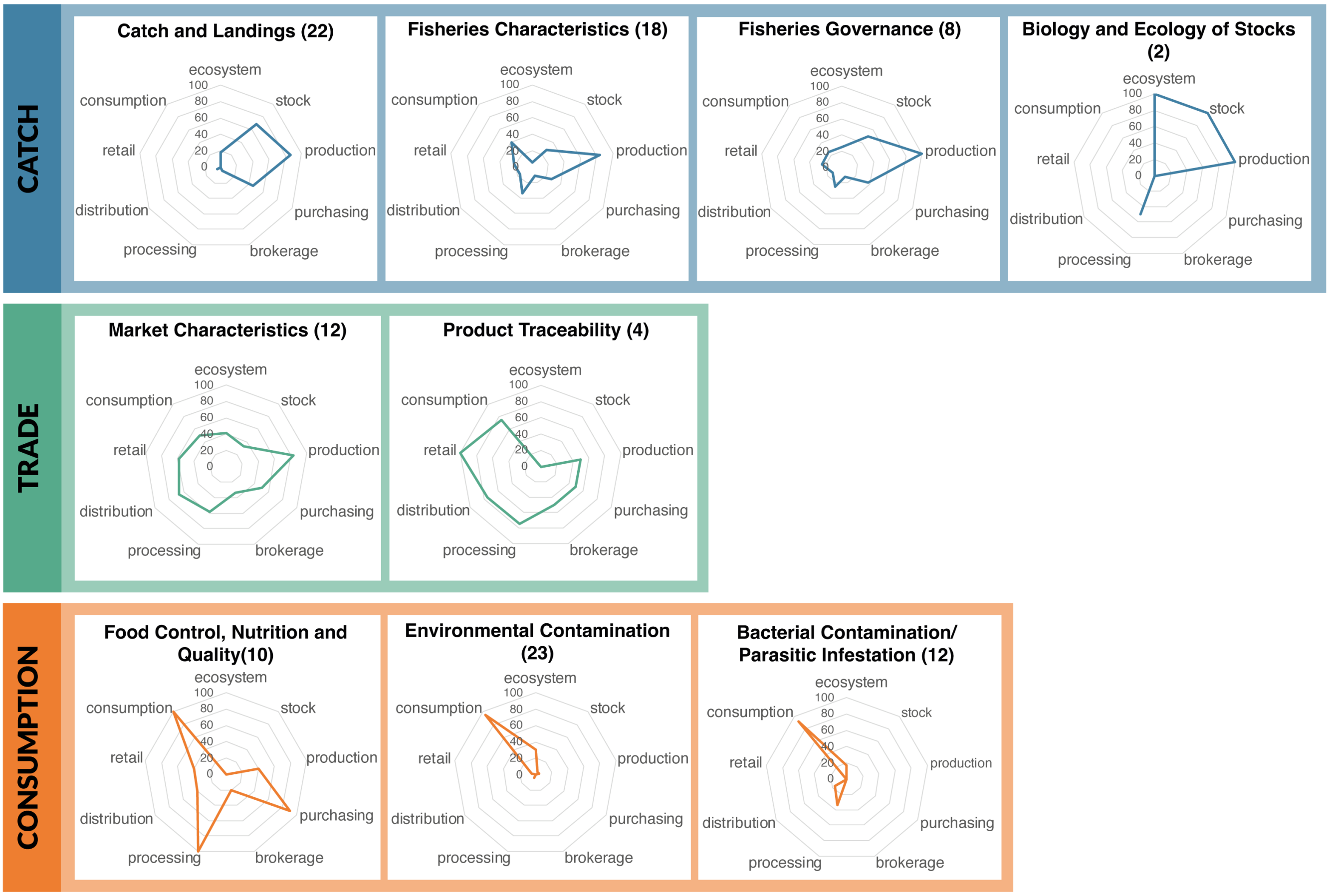

FIGURE 5 Proportion of individual drivers mentioning a supply chain element within each food system trait, showing number of individual drivers in brackets.

Findings revealed that cephalopod value chain structures differ significantly from those of other types of fisheries; for example, larger numbers of actor groups may be involved. Furthermore, income inequalities were found to occur across the chain; with fishers tending to fare worse than other kinds of actors regarding economic and decision-making power (Coronado et al., 2020; Diedhiou et al., 2019; Wamukota et al., 2014).

3.2.3 | Key market drivers

Four 'key market drivers' accounted for 46% of individual drivers and represent the main trends studied by literature captured in the review (Appendix S2). No individual indicators were shared by all four key drivers; however, two indicators—regulations, laws and norms (Governance) and environmental conditions (Ecological)—were frequently reported for three key drivers each.

Two of the key drivers were situated within the catch sector: *socio-ecological characteristics of cephalopod fisheries* (12%) (Fisheries Characteristics) and *volume, value and landings of cephalopod catches* (11%) (Catch and Landings). The characteristics of these two drivers appear distinct but tightly coupled, with several catch-related and trade-related indicator categories being common to both drivers (Figure 8). However, literature associated with the former driver placed greater emphasis on trade, while the latter emphasised catch.

The other two key drivers were situated within the consumption sector: *levels of heavy metal contamination in cephalopod products* (15%) (Environmental Contamination) and *levels of bacterial contamination in cephalopod products* (9%) (Bacterial Contamination/Parasitic Infestation). Although there was some overlap regarding the indicators reported, these key drivers were operationalised differently. Several catch-related, trade-related, trade/consumption-related and consumption-related indicators were common to both drivers, although to varying degrees (Figure 8). Literature associated with *levels of heavy metal contamination in cephalopod products* emphasised catch, while literature about *levels of bacterial contamination in cephalopod products* emphasised trade.

3.3 | Ecosystems, nature's contributions to people and good quality of life

Thirteen studies (11%) referred to the ecosystems that cephalopods inhabit or to ecosystem-based management of cephalopod fisheries. The examples provided (Appendix S2, Table S1) inform how cephalopod market sectors connect with food system traits, market drivers

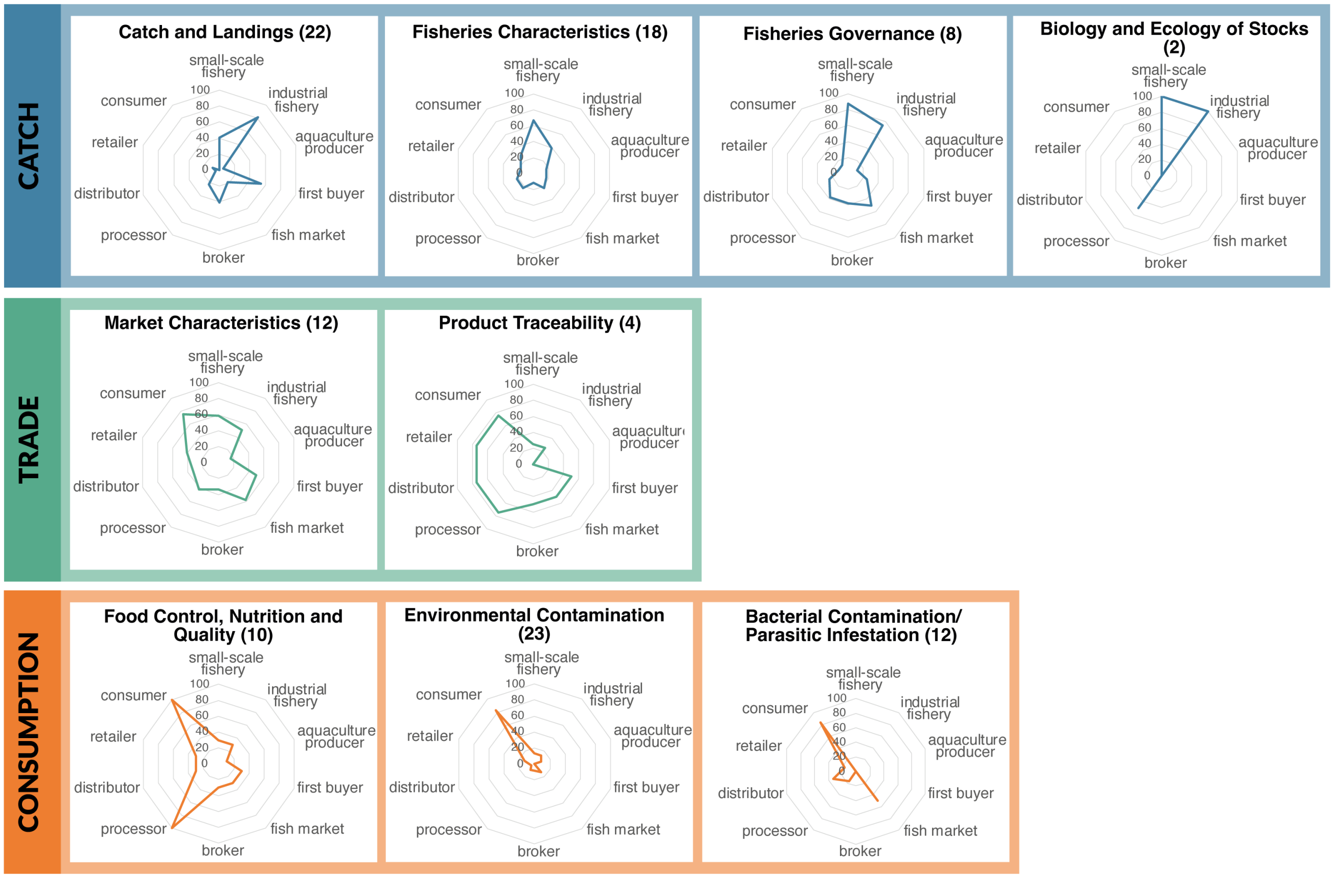

FIGURE 6 Proportion of individual drivers mentioning a value chain actor within each food system trait, showing number of individual drivers in brackets.

CATCH

Catch and Landings: live bait fisheries (6); California Department of Fish and Wildlife (5); recreational fishers/anglers (3); US Department of Fish and Wildlife (2); US Squid Fishery Advisory Committee; US Squid Research and Scientific Committee; US National Park Service

Fisheries Characteristics: professional fisheries associations; collectors; 'free-fishers'; recreational spear fishers; technicians, inspectors, government researchers

Fisheries Governance: fisheries managers and monitoring committees; Falkland Islands Government Fisheries Department; New Zealand Ministry of Primary Industries; California Department of Fish and Wildlife Coastal Pelagic Species teams; Senegal - Local Council for Artisanal Fisheries (LCAFs) and local authorities; restaurants

TRADE

Market Characteristics: tourists (2); fisheries certification schemes; restaurants; shipowners, fishing cooperatives

CONSUMPTION

Bacterial Contamination/Parasitic Infestation: food business operators (2); unlicensed fishers; storage facility operators; official control bodies (e.g. European Commission)

Food Control, Nutrition and Quality: government food safety agencies (4); policymakers (4); restaurants; pharmaceutical companies

Product Traceability: government food safety agencies (2); policymakers (2); local supermarkets; international traders

Environmental Contamination: European Union (EU) regulators (4); European Food Safety Authority Scientific Panel on Contaminants in the Food Chain (CONTAM); FAO/WHO JECFA-960 (Joint Expert Committee on Food Additives); Turkish Food Codex Regulation; US Environmental Protection Authority; US Food and Drug Administration; policymakers

FIGURE 7 'Other' value chain actors, regulations and policy documents mentioned, shown according to food system traits. Numbers in brackets indicate the frequency of mentions where mentioned in more than one study.

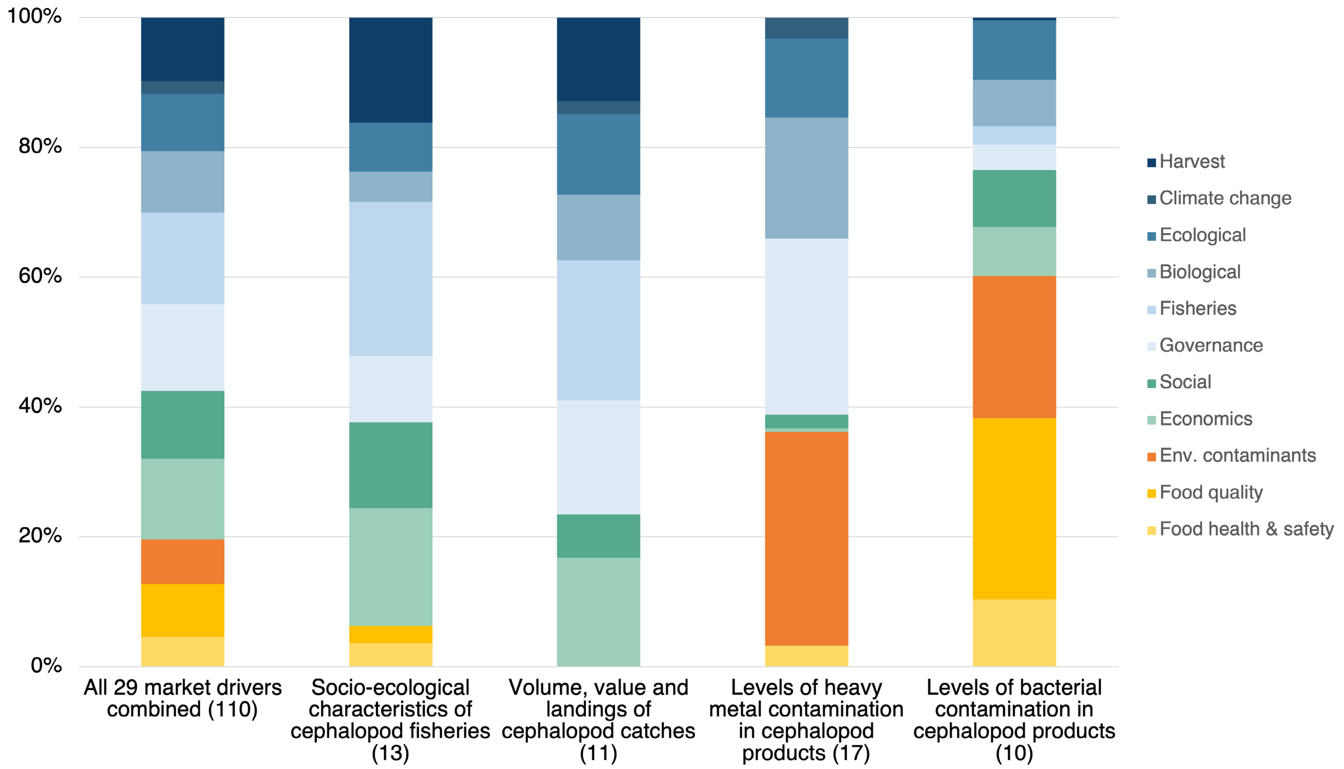

FIGURE 8 Comparison of the most frequently reported indicators for all 29 market drivers combined and for the four key market drivers (blue cells = catch sector-related data, green = trade, orange = consumption), showing number of individual drivers in brackets.

and ecosystems that cephalopods inhabit. However, rather than ecosystems, drivers were more often linked to ecological traits such as environmental conditions (39%), seasonality (37%), geographic layout of fishing grounds (35%), habitat (23%) or ecology (13%) of cephalopods.

Reviewing the literature in light of the NCP associated with the IPBES conceptual framework confirmed that all 101 studies framed cephalopods in the context of human consumption. This supports the idea that cephalopods can deliver provisioning services through access to food and contribute to GQL via the material dimension *Food and nutritional security*. Furthermore, cephalopods also deliver cultural services as indicated by: the social–ecological nature of all 29 cephalopod market drivers; the importance of cephalopod fishery characteristics (e.g. fishery type [50%]), and the commercial importance (e.g. supply [48%]) of a small number of cephalopod species to specific countries, regions and communities; the geographic research focus on 27 countries, mostly on a small subset therein; and the inclusion of different kinds of value chain actors and associated activities relating to catch, trade and consumption. Thus, cephalopods can also contribute culturally to GQL via the material dimension *Livelihood and income security* and the nonmaterial dimension *Cultural identity*.

3.4 | Mapping elements of the cephalopod food system to IPBES (in)direct drivers of change

Exploring associations between our indicators, food system traits and market drivers, and relevant IPBES (in)direct drivers of change revealed that the cephalopod food system comprised Economic, Governance, Sociocultural and Socio-psychological, and Technological indirect drivers; and Direct Exploitation, Pollution and Natural Processes direct drivers (Figure 9). Although potentially our climate change indicator (Climatic) could be associated with the direct driver Climate Change, it was coded in only seven studies (6% of drivers). The data captured related to all three market sectors, four food system traits and seven market drivers, although in all cases the effects reported corresponded with aspects primarily to do with the catch sector (e.g. cephalopod populations, environmental conditions). Therefore we highlight this finding but do not examine it further, just as we have not examined other potentially important direct drivers mentioned by a few studies, such as Land/sea use change and Invasive alien species.

Next, we explored associations between the most frequently reported indicators for the four key market drivers and the IPBES (in)direct drivers of change (Figure 10). Economics, Governance and Natural Processes drivers of change were significant to all four key market drivers while the relative importance of individual drivers of change demonstrates how market drivers operationalise differently. Both catch sector-related market drivers, *socio-ecological characteristics of cephalopod fisheries* and *volume, value and landings of cephalopod catches*, were associated with the same indirect and direct drivers of change: Economic, Governance, Sociocultural and Socio-psychological, Direct Exploitation and Natural Processes. However, in *socio-ecological characteristics of cephalopod fisheries* some Technological indicators were also frequently reported. It is likely this driver operates at a broader societal scale than *volume*,

Cephalopod market sector	Cephalopod indicator categories (no. of indicators)	Cephalopod food system traits (no. of individual drivers)	Cephalopod market drivers (no. of studies)	Primary IPBES drivers of change	IPBES types of drivers
Catch	Harvest (8); Climatic (2)*	Catch and Landings (22)	Catches, catch composition, landings of cephalopods (4)* Cephalopod stock status in relation to exploitation rates (1) Effect of gear type on cephalopod fisheries (5) **Volume, value and landings of cephalopods (11)***	Direct Exploitation	Direct-anthropogenic
Catch	Biological (5); Ecological (6); Climatic (2)*	Biology and Ecology of Stocks (2)	Ecological and biological characteristics of cephalopods and fisheries exploitation*	Natural Processes	Direct-natural
Catch	Fisheries (3)	Fisheries Characteristics (18)	Characteristics of cephalopod production (2) Effects of ecolabelling on price of cephalopod products (1) Opportunities for cephalopod aquaculture (2) **Socio-ecological characteristics of cephalopod fisheries (8)**	Sociocultural and Socio-psychological	Indirect
Catch	Governance (3); Climatic (2)*	Fisheries Governance (8)	Relationships between socio-economic variables of cephalopod fisheries and their sustainable governance (4) Use of management tools to improve sustainability of cephalopod fisheries (2)*	Governance	Indirect
Trade	Economics (9); Social (5); Climatic (2)*	Market Characteristics (12)	Consumer preferences regarding cephalopods (1) Factors affecting market integration of cephalopod products (2)* Potential for cephalopod mariculture (1) Relationships between cephalopod fisheries production and market demand (3)* Relationships between cephalopod trade and income distribution (2) Socio-economics of cephalopod trade (3)	Economic	Indirect
Trade	Food Health and Safety (5); Food Quality (1)	Product Traceability (4)	Relationships between cephalopod species misidentification and fraud (3) Relationships between cephalopod species traceability and sustainable stock management (1)	Technological	Indirect
Consumption	Food Health and Safety (5); Food Quality (1)	Food Control, Nutrition and Quality (10)	Controlling food safety and quality of cephalopods (4) Effects of cooking on cephalopod products (2) Nutritional benefits of consuming cephalopods (3) Optimizing cephalopod product recipes (1)	Technological	Indirect
Consumption	Environmental Contaminants (2); Climatic (2)	Environmental Contamination (22)	Bioaccessibility of essential and toxic elements in cephalopods (2) Effect of cooking on metal concentrations in cephalopod products (1) Health risks associated with consumption of cephalopods (2) **Levels of heavy metal contamination in cephalopod products (17)***	Pollution	Direct-anthropogenic
Consumption	Environmental Contaminants (2)	Bacterial Contamination/ Parasitic Infestation (12)	Impacts of parasitic infestation in cephalopods on human health (2) **Levels of bacterial contamination in cephalopod products (10)**	Pollution	Direct-natural-anthropogenic (-interaction)

FIGURE 9 Mapping elements of the cephalopod food system to IPBES (in)direct drivers of change (blue cells = catch sector-related data, green = trade, orange = consumption; arrows with green/orange gradient = overlap between trade and consumption; * = data relating to effects of climate change; bold text highlights the four key market drivers). IPBES drivers of change were associated with either a catch, trade or consumption market sector, except Technological which was associated with both trade and consumption.

value and landings of cephalopod catches, but that they interact with or reinforce each other.

Both consumption sector-related key market drivers, *levels of heavy metal contamination in cephalopod products* and *levels of bacterial contamination in cephalopod products* were associated with different indirect drivers of change from each other respectively: Governance; Economic and Technological, but the same direct drivers: Pollution, Natural Processes. The key driver *levels of heavy metal contamination in cephalopod products* was more strongly associated with direct drivers of change relating to catch and consumption than *levels of bacterial contamination in cephalopod products* which was more strongly associated with indirect drivers of change related to trade.

4 | DISCUSSION

4.1 | Transitioning towards increased food security

Transitioning from food systems that are major drivers of poor human health and environmental degradation, towards a sustainable and more diversified aquatic food production system, could support food security if accompanied by a better understanding of four key factors (SCAR-FISH, 2019). Our review contributes to understanding these factors as follows:

(1) 'The value of new aquatic food species'. We identified three market drivers within the Food Control, Nutrition and Quality food system trait (consumption sector) which offer insights into cephalopod products and their consumption: 'effects of cooking on cephalopod products', 'nutritional benefits of consuming cephalopods' and 'optimising cephalopod product recipes' (Ainsworth et al., 2023).

Cephalopods have high nutritional value, containing several trace elements, high levels of protein, unsaturated fatty acids and carbohydrates, low levels of fat, vitamins and calories, and no sugars or dietary fibres (Mouritsen & Styrbæk, 2018; Panse & Phalke, 2016). A versatile ingredient, cephalopods are often cooked whole, but body parts including the mantle, arms, ink and liver are popular and may be consumed fresh, raw, dried, fermented or using diverse culinary techniques (Mouritsen & Styrbæk, 2018; Pita et al., 2016).

Our research also highlights that cephalopod products and fisheries are favoured by particular regions and cultures distributed across the globe, suggesting that different kinds of market opportunities exist in different places. For example, cephalopod fisheries arguably could contribute more than at present to existing markets by supplying new nutritious products. Also, many markets are yet to be exploited in North America and Northern Europe, which have little tradition of consumption but an abundance of local edible cephalopod species. Efforts are being made to popularise edible species (e.g. *Loligo forbesii*) among northern fishing industries, retailers and

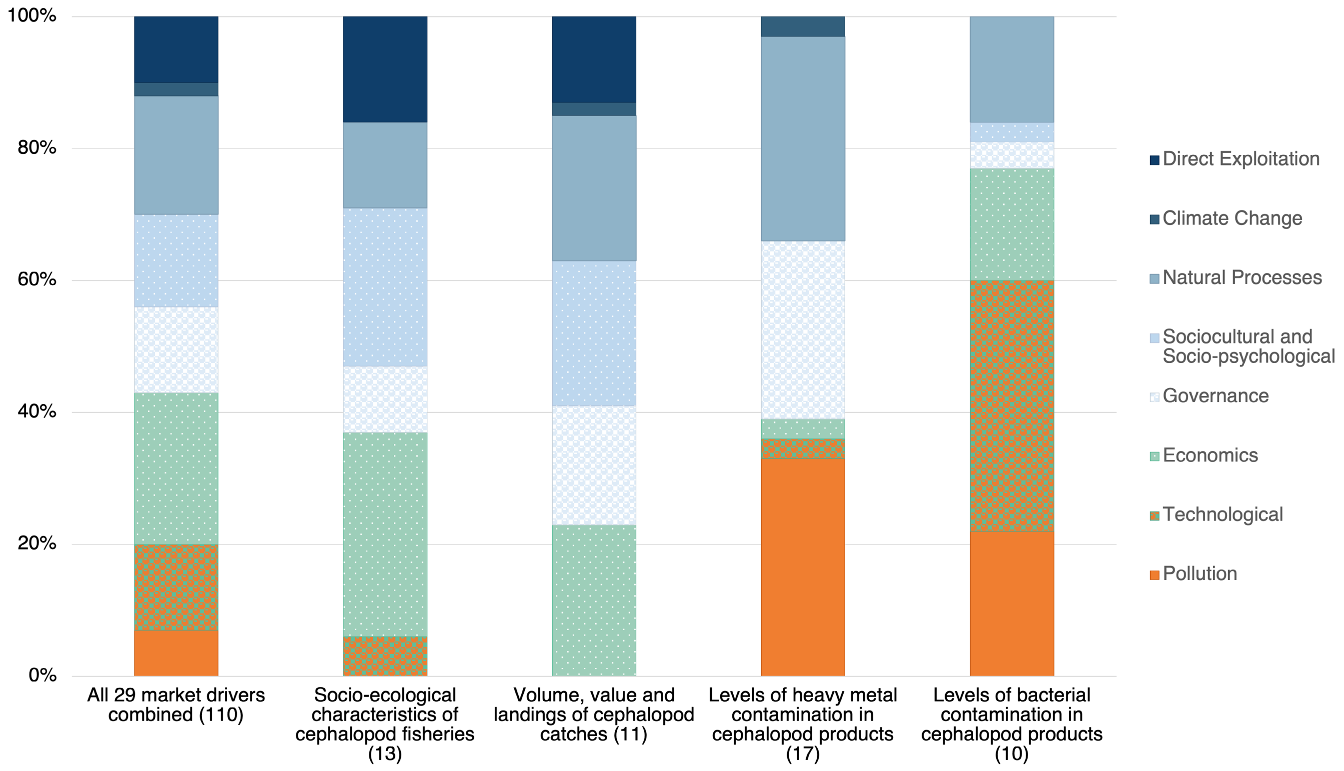

FIGURE 10 Mapping the most frequently reported indicators for all 29 market drivers combined and the four key market drivers to the IPBES (in)direct drivers of change (blue cells = catch sector-related data, green = trade, orange = consumption; green/orange = overlap between trade and consumption; patterned cells = indirect drivers of change; solid cells = direct drivers of change), showing number of individual drivers in brackets.

consumers as a (potentially) sustainable marine food resource and potential replacement for other animal proteins, and to reinvent their use in new types of preparations (Faxholm et al., 2018). Clearly there is a need to ensure sustainable fisheries management in any new market scenario, to avoid over-exploitation of associated cephalopod populations and be aware of the carbon footprint in cephalopod production, especially where food items have lower carbon footprint but are also nutritious (Bianchi et al., 2022).

(2) 'Food safety and authenticity systems to enhance consumer confidence in the food system'. Four cephalopod food system traits are relevant here from the trade and consumption sectors: Product Traceability; Environmental Contamination; Bacterial Contamination/Parasitic Infestation; and Food Control, Nutrition and Quality. The 12 associated market drivers and literature therein offer insights into important indirect (Technological), direct (Pollution) and natural–anthropogenic interactions (Natural Processes/Pollution) relating to current food safety and authenticity systems (e.g. methods for molecular identification or for testing levels of heavy metal contamination/parasitic infestation of cephalopod products).

Cephalopods are typically associated with a few health risks, which can be reduced by following certain measures (e.g. not eating digestive glands or viscera and by adequate cooking). Health and safety concerns are linked to connectivity and traceability of seafood products through the global trade network. The complexity of cephalopod trade flows along with variations in (or lack of) labelling systems and official lists of seafood trade names in different countries can make it difficult to accurately identify the origin of the raw material used in cephalopod products. The traceability issue could be improved by using DNA tests and identifying the catch area of cephalopods on product labelling (Armani et al., 2015; Pierce et al., 2021), although this would not necessarily allow determination of whether those cephalopod organs which accumulate higher amounts of contaminants were included in the product.

(3) 'Place-based innovations and empowerment of communities fostering inclusivity, fair trade and pricing'. The review identified 10 principal types of actors participating in cephalopod markets, from producers to consumers, as well as diverse kinds of policymakers and fisheries stakeholders. Each food system trait features different types of actors and the specific blend of value chain actors involved in a fishery may differ depending on its characteristics and seafood products. This suggests that cephalopod fisheries value chains require individual attention to understand how they operate (Burch & Maes, 2017). Understanding new and existing actor alliances and associated power structures is especially important in transformative change processes where political and economic support are essential components of success for progressive strategies (Hebinck et al., 2018).

According to our review, knowledge of the cephalopod food system is unevenly distributed across the value chain, as was found with previous cephalopod value chain analysis (e.g. Coronado et al., 2020;

Rosales Raya & Berdugo, 2019). Typically, only some types of actors are included (but not always) in fisheries governance decision-making (e.g. government agencies, scientists, fisheries managers, producers), hindering capacity for triggering sustainability transformations in production. Elsewhere in the value chain, 'keystone actors' (e.g. transnational seafood corporations) and other kinds of influential actors (e.g. chefs, gastronomists, nutrition experts) or tools (e.g. eco-certification and sustainability rating schemes) may drive the transition towards a socially, economically and environmentally sustainable cephalopod food system by working with business partners, creating incentives and providing support to other companies, among other things (Österblom et al., 2015). This approach may ensure political support for transformation but risks bias towards status quo planning, highlighting the need for cooperation and empowerment among network alliances at different levels of the stakeholder power hierarchy (Hebinck et al., 2018).

Demand for cephalopods is strong and global per capita consumption has increased slightly (0.1%) in the last 30 years to an average of 0.5 kg per person in 2017 (FAO, 2020a) against a background of rising human population size. Consequently, prices have risen but in recent years, supplies have become increasingly scarce as productivity of important fisheries has declined, requiring stringent management regimes (FAO, 2020a). The key market driver *volume, value and landings of cephalopod catches* provides insights into cephalopod fishery economics (Section 3.2.3; Appendix S2).

We found that cephalopod fisheries are important to the livelihoods and cultural identities of local communities and businesses, and associated tourism, through the cultural, provisioning and supporting services they provide. However, economic and decision-making powers tend to reside with actors in the middle of cephalopod supply and value chains (e.g. distributors, wholesalers).

(4) 'Consumer behaviour, lifestyle and motivations for better health and environmental sustainability along the food value chain'. This factor relates mainly to the catch and trade sectors. Within the Fisheries Characteristics food system trait (catch sector), the market driver *effects of ecolabelling on price of cephalopods* exemplifies how market initiatives (e.g. Marine Stewardship Council certification) and associated ecolabelling programs can foster a retail price premium for cephalopod products and provide economic benefits for small-scale and artisanal cephalopod fisheries fleets (Fernández Sánchez et al., 2020). The food system trait Market Characteristics (trade sector) revealed six market drivers that contribute to understanding this factor from the perspective of socio-economics of cephalopod mariculture, trade and consumer preferences, as well as cephalopod product market integration and demand (Ainsworth et al., 2023).

Local demand also impacts the cephalopod market. For example, tourism demand can cause an increase in cephalopod prices, and while many livelihoods may be positively impacted by this, such demand can have a negative impact on local food security and livelihoods especially where there is unequal distribution of income among actor groups and restricted access to marine protein sources (Garcia Rodrigues & Villasante, 2016). Consumer behaviour can have an important impact in cephalopod marketing when influenced by factors including geography, fishery heritage, political and social habits (Almeida et al., 2015). Increasing recognition of cephalopod sentience in law and concerns among consumers may present a potential barrier to their farming and consumption due to environmental (e.g. use of wild-caught fish associated with aquaculture) and ethical (e.g. welfare) reasons (Lara, 2021; UK Parliament, 2021).

4.2 | Cephalopod food system policies that value nature's contributions to people

Building on our analyses and mapping of key findings to IPBES conceptual framework elements (Figures 9 and 10), we propose a novel, market-based adaptation of the IPBES framework which we call a 'cephalopod food system framework' and which links ecosystems to GQL (Figure 11). Organising our conceptual elements in this way builds on previous knowledge about food systems which highlight food availability, access and utilisation (e.g. HLPE, 2017) and on interactions between society and nature (e.g. IPBES, 2019). Principal features of our food system framework are borrowed from IPBES (e.g. inclusion of plural knowledge systems, values and interests, coproduction of NCP) which help with conceiving how to govern a demand-driven, sustainable, interconnected and inclusive cephalopod food system at different geographic scales—important ingredients for future-proofing nutrition security (EC, 2021; EEA, 2016).

Our framework provides a simplified overview of the dynamics of cephalopod food systems depicting multi-dimensional relationships and feedback loops between cephalopod ecosystem services, fisheries and other institutions, anthropogenic assets, NCP and GQL which we link to the political realms of commerce and sustainable food systems through our suggested policy landscape (described below). At an international governance level, the way this framework functions can inform strategies to improve cohesion between ecosystem health, food system policies and social wellbeing, and can deliver insights into how the food system may need to be revised, or where major gaps in collaboration or knowledge exist, setting the stage for action through policy interventions. From an interdisciplinary research perspective the framework could be used as a tool to identify social–ecological considerations relevant to developing research programs to map and evaluate the direct effects of markets on cephalopod fisheries and associated ecosystems at different geographic and political scales (e.g. for a small-scale or industrial fishery), and potentially for other marine resources—research which appears to be lacking at the time of writing.

At another scale, the framework could be applied in a fisheries management context to better understand the mechanics of a local cephalopod food system. Populating the elements of the framework with available information according to the 51 indicators we identified could reveal strengths and weaknesses in understanding about and actors' involvement in the food system. This approach could also offer a means to explore localised consequences to the system (e.g. impacts on ecosystems, NCP, livelihoods) as a result of changing (in)

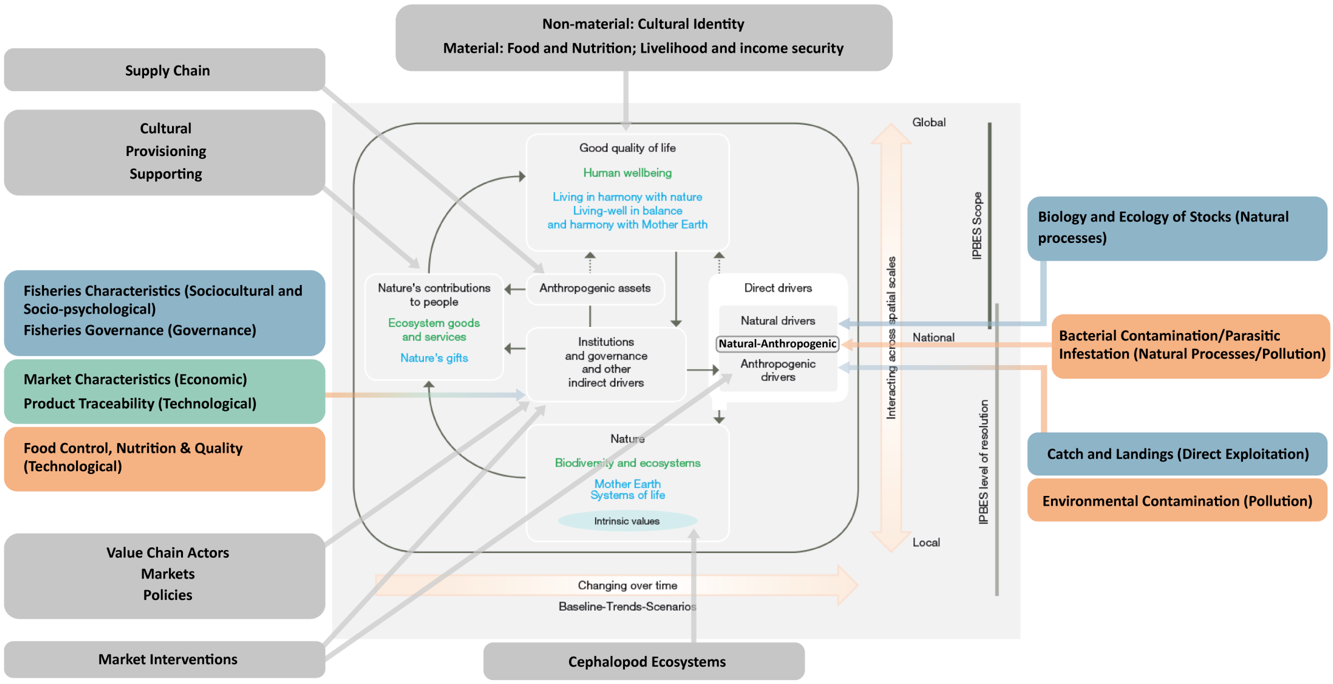

FIGURE 11 A market-based adaptation of the IPBES conceptual framework (building on IPBES, 2019) representing key elements of the cephalopod food system, based on results emerging from the review (blue cells = catch sector-related data, green = trade, orange = consumption; grey = nonsector specific data; brackets indicate IPBES (in)direct drivers of change.

direct drivers (e.g. fishery regulations, value chain actor activities/behaviour) and of associated opportunities and constraints.

Below we further illustrate how such a practical application could work. We do this by describing how our key findings are integrated into elements of the conceptual framework in concert with our strategic view of the cephalopod policy landscape.

4.2.1 | Direct drivers of change

Our results identified one direct–natural driver: Biology and Ecology of Stocks (Natural Processes) and two direct–anthropogenic drivers: Catch and Landings (Direct Exploitation) and Environmental Contamination (Pollution). We also identified one direct–natural–anthropogenic(–interaction) driver, Bacterial Contamination/Parasitic Infestation, which we associate with both Natural Processes and Pollution since it may be difficult to differentiate whether the origin of a given pathogen is natural or anthropogenic (e.g. contamination can arise from the natural environment, but cross-contamination of a natural pathogen from an infected animal to an uninfected animal can also arise from anthropogenic activities).

As with policies, food systems and markets can vary from a local to a global scale, namely through flows of international trade. For example, our key driver *levels of heavy metal contamination in cephalopod products* may operate locally (at the site of contamination) or regionally, and the drivers *socio-ecological characteristics of cephalopod fisheries* and *volume, value and landings of cephalopod catches* can operate at local, regional, national and international scales depending on the size of the fishery and associated operations. The driver *levels of bacterial contamination in cephalopod products* can operate across almost the entire food system if not detected, and potentially travel the world.

Climate change is also important to consider. Since climate change did not emerge as a dominant food system trait or market driver, we did not include it in our market-based framework. Rather, the impacts of climate change were infrequently related to various cephalopod market drivers, reflecting the diffuse and complex nature of climatic effects on the cephalopod food system as published in these studies. These limited data also likely reflect attempts within the still evolving knowledge base to disentangle climate change from other drivers, especially in less studied environments and species. However, there is increasing awareness that climate change impacts could have significant implications for the catch, trade and consumption sectors within food systems (Tigchelaar et al., 2021), and we expect the same for cephalopods, ranging from changes to their biology and ecology to supply chain disruptions.

4.2.2 | Institutions and governance and other indirect drivers

A dynamic multi-dimensional feedback loop exists in the interface between GQL, cephalopod-related policies and other indirect drivers of change whereby the market adjusts according to changes in the nature and extent of NCP provided by cephalopods and vice versa. Therefore, we situate value chain actors, markets, policies, market interventions and indirect drivers within the centre of the conceptual framework due to their relevance in market-related political, technical and consumer decision-making, and strategies to cope with ecosystem change.

Value chain actors modify food system traits through policies which influence behaviours that affect cephalopod ecosystems (nature), NCP and supply chains (anthropogenic assets). For example, several potentially powerful market interventions likely apply in the journey of cephalopods from sea to fork: the influence of international trade on production; the role of aquaculture in contributing to food security; a globalised supply chain with emerging partnerships; and market incentives and consumer choices for sustainability (e.g. EEA, 2016).

To illustrate, the EU is driving development of common food systems policies that incorporate systemic dimensions of food security to ensure better cohesion with social wellbeing and ecosystem health (EEA, 2016). The Joint Research Council Foresight on Global Food Security 2030 calls for actions to support a more balanced mix of local and global food systems and to foster more demand-driven food systems by empowering informed consumers who seek to control their nutritional intake and contribute to sustainability issues world-wide (Maggio et al., 2015). For example, knowledge about the carbon footprint and nutritional value of species can support more informed consumption choices and policy making (Aragão et al., 2022; Bianchi et al., 2022).

Currently, most marine-related policies for food and sustainability, such as the FAO Blue Growth Initiative (FAO, 2017) and the EU Marine Strategy Framework Directive (EEA, 2016) typically relate to the catch sector when considered in the context of food. Although trade policy may be used by countries as an indirect means of protecting marine resources and improving fishing practices (Asche & Smith, 2017), policies relating to different links across the fisheries supply chain are rarely if ever integrated (EEA, 2016). However, we identified five indirect drivers of change from across the catch, trade and consumption sectors that should also be considered in the policy context: Fisheries Characteristics (Sociocultural and Socio-psychological); Fisheries Governance (Governance); Market Characteristics (Economic); Product Traceability (Technological); and Food Control, Nutrition and Quality (Technological).

Relevant policies and strategies to address the various potential effects of climate change should also be integrated across the cephalopod market policy landscape. In other words, policies should integrate national and regional pathways towards food systems that are resilient, equitable, sustainable and inclusive/accessible but also healthy and nutritious, respecting planetary boundaries, cultural traditions and including the most vulnerable and local coastal communities. Finally, seafood trade can be partially hidden when it is conducted through unofficial channels (Garcia Rodrigues & Villasante, 2016), and thus a better understanding of the value chains is necessary and food systems need to be more transparent and inclusive than at present (Carducci et al., 2021). Managing emerging cephalopod markets therefore involves better understanding market (indirect) drivers such as incentives and barriers to the catch, trade and consumption of cephalopods, and the values, motives and behaviours of value chain actors.

4.2.3 | Nature's benefits to people

We situate cephalopod-related NCP within this element since they reflect the benefits people receive from cephalopod food systems. It is important to ensure that monetary and nonmonetary benefits from cephalopod resources are shared fairly and equitably (CBD, 2021). We propose that policies relating to each cephalopod market sector, food system trait and link in the supply chain should also be considered in the context of sustainable and equitable fisheries value chains, especially those policies focusing on trade, food health and safety, product traceability, fisheries governance and environmental pollution.

4.2.4 | Anthropogenic assets

We situate cephalopod supply chain components within this element since they reflect relevant knowledge, infrastructure, financial capital, technology and the institutions that mediate them within cephalopod markets. Local food systems can be affected by other external markets, associated with supply and demand dynamics. The COVID-19 pandemic has shown how the food supply chain and systems are intricately delicate and connected, causing major market disruptions and affecting people's diets and access to nutrition (Carducci et al., 2021; Villasante, Tubío, Ainsworth, et al., 2021). Diversity and connectivity to regional markets provides for a continuous supply of food, and consequently the strengthening of (local) food systems and security is essential (Carducci et al., 2021; Love et al., 2021). Cephalopods can play a major role in local communities where they may be considered as an essential aquatic food source.

4.2.5 | Good quality of life

In our conceptualisation, sustainable ecosystem health and GQL are inextricably linked, and influential drivers corresponding to different parts of the social–ecological system are revealed. In turn, these drivers affect the capacity for cephalopods to contribute to human social wellbeing via material: food and nutritional security, livelihood and income security and nonmaterial: cultural identity dimensions of GQL. These drivers also affect the capacity of cephalopods to provide supporting services and contribute to fisheries in marine ecosystems, requiring consideration of trade-offs.

4.2.6 | Nature

This element represents cephalopod populations and the ecosystems that cephalopods inhabit and is a focal point for considerations about the links between food and nutrition, achieving SDG goals and reversing biodiversity loss. There are many significant knowledge gaps that if filled could help with understanding and supporting transitions towards sustainable food systems according to our framework. These include: data, inventories and monitoring regarding nature and the drivers of change; inventories on understudied marine ecosystems; data, indicators and information relating to links between species, NCP and ecosystem functions; and links between nature, NCP and drivers with respect to SDG targets and goals (IPBES, 2019).

We propose that application of our cephalopod food system framework in a practical localised way (as described in the introduction to this section) and the learning that emerges from that process could help clarify the operationalisation of the EBFM for EU fisheries by depicting and linking key stages of the food system from ecosystems to human wellbeing, thus highlighting where different kinds of (in)direct drivers may influence how the cephalopod food system functions and advancing understanding of the relationships between cephalopod market drivers, NCP and GQL.

It is vital that cephalopod (and other) food systems policies should match ambitions relating to biodiversity conservation (e.g. CBD, 2021) with the following SDGs being particularly relevant to both ambitions: 1. No Poverty; 2. Zero Hunger; 3. Good Health and Wellbeing; 5. Gender Equality; 12. Responsible Consumption and Production; 13. Climate Action; 14. Life Below Water; and 15. Life on Land. Framing strategies to implement EBFM processes and improve food security through the lens of NCP can contribute to the development of more sustainable fisheries management and food system processes.

5 | CONCLUSIONS

Cephalopod products can play a key role within sustainable food systems since they are nutritionally and culturally important and can contribute to diversified seafood sourcing. Our conceptualisation of the complex processes involved in the cephalopod food system organises human activities and related policies into dynamic, multi-dimensional feedback loops that link to ecosystems. Furthermore, it locates relevant indicators for measuring the outcomes of market dynamics in terms of ecosystem health, social wellbeing and food security.

Our proposed approach facilitates interpretation of relationships between ecosystem health, market dynamics and social wellbeing through the lens of NCP and offers an equitable framework for conceptualising the interaction of policies, actors and drivers across temporal and spatial scales. Our findings indicate that cephalopod fisheries tend to be highly localised and small scale in nature but can be impacted by globalised drivers of change, suggesting that regional, national and international policies are relevant to the cephalopod food system. Thus, our cephalopod food system framework may operate from global to local scales, as required, depending on the scale of the cephalopod fishery in question and corresponding interaction with international, regional and local policies.

Our results suggest that a cohesive view of the policy landscape for the cephalopod food system would consider the role of multiple overlapping indirect and direct drivers of change including: Economic, Governance, Sociocultural and Socio-psychological, Technological, Direct Exploitation, Natural Processes and Pollution. Clearly, this landscape is highly complex in terms of interactions between sectors and actors involved, requiring integration and collaboration at various geographic, societal and temporal scales. Managing this policy landscape and associated measures requires linking pressures on cephalopod ecosystems and related NCP to societal actors, drivers and behaviours, for example through actor analyses (Sundblad et al., 2021).

Furthermore, we acknowledge that many challenges remain regarding transformations towards sustainable food systems, including significant knowledge gaps (e.g. data, indicators, inventories and scenarios that link ecosystem processes to NCP and GQL). We also recognise the multi-scale efforts are critical to address systemic problems in existing food systems and that translating and scaling insights and cooperation from global to local levels and vice versa requires many considerations, such as central drivers (e.g. political systems), potential opportunities (e.g. current policy development) and barriers (e.g. lack of awareness). Therefore, due to the novelty of our approach and the apparent lack of scientific research which specifically aims to study the direct effects of market drivers on ecosystems, NCP and GQL within a given fishery, we recommend first applying our cephalopod food system framework at local levels to understand how social and ecological dynamics operate at small scales and how these are influenced by local, national and international (in)direct drivers.

While the specific findings may be geographically skewed by the regions that were most represented in the studies synthesised here, and emerging threats such as climate change may not yet be sufficiently understood to feature prominently, we believe the strength of evidence presented based on the literature reviewed is sufficiently high to identify important knowledge gaps and research needs that can inform future multidisciplinary research. We recommend specifically investigating how links between cephalopod ecosystems, NCP and key cephalopod market drivers influence markets for cephalopod products and vice versa. Furthermore, applying the original IPBES framework and its associated features in novel settings, as we have done, extends its utility and leads the way for potential adaptations and applications to understand other social–ecological systems including other wild harvest commodities, with implications for diverse marine species and ecosystems. This approach can inform those working to deliver marine and terrestrial food security, while also preserving biodiversity functions of ecosystems.

AUTHOR CONTRIBUTIONS

Gillian B. Ainsworth and Sebastián Villasante were involved in conceptualisation. Gillian B. Ainsworth, Pablo Pita, João Garcia Rodrigues and Sebastián Villasante were involved in data curation. Gillian B. Ainsworth was involved in formal analysis. Anne Marie Power, Graham J. Pierce, Cristina Pita and Sebastián Villasante were involved in funding acquisition. Gillian B. Ainsworth, Pablo Pita, João Garcia Rodrigues, Cristina Pita, Katina Roumbedakis, Tereza Fonseca, Daniela Castelo, Catherine Longo, Anne Marie Power, Graham J. Pierce and Sebastián Villasante were involved in investigation, methodology, validation and writing—review and editing. Sebastián Villasante was involved in project administration and supervision. Gillian B. Ainsworth and Katina Roumbedakis were involved in visualisation. Gillian B. Ainsworth, Pablo Pita and Sebastián Villasante were involved in writing—original draft.

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CONFLICT OF INTEREST

No conflict of interest was reported by the authors.

DATA AVAILABILITY STATEMENT

All supporting data are archived on Dryad Digital Repository https://doi.org/10.5061/dryad.69p8cz95r (Ainsworth et al., 2023).

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DATA SOURCES

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1: Protocol. A priori protocol used to define and agree research parameters.

Appendix S2: Limitations, Issues, Gaps and Needs. Qualitative description of the study limitations and methodological issues identified by the authors as well as knowledge gaps and research needs identified in the study. **Key Market Drivers**. Qualitative description of four 'key market drivers' representing the main trends studied by literature captured in the review. **Table 1**. Examples linking cephalopod market sectors with ecosystems that cephalopods inhabit and the ecosystem services they provide. For references, see section **Data Sources** above.

Appendix S3: Figure A1. Flowchart representing the literature review search and screening processes.

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