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Current challenges of the Spanish demersal fisheries: from climate vulnerability to global markets

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CURRENT CHALLANGES OF THE SPANISH DEMERSAL FISHERIES: FROM CLIMATE VULNERABILITY TO GLOBAL MARKETS

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“Quando eu morrer voltarei para buscar os instantes que não vivi junto do mar.”

Sophia de Mello Breyner Andrese

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List of Publications & Contributions

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Chapter 1: The importance of regional differences in vulnerability to climate change for demersal fisheries.

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Chapter 2: The carbon footprint of the hake supply chain in Spain: Accounting for fisheries, international transportation and domestic distribution

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Chapter 3: Global hake production and trade: Considerations for food security and supply chain resilience

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RESUMO (GALEGO)

O sector pesqueiro mundial, un dos piares da seguridade alimentaria e da estabilidade económica, afronta retos sen precedentes debido ao cambio climático e á dinámica do mercado impulsada pola crecente demanda mundial de produtos do mar, que está a exercer unha presión aínda maior sobre os recursos mariños que xa están moi sobreexplotados. . O cambio climático ten un impacto negativo nos ecosistemas mariños, afectando tanto ás poboacións de peixes como ás actividades pesqueiras, o que ameaza a dispoñibilidade de produtos do mar e os ingresos xerados por este sector (Scheffers et al., 2016; Pinsky et al., 2018; Olsen et al., 2019). En resposta ao descenso das capturas das poboacións de peixe, algunhas flotas mundiais acaban intensificando as súas operacións de pesca, o que á súa vez aumenta as emisións de GEI debido ao uso intensivo de combustibles fósiles, contribuíndo ao cambio climático (Tickler et al., 2018; Sala et al., 2022). A escaseza de recursos, unida aos cambios normativos na xestión pesqueira, impulsa o comercio mundial a satisfacer a crecente demanda destes alimentos que son fundamentais para a calidade nutricional de millóns de persoas (Gephart e Pace, 2015; FAO, 2018). A intensificación do comercio internacional, que á súa vez optimiza a distribución de alimentos, diversifica as dietas e estabiliza os prezos (D'Odorico et al. 2014; Ge et al. 2021), tamén xera redes de gran interdependencia, sendo algúns países dominando os fluxos comerciais mundiais. , ademais de contribuír ao aumento das emisións de GEI debido ao transporte a longa distancia, ampliando a pegada de carbono relacionada co consumo de produtos do mar (FAO, 2018; Crippa et al., 2021; Xu et al., 2021). Abordar estes desafíos require unha estratexia integrada que inclúa unha xestión sostible da pesca, prácticas pesqueiras de baixas emisións, comercio internacional responsable e adaptación ao cambio climático.

Nesta complexa interacción entre os impactos do cambio climático na produción pesqueira e a contribución da pesca ao cambio climático, os efectos non se senten uniformemente a escala global e os impactos do cambio climático dependen das características ambientais e socioeconómicas de cada un. rexión (Allison et al., 2009; IPCC, 2014; Payne et al., 2020). Para abordar estes problemas, aplicáronse amplamente as Avaliacións da Vulnerabilidade Climática (CVA) para comprender, cuantificar e sintetizar os impactos do cambio climático no sector pesqueiro, establecer prioridades para a asignación de fondos de adaptación e proporcionar aos responsables políticos os coñecementos necesarios para facer prácticas. decisións (por exemplo, Allison et al., 2009; Cinner et al., 2012; Colburn et al., 2016; Pinnegar et al., 2019; Payne et al., 2020). A medida que avanzamos na comprensión dos impactos do cambio climático na pesca, é fundamental recoñecer tamén a importante contribución do sector á pegada de carbono global. A actividade pesqueira, aínda que é esencial para a seguridade alimentaria e a economía de moitas comunidades, é unha fonte notable de emisións de gases de efecto invernadoiro (IPCC, 2019).

Neste contexto, a pegada de carbono dun produto fai referencia ás emisións de GEI avaliadas ao longo do seu ciclo de vida, desde as materias primas ata a produción, distribución, uso e eliminación por parte dos consumidores (Carbon Trust et al., 2008). Os estudos de pegada de carbono aplicáronse amplamente en varios sectores económicos, incluído o sector alimentario, que é responsable dun terzo das emisións antropoxénicas mundiais de GEI (Crippa et al., 2021; Xu et al., 2021). A pesar dos avances, os produtos pesqueiros mariños foron historicamente desatendidos, realizándose recomendacións de xestión baseadas en estudos que non recollen a gran variabilidade das emisións entre as pesqueiras dirixidas a diferentes especies utilizando diferentes artes de pesca (Parker et al., 2018). Aínda que as análises de GEI destacan a relevancia das emisións das pesqueiras de captura, investigacións recentes apuntan á relevancia de considerar todas as etapas do ciclo de vida do produto, como o procesamento, o envasado e o transporte (Crippa et al., 2021; Xu et al., 2021).). De feito, o transporte cobra

especial importancia no contexto actual de globalización, caracterizado por unha demanda crecente de produtos do mar, cadeas de subministración máis longas e unha maior dependencia das importacións de alimentos.

Os factores económicos, tecnolóxicos e culturais derivados da globalización impulsaron o comercio internacional de produtos acuáticos nas últimas décadas. A liberalización das políticas comerciais e os avances na loxística e as tecnoloxías da comunicación contribuíron a promover a interdependencia económica e a difusión cultural, incluída a diversificación dos hábitos alimentarios. Ademais de desempeñar un papel importante na seguridade alimentaria mundial, a expansión do comercio de produtos acuáticos ten un impacto significativo na economía mundial, xerando ingresos por exportación, emprego e valor engadido (FAO, 2022). O comercio de produtos acuáticos tamén reflicte as disparidades económicas mundiais, cun patrón xeral onde os países en desenvolvemento fornecen produtos aos países desenvolvidos, que teñen máis ingresos dispoñibles e unha oferta interna insuficiente para satisfacer a demanda. A diminución das poboacións de peixes, a sobreexplotación e os cambios na distribución e abundancia de especies de valor comercial impulsados polo cambio climático teñen implicacións de gran alcance para a seguridade alimentaria mundial, pero tamén teñen profundas consecuencias para os produtores e, en consecuencia, para as redes de comercio internacional (Gephart et al. 2017). A cartografía destas complexas redes é vital para unha xestión eficaz da pesca que garanta os beneficios do comercio sen comprometer a sustentabilidade a longo prazo dos recursos mariños (Giron-Nava et al. 2021).

Cun litoral aproximado de 8.000 km e 340 portos pesqueiros rexistrados (EUMOFA, 2020), España sitúase entre os 25 maiores produtores de produtos pesqueiros e alberga o maior sector pesqueiro da UE, representando o 21% do total de empresas activas e 25. % dos ingresos xerados polo sector (STECF, 2019a). En 2020, España foi o cuarto importador mundial de peixe e marisco e o maior importador da Unión Europea, que á súa vez foi o maior mercado de importación, representando o 34% do valor global das importacións de produtos acuáticos (FAO, 2022).

A pescada é moi consumida en todo o mundo e destaca como unha especie crucial para o sector pesqueiro. A súa importancia vai máis aló da nutrición; é un símbolo do patrimonio cultural gastronómico para a poboación de Europa Occidental, especialmente en países como España, onde ten unha gran importancia no seu mercado, e un peso importante para a economía do sector pesqueiro e do comercio internacional (MAPA, 2017). Cada etapa da cadea de valor da pescada implica a diferentes actores, como pescadores, vendedores e/ou intermediarios, mercados tradicionais, transportistas, empresas por xunto e polo miúdo, restauradores, grandes almacéns, ata chegar á mesa do consumidor. E esta cadea de valor difire tanto pola súa relevancia económica para as rexións españolas como pola súa pesca, distribución, transporte poscosecha e comercio exterior.

Esta tese xustifícase, pois, nun escenario caracterizado por i) a importancia do sector pesqueiro para a subsistencia e a seguridade alimentaria; ii) a relevancia da pescada para o sector pesqueiro; iii) o aumento do consumo global per cápita de produtos pesqueiros; e iv) a necesidade dunha explotación sostible dos recursos pesqueiros. Os países deben ser máis responsables na xestión do sector pesqueiro para garantir a sustentabilidade ambiental e a calidade nutricional para unha poboación mundial en crecemento (FAO, 2020).

Obxectivos e Cuestións de Investigación

Neste contexto, utilizando como estudo de caso a pesca demersal en España e a pescada, o obxectivo xeral desta tese é achegar unha visión dos retos e dinámicas do sector pesqueiro, desde o impacto do cambio climático na pesca rexional ata a sustentabilidade ambiental do sector pesqueiro. as prácticas pesqueiras e as influencias do comercio mundial, co obxectivo de

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contribuír ao desenvolvemento de estratexias eficaces de xestión pesqueira e á resiliencia futura do sector, en beneficio dos seus traballadores e das comunidades implicadas. Para iso, buscamos comprender como podemos desenvolver unha planificación personalizada de adaptación da pesca a escala rexional que aborde as vulnerabilidades específicas das pesqueiras ao cambio climático, investigar as implicacións da pegada de carbono da cadea de subministración pesqueira para a sustentabilidade e a política ambiental e afondar nos retos e oportunidades da xestión pesqueira sostible no contexto das tendencias do mercado comercial global. Así, exploramos como se pode xestionar a pesca para ser resistente ao cambio climático, garantir a seguridade alimentaria e abordar os problemas de xustiza climática.

As preguntas que pretendemos responder para explorar e contribuír á creación de coñecemento científico sobre a socioecoloxía da pesca ante o cambio climático son:

1. Cal é a relevancia da vulnerabilidade rexional das pesqueiras demersais españolas ante o cambio climático, e que estratexias de xestión se poden aplicar para garantir a viabilidade a longo prazo dos recursos mariños? (Capítulo 2)
2. Cal é a pegada de carbono da pesca, do transporte internacional e da distribución nacional sobre a pegada de carbono da cadea de subministración da pescada, e as súas implicacións para a sustentabilidade e a política ambiental? (Capítulo 3).
3. Como participan os diferentes países e rexións no mercado comercial, e cales son os retos e oportunidades para a xestión sustentable da pesca da pescada no contexto das tendencias do mercado comercial global? (Capítulo 4).

Estrutura da Tese

Esta tese consta de tres capítulos en forma de artigos científicos, os capítulos 2, 3 e 4. No capítulo 2, titulado "A importancia das diferenzas rexionais na vulnerabilidade ao cambio climático para as pesqueiras demersais", esforzámonos por expoñer e iluminar a importancia da diferenzas rexionais na vulnerabilidade ao cambio climático para as comunidades pesqueiras e costeiras. Utilizando a frota demersal española como caso de estudo, desenvolvemos unha Avaliación da Vulnerabilidade Climática (CVA) nun marco que considera a vulnerabilidade en función da sensibilidade, exposición e capacidade de adaptación. Apoiándonos nun sólido conxunto de indicadores, avaliamos nove rexións costeiras do país (comunidades autónomas), contrastándoas entre si e coas zonas mediterránea e atlántica. O capítulo aplica este marco á pesca demersal para identificar as rexións costeiras de España máis expostas ao cambio climático, así como para identificar potenciais estratexias de xestión que garantan a resiliencia a longo prazo das comunidades e dos recursos pesqueiros. Comezamos o capítulo destacando o papel crucial do océano na seguridade alimentaria e nos medios de vida de millóns de persoas en todo o mundo. Despois examinamos o impacto do cambio climático no medio mariño e as súas posibles consecuencias para os desembarques pesqueiros, a economía e a seguridade alimentaria. Subliñamos que os efectos do cambio climático non se senten uniformemente en todo o mundo e dependen das características ambientais e socioeconómicas de cada rexión. Polo tanto, é fundamental desenvolver unha planificación personalizada de adaptación da pesca a escala rexional para abordar as vulnerabilidades específicas das pesqueiras ao cambio climático. Os nosos resultados destacan diferenzas significativas no índice de vulnerabilidade ao cambio climático entre as comunidades autónomas, así como entre as zonas mediterránea e atlántica, apoiadas en gran medida por factores de exposición e capacidade de adaptación.

No capítulo 3 da tese, "A pegada de carbono da cadea de subministración de pescada en España: contabilidade da pesca, do transporte internacional e da distribución doméstica", reconstruímos, por primeira vez, a cadea de subministración de produtos mariños da pescada en España para comprender os impactos ambientais do sector relacionados coas emisións de

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gases de efecto invernadoiro, así como para identificar oportunidades de sustentabilidade, xestión pesqueira e políticas ambientais. O capítulo reforza a importancia de reducir as emisións de GEI para mitigar o cambio climático e destaca o papel do sector pesqueiro para contribuír a estas emisións. Usando un enfoque de avaliación do ciclo de vida (ACV), presentamos unha análise exhaustiva da pegada de carbono da cadea de subministración da pescada en España, incluíndo as operacións pesqueiras, o transporte internacional e a distribución doméstica, tendo en conta os modos aéreo, terrestre e marítimo e as súas especificidades. O enfoque LCA permite unha análise sólida do impacto ambiental da cadea de subministración. Os nosos resultados indican unha contribución significativamente maior das operacións pesqueiras á pegada de carbono da cadea de subministración da pescada en comparación co transporte. Tamén identificamos oportunidades para reducir a pegada de carbono da cadea de subministración de pescada, como mellorar a eficiencia do combustible nas operacións de pesca, reducir o desperdicio de alimentos e promover patróns de consumo máis sostibles.

No capítulo 4, "Global Production and Trade of Hake: Considerations for Food Security and Supply Chain Resilience", mediante unha metodoloxía complexa de análise de redes e ferramentas de visualización gráfica, descodificamos a International Hake Global Trade Network (HGTN) analizando a posición de varios países para arroxar luz sobre a susceptibilidade do mercado mundial de produtos do mar aos cambios económicos, políticos e ecolóxicos, destacando a necesidade de prácticas comerciais resilientes, adaptables e específicas para xestionar de forma sostible o comercio mundial de produtos do mar. Os nosos descubrimentos subliñan a importancia de xestionar os recursos e manter o equilibrio do mercado para apoiar a seguridade alimentaria mundial e reflectir o dinamismo do sector pesqueiro. Examinamos as tendencias temporais dos desembarques de pescada para comprender as principais especies de pescada explotadas e os países pesqueiros dominantes. Despois, para comprender mellor a rede comercial mundial, centrámonos en determinar onde se produce o maior consumo aparente de pescada. Ademais, presentamos as importacións e exportacións de pescada conxelada de 193 países durante o período 2016 a 2020, explorando diferentes medidas de centralidade da rede para identificar os participantes máis relevantes. O capítulo tamén analiza o efecto da sobreexplotación das zonas de pesca tradicionais nos países desenvolvidos, que provocou importantes reformas na xestión pesqueira, reducindo a presión pesqueira e reconstruíndo poboacións. Isto levou a unha redución da produción interna de produtos do mar e a autosuficiencia, o que provocou un aumento das importacións de produtos do mar a través do comercio internacional, principalmente de países en desenvolvemento. Destacamos a interdependencia das nacións na era moderna e o papel que xoga o comercio internacional na conexión de poboacións diversas cunha ampla gama de fontes de alimentos.

Contribución da Tese

A tese revela a complexa interacción entre a demanda de produtos pesqueiros, os impactos do cambio climático na pesca, a dinámica do comercio mundial da pescada e o ciclo de retroalimentación da pesca que exacerba os efectos do cambio climático. Todos estes eixes contribúen a unha narrativa máis ampla da sustentabilidade e a resiliencia do sector pesqueiro. A nosa análise mostra que, aínda que a pesca ofrece oportunidades importantes para abordar a escaseza mundial de alimentos e garantir dietas saudables e equilibradas, a súa xestión está chea de desafíos relacionados coa sobreexplotación, a sustentabilidade e as disparidades económicas. O aumento da poboación mundial e a crecente demanda de fontes de alimentos nutritivos fan que a xestión pesqueira sostible sexa máis crítica que nunca. Esta tese proporciona evidencias científicas e novos coñecementos que poden ser útiles para deseñar solucións que axuden a xestionar a explotación da pescada a niveis de produción sostibles, apoiando a mitigación do cambio climático e as dietas saudables. E coñecementos que poden servir de inspiración e base

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para un contexto máis amplo, doutras especies, zonas xeográficas e artes de pesca. Entregamos unha proposta sólida que pasa pola identificación da vulnerabilidade para priorizar estratexias de xestión e adaptación, seguindo os impactos da cadea de produción para establecer un equilibrio entre os patróns saudables de consumo de peixe e os impactos ambientais asociados, e as complexas redes de comercio internacional que exemplificar os retos e oportunidades inherentes aos mercados mundiais de produtos do mar, destacando a necesidade de prácticas de xestión sostible, políticas comerciais equitativas e redes comerciais resistentes. En conclusión, este estudo proporciona evidencias que destacan a necesidade dun enfoque colaborativo a nivel nacional e internacional para abordar os retos da sustentabilidade da pesca, implicando a todas as partes interesadas, desde os pescadores ata os responsables políticos.

Recomendacións para a Xestión e Politicas Pesqueiras

Esta tese ofrece recomendacións para os responsables políticos e políticos:

1. Avogamos por accións de xestión estratéxica e políticas pesqueiras a escala global que inclúan contextos locais para o desenvolvemento resiliente ao clima. Solicitamos: (a) realizar avaliacións detalladas da vulnerabilidade a escala local para descubrir fontes socioecolóxicas adicionais e significativas de vulnerabilidade para as pesqueiras e as súas poboacións ante o cambio climático; (b) políticas que protexan as comunidades humanas, os ecosistemas mariños e as pesqueiras máis vulnerables; (c) estratexias de xestión pesqueira que aborden as desigualdades sociais e económicas e as diferenzas resultantes na capacidade de adaptación, garantindo así a produción de peixe a longo prazo, así como a seguridade alimentaria e dos ingresos.

2. Avogamos polo liderado empresarial e as políticas públicas dirixidas a adoptar solucións innovadoras en toda a cadea de valor, como (a) reducir as emisións de GEI nas operacións e nas cadeas de subministración mediante solucións climáticas baseadas na natureza; (b) ampliar e normalizar a etiquetaxe dos alimentos para incluír información sobre as implicacións para a saúde e a sustentabilidade dos produtos alimenticios; (c) apoiar o sector pesqueiro nesta transición con formación e desenvolvemento, asistencia e recoñecemento; (d) promover prácticas de comercialización transparentes que fomenten o consumo de alimentos sans e sostibles; (e) axudar aos consumidores a reducir o desperdicio de alimentos con ideas para as sobras e o tamaño das porcións; e (f) adoptar unha mestura de proteínas diversa e sostible aumentando a diversidade de fontes de proteínas de orixe vexetal.

3. Recomendamos realizar análises complexas das redes de comercio internacional doutras especies comerciais e destacar a necesidade dun enfoque colaborativo para promover redes máis eficientes no que se refire á sustentabilidade ambiental, máis resistentes aos cambios políticos, económicos e ecolóxicos, que impliquen as partes interesadas de todo o mundo. espectro, desde pescadores ata responsables políticos.

Palabras clave: cambio climático, avaliación da vulnerabilidade climática, pesqueiras demersais, pegada de carbono, España, pescada, comercio global.

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RESUMEN (CASTELLANO)

El sector pesquero mundial, uno de los pilares de la seguridad alimentaria y la estabilidad económica, se enfrenta a desafíos sin precedentes debido al cambio climático y a la dinámica del mercado impulsada por una creciente demanda mundial de productos del mar, que está ejerciendo una presión aún mayor sobre los recursos marinos que ya están enormemente sobreexplotados. . El cambio climático tiene un impacto negativo en los ecosistemas marinos, afectando tanto a las poblaciones de peces como a las actividades pesqueras, lo que amenaza la disponibilidad de productos del mar y los ingresos generados por este sector (Pinsky et al., 2013; Scheffers et al., 2016; Olsen et al. , 2019). En respuesta a la disminución de las capturas de poblaciones de peces, algunas flotas mundiales terminan intensificando sus operaciones pesqueras, lo que a su vez aumenta las emisiones de GEI debido al uso intensivo de combustibles fósiles, lo que contribuye al cambio climático (Tickler et al., 2018; Sala et al. , 2022). La escasez de recursos, sumada a los cambios regulatorios en la gestión pesquera, impulsa el comercio mundial para satisfacer la creciente demanda de estos alimentos que son fundamentales para la calidad nutricional de millones de personas (Gephart y Pace, 2015; FAO, 2018). La intensificación del comercio internacional, que a su vez optimiza la distribución de alimentos, diversifica las dietas y estabiliza los precios (D'Odorico et al. 2014; Ge et al. 2021), también genera redes de gran interdependencia, con unos pocos países dominando los flujos comerciales globales. , además de contribuir al aumento de las emisiones de GEI debido al transporte de larga distancia, ampliando la huella de carbono relacionada con el consumo de productos del mar (FAO, 2018; Crippa et al., 2021; Xu et al., 2021). Abordar estos desafíos requiere una estrategia integrada que incluya la gestión pesquera sostenible, prácticas pesqueras bajas en emisiones, comercio internacional responsable y adaptación al cambio climático.

En esta compleja interacción entre los impactos del cambio climático en la producción pesquera y la contribución de la pesca al cambio climático, los efectos no se sienten uniformemente a escala global, y los impactos del cambio climático dependen de las características ambientales y socioeconómicas de cada país. región (Allison et al., 2009; IPCC, 2014; Payne et al., 2020). Para abordar estos problemas, se han aplicado ampliamente las Evaluaciones de Vulnerabilidad Climática (CVA) para comprender, cuantificar y sintetizar los impactos del cambio climático en el sector pesquero, establecer prioridades para la asignación de fondos de adaptación y proporcionar a los responsables de políticas el conocimiento necesario para hacer prácticas. decisiones (por ejemplo, Allison et al., 2009; Cinner et al., 2012; Colburn et al., 2016; Pinnegar et al., 2019; Payne et al., 2020). A medida que avanzamos en nuestra comprensión de los impactos del cambio climático en la pesca, es crucial reconocer también la importante contribución del sector a la huella de carbono global. La actividad pesquera, si bien es esencial para la seguridad alimentaria y la economía de muchas comunidades, es una fuente notable de emisiones de gases de efecto invernadero (IPCC, 2019). En este contexto, la huella de carbono de un producto se refiere a las emisiones de GEI evaluadas a lo largo de su ciclo de vida, desde las materias primas hasta la producción, distribución, uso por parte del consumidor y eliminación (Carbon Trust et al., 2008). Los estudios de huella de carbono se han aplicado ampliamente en diversos sectores económicos, incluido el sector alimentario, que es responsable de un tercio de las emisiones antropogénicas globales de GEI (Crippa et al., 2021; Xu et al., 2021). A pesar de los avances, los productos de la pesca marina históricamente han sido desatendidos, y las recomendaciones de gestión se

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basan en estudios que no captan la gran variabilidad de las emisiones entre pesquerías que se dirigen a diferentes especies y utilizan diferentes artes de pesca (Parker et al., 2018). Si bien los análisis de GEI resaltan la relevancia de las emisiones de la pesca de captura, investigaciones recientes señalan la relevancia de considerar todas las etapas del ciclo de vida del producto, como el procesamiento, el embalaje y el transporte (Crippa et al., 2021; Xu et al., 2021). De hecho, el transporte adquiere especial importancia en el contexto actual de globalización, caracterizado por una creciente demanda de productos del mar, cadenas de suministro más largas y una mayor dependencia de las importaciones de alimentos.

Los factores económicos, tecnológicos y culturales resultantes de la globalización han impulsado el comercio internacional de productos acuáticos en las últimas décadas. La liberalización de las políticas comerciales y los avances en logística y tecnología de las comunicaciones han ayudado a promover la interdependencia económica y la difusión cultural, incluida la diversificación de los hábitos alimentarios. Además de desempeñar un papel importante en la seguridad alimentaria mundial, la expansión del comercio de productos acuáticos tiene un impacto significativo en la economía mundial, generando ingresos de exportación, empleo y valor agregado (FAO, 2022). El comercio de productos acuáticos también refleja disparidades económicas mundiales, con un patrón general en el que los países en desarrollo suministran productos a los países desarrollados, que tienen más ingresos disponibles y una oferta interna insuficiente para satisfacer la demanda. Disminución de las poblaciones de peces, sobreexplotación y cambios en la distribución la proliferación y abundancia de especies comercialmente valiosas impulsadas por el cambio climático tienen implicaciones de gran alcance para la seguridad alimentaria mundial, pero también tienen consecuencias profundas para los productores y, en consecuencia, para las redes comerciales internacionales (Gephart et al. 2017). Mapear estas complejas redes es vital para una gestión pesquera eficaz que garantice los beneficios del comercio sin comprometer la sostenibilidad a largo plazo de los recursos marinos (Giron-Nava et al. 2021).

Con un litoral de aproximadamente 8.000 km y 340 puertos pesqueros registrados (EUMOFA, 2020), España se encuentra entre los 25 mayores productores de productos pesqueros y alberga el mayor sector pesquero de la UE, representando el 21% de todas las empresas activas y 25 % de los ingresos generados por el sector (STECF, 2019a). En 2020, España fue el cuarto importador de pescados y mariscos del mundo y el mayor importador de la Unión Europea, que a su vez fue el mayor mercado de importación, representando el 34% del valor global de las importaciones de productos acuáticos (FAO, 2022). La merluza se consume ampliamente en todo el mundo y destaca como una especie crucial para la industria pesquera. Su importancia va más allá de la nutrición; es un símbolo de patrimonio cultural gastronómico para la población de Europa Occidental, especialmente en países como España, donde tiene una gran importancia en su mercado, y un peso significativo para la economía del sector pesquero y el comercio internacional (MAPA, 2017). Cada etapa de la cadena de valor de la merluza involucra a diferentes actores, como pescadores, vendedores y/o intermediarios, mercados tradicionales, transportistas, empresas mayoristas y minoristas, dueños de restaurantes, grandes almacenes, hasta llegar a la mesa del consumidor. Y esta cadena de valor se diferencia tanto por su relevancia económica para las regiones españolas como por su pesca, distribución, transporte poscosecha y comercio exterior.

Por tanto, esta tesis se justifica en un escenario caracterizado por i) la importancia del sector pesquero para la subsistencia y la seguridad alimentaria; ii) la relevancia de la merluza

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para el sector pesquero; iii) el aumento del consumo mundial per cápita de productos pesqueros; y iv) la necesidad de una explotación sostenible de los recursos pesqueros. Los países deben ser más responsables en la gestión del sector pesquero para garantizar la sostenibilidad ambiental y la calidad nutricional de una población mundial en crecimiento (FAO, 2020).

Objetivos y Preguntas de Investigación

En este contexto, utilizando la pesca demersal en España y la merluza como caso de estudio, el objetivo general de esta tesis es proporcionar información sobre los desafíos y la dinámica del sector pesquero, desde el impacto del cambio climático en las pesquerías regionales hasta la sostenibilidad ambiental de las prácticas pesqueras y las influencias del comercio global, con el objetivo de contribuir al desarrollo de estrategias efectivas para la gestión pesquera y la resiliencia futura del sector, en beneficio de sus trabajadores y las comunidades involucradas. Con este fin, buscamos comprender cómo podemos desarrollar una planificación personalizada de adaptación pesquera a escala regional que aborde las vulnerabilidades específicas de la pesca al cambio climático, investigar las implicaciones de la huella de carbono de la cadena de suministro pesquera para la sostenibilidad y la política ambiental, y Profundizar en los desafíos y oportunidades de la gestión pesquera sostenible en el contexto de las tendencias del mercado comercial global. Por lo tanto, exploramos cómo se pueden gestionar las pesquerías para que sean resilientes al cambio climático, garanticen la seguridad alimentaria y aborden cuestiones de justicia climática.

Las preguntas que pretendemos responder para explorar y contribuir a la creación de conocimiento científico sobre la socioecología de la pesca ante el cambio climático son:

1. ¿Cuál es la relevancia de la vulnerabilidad regional de las pesquerías demersales españolas al cambio climático y qué estrategias de gestión se pueden aplicar para asegurar la viabilidad a largo plazo de los recursos marinos? (Capitulo 2)

2. ¿Cuál es la huella de carbono de la pesca, el transporte internacional y la distribución nacional sobre la huella de carbono de la cadena de suministro de la merluza, y sus implicaciones para la sostenibilidad y la política ambiental? (Capítulo 3).

3. ¿Cómo participan los diferentes países y regiones en el mercado comercial y cuáles son los desafíos y oportunidades para la gestión sostenible de la pesca de merluza en el contexto de las tendencias del mercado comercial global? (Capítulo 4).

Estructura de la Tesis

Esta tesis consta de tres capítulos en forma de artículos científicos, Capítulos 2, 3 y 4. En el Capítulo 2, titulado "La importancia de las diferencias regionales en la vulnerabilidad al cambio climático para las pesquerías demersales", nos esforzamos por exponer e iluminar la importancia de diferencias regionales en la vulnerabilidad al cambio climático para las pesquerías y las comunidades costeras. Utilizando la flota demersal española como caso de estudio, desarrollamos una Evaluación de Vulnerabilidad Climática (CVA) dentro de un marco que considera la vulnerabilidad en función de la sensibilidad, la exposición y la capacidad de adaptación. A partir de un conjunto robusto de indicadores, evaluamos nueve regiones costeras del país (Comunidades Autónomas), comparándolas entre sí y con las zonas mediterránea y atlántica. El capítulo aplica este marco a la pesca demersal para identificar las regiones costeras de España más expuestas al cambio climático, así como para identificar posibles estrategias de

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gestión que aseguren la resiliencia a largo plazo de las comunidades y los recursos pesqueros. Comenzamos el capítulo destacando el papel crucial del océano en la seguridad alimentaria y los medios de vida de millones de personas en todo el mundo. Luego examinamos el impacto del cambio climático en el medio marino y sus posibles consecuencias para los desembarques pesqueros, la economía y la seguridad alimentaria. Subrayamos que los efectos del cambio climático no se sienten de manera uniforme en todo el mundo y dependen de las características ambientales y socioeconómicas de cada región. Por lo tanto, es esencial desarrollar una planificación personalizada de la adaptación pesquera a escala regional para abordar las vulnerabilidades específicas de la pesca al cambio climático. Nuestros resultados resaltan diferencias significativas en el índice de vulnerabilidad al cambio climático entre las comunidades autónomas, así como entre las zonas mediterránea y atlántica, respaldadas en gran medida por factores de exposición y capacidad de adaptación.

En el Capítulo 3 de la tesis, “La Huella de Carbono de la Cadena de Suministro de Merluza en España: Contabilización de la Pesca, el Transporte Internacional y la Distribución Nacional”, reconstruimos, por primera vez, la cadena de suministro de productos marinos de merluza en España para comprender los impactos ambientales del sector relacionados con las emisiones de gases de efecto invernadero, así como identificar oportunidades de sostenibilidad, gestión pesquera y políticas ambientales. El capítulo refuerza la importancia de reducir las emisiones de GEI para mitigar el cambio climático y destaca el papel del sector pesquero en la contribución a estas emisiones. Utilizando un enfoque de análisis del ciclo de vida (ACV), presentamos un análisis integral de la huella de carbono de la cadena de suministro de la merluza en España, incluidas las operaciones de pesca, el transporte internacional y la distribución nacional, considerando los modos aéreo, terrestre y marítimo y sus especificidades. El enfoque ACV permite un análisis sólido del impacto ambiental de la cadena de suministro. Nuestros resultados indican una contribución significativamente mayor de las operaciones pesqueras a la huella de carbono de la cadena de suministro de la merluza en comparación con el transporte. También identificamos oportunidades para reducir la huella de carbono de la cadena de suministro de merluza, como mejorar la eficiencia del combustible en las operaciones pesqueras, reducir el desperdicio de alimentos y promover patrones de consumo más sostenibles.

En el Capítulo 4, "Producción y comercio global de merluza: consideraciones para la seguridad alimentaria y la resiliencia de la cadena de suministro", a través de una metodología compleja de análisis de redes y herramientas de visualización de gráficos, decodificamos la Red Internacional de Comercio Global de Merluza (HGTN) analizando la posición de varios países para arrojar luz sobre la susceptibilidad del mercado mundial de productos pesqueros a los cambios económicos, políticos y ecológicos, destacando la necesidad de prácticas comerciales resilientes, adaptables y específicas para gestionar de manera sostenible el comercio mundial de productos pesqueros. Nuestros hallazgos subrayan la importancia de gestionar los recursos y mantener el equilibrio del mercado para apoyar la seguridad alimentaria mundial y reflejar el dinamismo del sector pesquero. Examinamos las tendencias temporales en los desembarques de merluza para comprender las principales especies de merluza explotadas y los países pesqueros dominantes. Luego, para comprender mejor la red comercial mundial, nos centramos en determinar dónde se produce el mayor consumo aparente de merluza. Además, presentamos las importaciones y exportaciones de merluza congelada de 193 países durante el período 2016 a 2020, explorando diferentes medidas de centralidad de la red para identificar a los

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participantes más relevantes. El capítulo también analiza el efecto de la sobreexplotación de las zonas pesqueras tradicionales en los países desarrollados, que ha impulsado importantes reformas en la gestión pesquera, reduciendo la presión pesquera y reconstruyendo las poblaciones. Esto ha llevado a una reducción de la producción nacional de productos del mar y a la autosuficiencia, lo que ha resultado en un aumento de las importaciones de productos pesqueros a través del comercio internacional, principalmente de países en desarrollo. Enfatizamos la interdependencia de las naciones en la era moderna y el papel que desempeña el comercio internacional al conectar poblaciones diversas con una amplia gama de fuentes de alimentos.

Aporte de Tesis

La tesis revela la compleja interacción entre la demanda de productos pesqueros, los impactos del cambio climático en la pesca, la dinámica del comercio mundial de merluza y el circuito de retroalimentación de la pesca que exacerba los efectos del cambio climático. Todos estos ejes contribuyen a una narrativa más amplia de la sostenibilidad y resiliencia del sector pesquero. Nuestro análisis muestra que, si bien la pesca ofrece importantes oportunidades para abordar la escasez mundial de alimentos y garantizar dietas saludables y equilibradas, su gestión está plagada de desafíos relacionados con la sobreexplotación, la sostenibilidad y las disparidades económicas. El aumento de la población mundial y la creciente demanda de fuentes de alimentos nutritivos hacen que la gestión pesquera sostenible sea más crítica que nunca. Esta tesis proporciona evidencia científica y nuevos conocimientos que pueden ser útiles para diseñar soluciones que ayuden a gestionar la explotación de merluza a niveles de producción sostenibles, apoyando la mitigación del cambio climático y dietas saludables. Y conocimientos que pueden servir de inspiración y fundamento para un contexto más amplio, de otras especies, zonas geográficas y artes de pesca. Hemos entregado una propuesta sólida que pasa por la identificación de la vulnerabilidad para priorizar estrategias de manejo y adaptación, siguiendo los impactos de la cadena productiva para establecer un equilibrio entre los patrones saludables de consumo de pescado y los impactos ambientales asociados, y las complejas redes de comercio internacional que ejemplificar los desafíos y oportunidades inherentes a los mercados mundiales de productos del mar, destacando la necesidad de prácticas de gestión sostenible, políticas comerciales equitativas y redes comerciales resilientes. En conclusión, este estudio proporciona evidencia que resalta la necesidad de un enfoque colaborativo a nivel nacional e internacional para abordar los desafíos de la sostenibilidad pesquera, involucrando a partes interesadas de todo el espectro, desde pescadores hasta formuladores de políticas.

Recomendaciones para la Gestión y Políticas Pesqueras

Esta tesis ofrece recomendaciones para tomadores de decisiones y formuladores de políticas:

1. Abogamos por acciones de gestión estratégica y políticas pesqueras a escala global que incluyan contextos locales para un desarrollo resiliente al clima. Solicitamos: (a) realizar evaluaciones detalladas de la vulnerabilidad a escala local para descubrir fuentes socioecológicas adicionales e importantes de vulnerabilidad de las pesquerías y sus poblaciones al cambio climático; (b) políticas que protejan a las comunidades humanas, los ecosistemas marinos y las pesquerías más vulnerables; c) estrategias de ordenación pesquera que aborden las desigualdades sociales y económicas y las diferencias resultantes en la capacidad de

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adaptación, garantizando así la producción pesquera a largo plazo, así como la seguridad alimentaria y de ingresos.

2. Abogamos por el liderazgo empresarial y políticas públicas encaminadas a adoptar soluciones innovadoras en toda la cadena de valor, como (a) reducir las emisiones de GEI en las operaciones y cadenas de suministro que utilizan soluciones climáticas basadas en la naturaleza; (b) ampliar y estandarizar el etiquetado de los alimentos para incluir información sobre las implicaciones de los productos alimenticios para la salud y la sostenibilidad; (c) apoyar al sector pesquero en esta transición con capacitación y desarrollo, asistencia y reconocimiento; (d) promover prácticas de marketing transparentes que fomenten el consumo de alimentos saludables y sostenibles; (e) ayudar a los consumidores a reducir el desperdicio de alimentos con ideas sobre sobras y tamaños de porciones; y (f) adoptar una mezcla de proteínas diversa y sostenible aumentando la diversidad de fuentes de proteínas de origen vegetal.

3. Recomendamos realizar análisis complejos de las redes de comercio internacional de otras especies comerciales y resaltar la necesidad de un enfoque colaborativo para promover redes más eficientes con respecto a la sostenibilidad ambiental, más resilientes a los cambios políticos, económicos y ecológicos, involucrando a las partes interesadas de todo el mundo. espectro, desde los pescadores hasta los responsables de la formulación de políticas.

Palabras clave: cambio climático, evaluación de la vulnerabilidad climática, pesquerías demersales, huella de carbono, España, merluza, comercio global.

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SUMMARY (ENGLISH)

The global fisheries sector, one of the pillars of food security and economic stability, is facing unprecedented challenges due to climate change and market dynamics leveraged by a growing global demand for seafood, which is putting even greater pressure on marine resources that are already vastly overexploited. Climate change has a negative impact on marine ecosystems, affecting both fish populations and fishing activities, which threatens the availability of seafood and the income generated by this sector (Scheffers et al., 2016; Pinsky et al., 2018; Olsen et al., 2019). In response to declining catches of fish stocks, some global fleets end up intensifying their fishing operations, which in turn increases GHG emissions due to the intensive use of fossil fuels, contributing to climate change (Tickler et al., 2018; Sala et al., 2022). The scarcity of resources, coupled with regulatory changes in fisheries management, drives global trade to meet the growing demand for these foods that are fundamental to the nutritional quality of millions of people (Gephart and Pace, 2015; FAO, 2018). The intensification of international trade, which in turn optimizes food distribution, diversifies diets, and stabilizes prices (D'Odorico et al. 2014; Ge et al. 2021), also generates networks of great interdependence, with a few countries dominating global trade flows, as well as contributing to increased GHG emissions due to long-distance transport, expanding the carbon footprint related to seafood consumption (FAO, 2018; Crippa et al., 2021; Xu et al., 2021). Addressing these challenges requires an integrated strategy that includes sustainable fisheries management, low-emission fishing practices, responsible international trade and adaptation to climate change.

In this complex interaction between the impacts of climate change on fisheries production and the contribution of fisheries to climate change, the effects are not felt uniformly on a global scale, and the impacts of climate change depend on the environmental and socio-economic characteristics of each region (Allison et al., 2009; IPCC, 2014; Payne et al., 2020). To address these issues, Climate Vulnerability Assessments (CVAs) have been widely applied to understand, quantify and synthesize the impacts of climate change on the fishing sector, set priorities for the allocation of adaptation funds, and provide policymakers with the necessary knowledge to make practical decisions (for example, Allison et al., 2009; Cinner et al., 2012; Colburn et al., 2016; Pinnegar et al., 2019; Payne et al., 2020). As we advance our understanding of the impacts of climate change on fisheries, it is crucial to also recognize the sector's significant contribution to the global carbon footprint. Fishing activity, while essential for food security and the economy of many communities, is a notable source of greenhouse gas emissions (IPCC, 2019).

In this context, the carbon footprint of a product refers to the GHG emissions assessed throughout its life cycle, from raw materials to production, distribution, consumer use and disposal (Carbon Trust et al., 2008). Carbon footprint studies have been widely applied in various economic sectors, including the food sector, which is responsible for a third of global anthropogenic GHG emissions (Crippa et al., 2021; Xu et al., 2021). Despite the advances, marine fisheries products have historically been neglected, with management recommendations being made based on studies that do not capture the large variability in emissions between fisheries that target different species using different fishing gear (Parker et al., 2018). While GHG analyses highlight the relevance of emissions from capture fisheries, recent research points to the relevance of considering all stages of the product life cycle, such as processing, packaging, and transportation (Crippa et al., 2021; Xu et al., 2021). In fact, transport takes on particular importance in the current context of globalisation, characterised by a growing demand for seafood, longer supply chains, and a greater dependence on food imports.

Economic, technological, and cultural factors resulting from globalisation have boosted international trade in aquatic products in recent decades. The liberalization of trade policies and

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advances in logistics and communication technology have helped to promote economic interdependence and cultural diffusion, including the diversification of food habits. In addition to playing an important role in global food security, the expansion of trade in aquatic products has a significant impact on the world economy, generating export revenue, employment and added value (FAO, 2022). Trade in aquatic products also reflects global economic disparities, with a general pattern where developing countries supply products to developed countries, which have more disposable income and insufficient domestic supply to meet demand. Declining fish stocks, overexploitation and changes in the distribution and abundance of commercially valuable species driven by climate change have far-reaching implications for global food security, but also have profound consequences for producers and consequently for international trade networks (Gephart et al. 2017). Mapping these complex networks is vital for effective fisheries management that ensures the benefits of trade without compromising the long-term sustainability of marine resources (Giron-Nava et al. 2021).

With a coastline of approximately 8,000 km and 340 registered fishing ports (EUMOFA, 2020), Spain is among the 25 largest producers of fish products and is home to the largest fishing sector in the EU, accounting for 21% of all active companies and 25% of the revenue generated by the sector (STECF, 2019a). In 2020, Spain was the fourth largest importer of fish and seafood in the world and the largest importer in the European Union, which in turn was the largest import market, accounting for 34% of the global value of imports of aquatic products (FAO, 2022).

Hake is widely consumed around the world and stands out as a crucial species for the fishing industry. Its importance goes beyond nutrition; it is a symbol of gastronomic cultural heritage for the population of Western Europe, especially in countries like Spain, where it has great importance in its market, and a significant weight for the economy of the fishing sector and international trade (MAPA, 2017). Each stage of the hake value chain involves different actors, such as fishermen, sellers and/or intermediaries, traditional markets, transporters, wholesale and retail companies, restaurant owners, department stores, until it reaches the consumer's table. And this value chain differs both in its economic relevance for Spanish regions and in its fishing, distribution, post-harvest transportation and foreign trade.

This thesis is therefore justified in a scenario characterized by i) the importance of the fisheries sector for subsistence and food security; ii) the relevance of hake for the fisheries sector; iii) the increase in global per capita consumption of fisheries products; and iv) the need for sustainable exploitation of fisheries resources. Countries need to be more responsible in managing the fisheries sector to ensure environmental sustainability and nutritional quality for a growing global population (FAO, 2020).

Objetives and Research Questions

In this context, using demersal fishing in Spain and hake as a case study, the overarching goal of this thesis is to provide insight into the challenges and dynamics of the fishing sector, from the impact of climate change on regional fisheries to the environmental sustainability of fishing practices and the influences of global trade, aiming to contribute to the development of effective strategies for fisheries management and the future resilience of the sector, for the benefit of its workers and the involved communities. To this end, we seek to understand how we can develop customised fishery adaptation planning at the regional scale that addresses the specific vulnerabilities of fisheries to climate change, investigate the implications of the carbon footprint of the fishery supply chain for sustainability and environmental policy, and delve into the challenges and opportunities of sustainable fisheries management in the context of global

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commercial market trends. Thus, we explore how fisheries can be managed to be resilient to climate change, ensure food security, and address climate justice issues.

The questions we intend to answer to explore and contribute to the creation of scientific knowledge on the socio-ecology of fisheries in the face of climate change are:

1. What is the relevance of the regional vulnerability of Spanish demersal fisheries to climate change, and what management strategies can be applied to ensure the long-term viability of marine resources? (Chapter 2)
2. What is the carbon footprint of fishing, international transport, and national distribution on the carbon footprint of the hake supply chain, and its implications for sustainability and environmental policy? (Chapter 3).
3. How do different countries and regions participate in the commercial market, and what are the challenges and opportunities for the sustainable management of hake fisheries in the context of global commercial market trends? (Chapter 4).

Thesis Structure

This thesis comprises three chapters in the form of scientific articles, Chapters 2, 3, and 4. In Chapter 2, entitled "The Importance of Regional Differences in Vulnerability to Climate Change for Demersal Fisheries," we endeavor to expose and illuminate the significance of regional differences in vulnerability to climate change for fisheries and coastal communities. Utilizing the Spanish demersal fleet as a case study, we develop a Climate Vulnerability Assessment (CVA) within a framework that considers vulnerability as a function of sensitivity, exposure, and adaptive capacity. Relying on a robust set of indicators, we evaluate nine coastal regions of the country (Autonomous Communities), contrasting them with each other and with the Mediterranean and Atlantic zones. The chapter applies this framework to demersal fishing to identify the coastal regions of Spain most exposed to climate change, as well as to identify potential management strategies that ensure the long-term resilience of communities and fishery resources. We begin the chapter by highlighting the crucial role of the ocean in food security and the livelihoods of millions of people worldwide. We then examine the impact of climate change on the marine environment and its potential consequences for fishery landings, the economy, and food security. We underscore that the effects of climate change are not felt uniformly across the globe and depend on the environmental and socioeconomic characteristics of each region. Therefore, it is essential to develop customized fishery adaptation planning at the regional scale to address the specific vulnerabilities of fisheries to climate change. Our results highlight significant differences in the climate change vulnerability index among the Autonomous Communities as well as between the Mediterranean and Atlantic zones, largely supported by exposure and adaptive capacity factors.

In Chapter 3 of the thesis, "The Carbon Footprint of the Hake Supply Chain in Spain: Accounting for Fisheries, International Transportation, and Domestic Distribution," we reconstruct, for the first time, the supply chain of hake marine products in Spain to understand the environmental impacts of the sector related to greenhouse gas emissions, as well as to identify opportunities for sustainability, fishery management, and environmental policies. The chapter reinforces the importance of reducing GHG emissions to mitigate climate change and highlights the role of the fishing sector in contributing to these emissions. Using a life cycle assessment (LCA) approach, we present a comprehensive analysis of the carbon footprint of the hake supply chain in Spain, including fishing operations, international transport, and domestic distribution, considering air, land, and maritime modes and their specificities. The LCA approach allows for a robust analysis of the environmental impact of the supply chain.

Our results indicate a significantly greater contribution of fishing operations to the carbon footprint of the hake supply chain compared to transport. We also identify opportunities to reduce the carbon footprint of the hake supply chain, such as improving fuel efficiency in fishing operations, reducing food waste, and promoting more sustainable consumption patterns. In Chapter 4, "Global Production and Trade of Hake: Considerations for Food Security and Supply Chain Resilience," through a complex methodology of network analysis and graph visualization tools, we decode the International Hake Global Trade Network (HGTN) by analyzing the position of various countries to shed light on the susceptibility of the global seafood market to economic, political, and ecological changes, highlighting the need for resilient, adaptable, and specific trade practices to sustainably manage global seafood trade. Our findings underline the importance of managing resources and maintaining market balance to support global food security and reflect the dynamism of the fishing sector. We examine temporal trends in hake landings to understand the main hake species exploited and the dominant fishing countries. Then, to better understand the global trade network, we focus on determining where the highest apparent consumption of hake occurs. Furthermore, we present the imports and exports of frozen hake from 193 countries over the period 2016 to 2020, exploring different network centrality measures to identify the most relevant participants. The chapter also analyzes the effect of overexploitation of traditional fishing zones in developed countries, which has prompted significant reforms in fishery management, reducing fishing pressure and rebuilding populations. This has led to a reduction in domestic seafood production and self-sufficiency, resulting in an increase in seafood product imports through international trade, mainly from developing countries. We emphasize the interdependence of nations in the modern era and the role that international trade plays in connecting diverse populations with a wide range of food sources.

Thesis Contribution

The thesis reveals the complex interaction between the demand for fish products, the impacts of climate change on fishing, the dynamics of the global hake trade, and the feedback loop of fishing exacerbating the effects of climate change. All these axes contribute to a broader narrative of the sustainability and resilience of the fishing sector. Our analysis shows that while fisheries offer significant opportunities for addressing global food shortages and ensuring healthy and balanced diets, their management is fraught with challenges related to overexploitation, sustainability and economic disparities. The increase in global population and the growing demand for nutritious food sources make sustainable fisheries management more critical than ever. This thesis provides scientific evidence and new insights that can be useful for designing solutions to help manage hake exploitation at sustainable production levels, supporting climate change mitigation and healthy diets. And knowledge that can serve as inspiration and foundation for a wider context, of other species, geographical areas and fishing gear. We have delivered a solid proposal that goes through the identification of vulnerability to prioritise management and adaptation strategies, following the impacts of the production chain to establish a balance between healthy patterns of fish consumption and the associated environmental impacts, and the complex international trade networks that exemplify the challenges and opportunities inherent in global seafood markets, highlighting the need for sustainable management practices, equitable trade policies and resilient trade networks. In conclusion, this study provides evidence that highlights the need for a collaborative approach at national and international level to address the challenges of fisheries sustainability, involving stakeholders across the spectrum, from fishermen to policymakers.

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Recommendations for Fishery Management and Policies

This thesis offers recommendations for decision-makers and policymakers:

1. We advocate for strategic management actions and fishery policies on a global scale that include local contexts for climate-resilient development. We call for: (a) conducting detailed vulnerability assessments at the local scale to uncover additional and significant socio-ecological sources of vulnerability for fisheries and their populations to climate change; (b) policies that protect human communities, marine ecosystems, and the most vulnerable fisheries; (c) fishery management strategies that address social and economic inequalities and the resulting differences in adaptive capacity, thus ensuring long-term fish production as well as food and income security.

2. We advocate for business leadership and public policies aimed at adopting innovative solutions throughout the value chain, such as (a) reducing GHG emissions in operations and supply chains using nature-based climate solutions; (b) expanding and standardising food labelling to include information about the health and sustainability implications of food products; (c) supporting the fishing sector in this transition with training and development, assistance, and recognition; (d) promoting transparent marketing practices that encourage the consumption of healthy and sustainable foods; (e) assisting consumers in reducing food waste with ideas for leftovers and portion sizes; and (f) adopting a diverse and sustainable protein mix by increasing the diversity of plant-based protein sources.

3. We recommend conducting complex analyses of the international trade networks of other commercial species and highlight the need for a collaborative approach to promote more efficient networks with respect to environmental sustainability, more resilient to political, economic, and ecological changes, involving stakeholders across the spectrum, from fishermen to policymakers.

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Abstract

The global fishing sector, being one of the pillars of food security and economic stability, faces unprecedented challenges due to climate change and market dynamics driven by growing global demand for seafood (FAO, 2022). This scenario puts even more pressure on already widely exploited marine resources. Climate change negatively impacts marine ecosystems, affecting both fish populations and fishing activities, threatening the availability of seafood and the income generated by this sector (Pinsky et al., 2013; Scheffers et al., 2016; Olsen et al., 2019). In response to declining catches from fish stocks, some global fleets end up intensifying their fishing operations, which in turn increases greenhouse gas emissions due to the intensive use of fossil fuels, contributing to climate change (Tickler et al., 2018; Sala et al., 2022).

The scarcity of resources, combined with regulatory changes in fisheries management, drives global trade to meet the growing demand for these foods, essential for the nutritional quality of millions of people (Gephart and Pace, 2015; FAO, 2018). The intensification of international trade, which in turn optimizes food distribution, diversifies diets and stabilizes prices (D'Odorico et al., 2014; Ge et al., 2021), also generates networks of great interdependence, with some countries dominating global trade flows, in addition to contributing to the increase in greenhouse gas emissions due to long-distance transport, increasing the carbon footprint related to seafood consumption (FAO, 2018; Crippa et al., 2021; Xu et al., 2021).

Addressing these challenges requires an integrated strategy that includes sustainable fisheries management, low-carbon fishing practices, responsible international trade and adaptation to climate change. In this complex context, the interaction between the impacts of climate change on fish production and the contribution of fisheries to climate change is not uniformly felt on a global scale, and the impacts of climate change depend on the environmental and socioeconomic characteristics of each region (Alison et al. al., 2009; IPCC, 2014; Payne et al., 2020).

To address these issues, Climate Vulnerability Assessments (CVAs) have been widely applied to understand, quantify and synthesize the impacts of climate change on the fisheries sector, establish priorities for the allocation of adaptation funds and provide policymakers with the necessary knowledge to make practical decisions (e.g., Alison et al., 2009; Cinner et al., 2012; Colburn et al., 2016; Pinnegar et al., 2019; Payne et al., 2020). As we advance in understanding the impacts of climate change on fisheries, it is crucial to also recognize the sector's significant contribution to the global carbon footprint.

Carbon footprint studies have been widely applied in various economic sectors, including the food sector, responsible for one third of global anthropogenic greenhouse gas emissions (Crippa et al., 2021; Xu et al., 2021). While greenhouse gas analyzes highlight the relevance of emissions from capture fisheries, recent research points to the relevance of considering all stages of the product's life cycle, such as processing, packaging and transportation (Crippa et al., 2021; Xu et al., 2021). International trade in aquatic products has expanded due to globalization, impacting the world economy and global food security (FAO, 2022). However, this trade reflects economic disparities and environmental concerns, highlighting the need for sustainable fisheries management and equitable trade policies (Gephart et al., 2017). Mapping these complex networks is vital for effective fisheries management that ensures the benefits of trade without compromising the long-term sustainability of marine resources (Giron-Nava et al., 2021).

The thesis addresses these challenges and dynamics, with a specific focus on demersal fishing in Spain and hake. The overall objective is to provide insights into the challenges and

dynamics of the fishing sector, from the impact of climate change on regional fisheries to the environmental sustainability of fishing practices and the influences of global trade, with the aim of contributing to the development of effective fisheries management strategies. and the future resilience of the sector, to the benefit of its workers and the communities involved. In chapter 2, entitled "The Importance of Regional Differences in Vulnerability to Climate Change for Demersal Fisheries", the thesis seeks to expose and illuminate the significance of regional differences in vulnerability to climate change for fisheries and coastal communities. In chapter 3 of the thesis, "The Carbon Footprint of the Hake Supply Chain in Spain: Accounting for Fisheries, International Transport and National Distribution", the supply chain of marine hake products in Spain is reconstructed for the first time to understand the sector's environmental impacts related to greenhouse gas emissions, as well as to identify opportunities for sustainability, fisheries management and environmental policies. In chapter 4, "Global Hake Production and Trade: Considerations for Food Security and Supply Chain Resilience", through a complex network analysis methodology and graph visualization tools, the Global International Trade Network is decoded de Pescada (HGTN) analyzing the position of several countries to shed light on the susceptibility of the global seafood market to economic, political and ecological changes, highlighting the need for resilient, adaptable and specific trade practices to sustain the global seafood trade of the sea in a sustainable way.

The thesis reveals the complex interaction between the demand for fish products, the impacts of climate change on fisheries, the dynamics of global fish trade and the fisheries feedback loop exacerbating the effects of climate change. All of these axes contribute to a broader narrative of the sustainability and resilience of the fishing sector. The analysis shows that although fisheries offer significant opportunities to address global food shortages and ensure healthy and balanced diets, their management is permeated by challenges related to overexploitation, sustainability and economic disparities. Rising global populations and growing demand for nutritious food sources make sustainable fisheries management more critical than ever. The thesis provides scientific evidence and new insights that can be useful for designing solutions that help manage hake exploitation at sustainable production levels, supporting climate change mitigation and healthy diets. And knowledge that can serve as inspiration and basis for a broader context, of other species, geographic areas and fishing gear. We deliver a solid proposal that involves identifying vulnerability to prioritize management and adaptation strategies, following the impacts of the production chain to establish a balance between healthy patterns of fish consumption and the associated environmental impacts, and the complex international trade networks that exemplify the challenges and opportunities inherent in global seafood markets, highlighting the need for sustainable management practices, equitable trade policies and resilient trade networks. In conclusion, this study provides evidence that highlights the need for a collaborative approach at national and international levels to address fisheries sustainability challenges, involving stakeholders across the spectrum, from fishermen to policymakers.

Keywords: climate change, climate vulnerability assessment, demersal fisheries, carbon footprint, Spain, hake, global trade.

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1 GENERAL INTRODUCTION

The global fisheries sector, one of the pillars of food security and economic stability, is facing unprecedented challenges due to climate change and market dynamics leveraged by a growing global demand for seafood, which is putting even greater pressure on marine resources that are already vastly overexploited. This is highlighted by the FAO assessment, in which the fraction of fish populations that are within biologically sustainable levels has decreased from 90% in 1974 to 65.8% in 2017 (FAO, 2020; FAO, 2022; Golden et al., 2021). This scenario presents a complex challenge: balancing the need to increase seafood production with sustainable fishing practices that ensure the long-term viability of these resources.

Climate change has a negative impact on marine ecosystems, affecting both fish populations and fishing activities, which threatens the availability of seafood and the income generated by this sector (Scheffers et al., 2016; Pinsky et al., 2018; Olsen et al., 2019). In response to declining catches of fish stocks, some fleets are intensifying their fishing operations, sailing longer distances, and accessing wider areas, which increases their adaptability, while at the same time increasing GHG emissions due to the intensive use of fossil fuels, amplifying the climate changes (Tickler et al., 2018; Sala et al., 2022). The scarcity of resources, coupled with regulatory changes in fisheries management, and the drives global trade to meet the growing demand for these foods that are fundamental to the nutritional quality of millions of people (Gephart & Pace, 2015; FAO, 2018).

The intensification of international trade, which optimizes food distribution, diversifies diets and stabilizes prices (D'Odorico et al. 2014; Ge et al. 2021), also generates networks of great interdependence, with a small number of countries dominating global trade flows, as well as contributing to increased GHG emissions due to long-distance transport, expanding the carbon footprint related to seafood consumption (FAO, 2018; Crippa et al., 2021; Xu et al., 2021). Addressing these challenges requires an integrated strategy that includes sustainable fisheries management, low-emission fishing practices, responsible international trade and adaptation to climate change.

1.1 CLIMATE VULNERABILITY ASSESSMENT

Climate change can impact fisheries in many ways, including their contribution to local economies, global trade flows and the supply of fish products to consumers. The worsening frequency and severity of extreme weather events have the potential to increase the vulnerability of fishing communities. Extreme weather patterns can result in lost fishing days, danger to fishermen's lives, and damage to or loss of fishing equipment and landing and landing sites (Holowed etal., 2013; FAO. 2018). In addition, rising sea levels have the potential to erode and flood vital coastal infrastructure, including fishing ports and processing facilities, damaging the supply chain and fish trade. These impacts require significant investments for adaptation and mitigation, increasing the operating cost for the sector and affecting the prices of seafood products (Halpern et al., 2015; FAO, 2018).

Climate change also influences fuel prices and impacts fishing by increasing the operating costs of fishing fleets. Rising fuel prices, driven in part by climate mitigation policies and strategies aimed at reducing greenhouse gas emissions, can make fishing fleet operations more expensive. This, in turn, puts pressure on the fishing industry to seek more fuel-efficient alternatives or to reduce the time spent at sea, which can influence the sustainability and effectiveness of fishing (Cheilari et al., 2013; Parker & Tyedmers, 2015; Guillen et al., 2016). Considering that fuel constitutes a significant component of fishing costs, the cost of fuel is a relevant concern, where the price of oil directly affects the economic viability of fishing, given that fishing activities are energy intensive.

Increased costs not only decrease profit margins but can also lead to unsustainable fishing practices as fishermen try to maintain income and can also cause seafood prices to rise (Sumaila et al., 2011; Parker & Tyedmers, 2013; Guillen et al., 2016).

In addition, the impacts of climate change on marine environments are inducing changes in the distribution and abundance of commercially valuable species, mass mortality of populations and decline of important habitats for the life cycle of commercial species, affecting their availability (Scheffers et al., 2016; Pinsky et al., 2018; Olsen et al., 2019; Gallagher et al., 2023). These changes usually lead to a reduction in catches of target species and, as a result, fishermen are forced to travel greater distances to maintain their production, thus increasing operating costs, fuel consumption and consequently environmental impacts, including greenhouse gas emissions (Cheung et al., 2010; Sumaila et al., 2011; Ojea et al., 2020). The changes in fishing dynamics not only have significant economic implications for the communities that depend on fishing, but also exacerbate the environmental impacts associated with fishing activities, contributing to a challenging sustainability cycle in the sector (IPCC, 2014).

In this complex interaction between the impacts of climate change on fisheries production and the contribution of fisheries to climate change, the effects are not felt uniformly on a global scale, and the impacts of climate change depend on the environmental and socio-economic characteristics of each region (Allison et al., 2009; IPCC, 2014; Payne et al., 2020). To address these issues, Climate Vulnerability Assessments (CVAs) have been widely applied to understand, quantify and synthesize the impacts of climate change on the fishing sector, set priorities for the allocation of adaptation funds, and provide policymakers with the necessary knowledge to make practical decisions (for example, Allison et al., 2009; Cinner et al., 2012; Colburn et al., 2016; Pinnegar et al., 2019; Payne et al., 2020).

As we advance our understanding of the impacts of climate change on fisheries, it is crucial to also recognize the sector's significant contribution to the global carbon footprint. Fishing activity, while essential for food security and the economy of many communities, is a notable source of greenhouse gas emissions (IPCC, 2019). This feedback loop highlights the importance of integrated approaches that not only assess vulnerability and adapt fishing practices to climate change but also seek to reduce the carbon footprint associated with these activities. Strategies such as improving the energy efficiency of fishing fleets, adopting renewable energy sources and implementing low-carbon fishing practices are essential for mitigating the sector's emissions and contributing to global efforts to combat climate change. Thus, the transition to more sustainable fishing practices not only protects marine ecosystems but also plays a critical role in reducing the global environmental impact of fishing.

1.2 Carbon Footprint Of Fisheries

Fishing is recognized as an energy-intensive food production activity and generates most of its emissions through the burning of fossil fuels (Sala et al., 2022; Muñoz et al., 2023). Technological advances that have greatly increased the efficiency and effectiveness of fishing operations have also made vessels more powerful, consequently increasing the demand for fuels (Wakeford et al., 2006; Thomas et al., 2010; Sala et al., 2022). At the same time, overfishing and the impacts of climate change on marine species and communities have driven greater fishing effort and the move towards more distant fishing grounds in order to ensure the economic viability of these activities (Anticamara et al., 2011; Watson et al., 2013; Tickler et al., 2018). Recent studies have emphasised the significant carbon footprint associated with the fishing sector, highlighting the need for comprehensive energy audits and a better understanding of greenhouse gas (GHG) emissions from fishing operations (Parker et al., 2018; IPCC, 2018).

Meticulously assessing both direct and indirect CO2 emissions throughout the product life cycle is crucial for detecting inefficiencies, enabling the adoption of corrective measures and informed mitigation strategies. This is vital to ensure that fisheries can continue to offer food options that are both sustainable and healthy in the future (Parker et al., 2018; Ziegler & Hornborg, 2023). In

this context, the carbon footprint of a product refers to the GHG emissions assessed throughout its life cycle, from raw materials to production, distribution, consumer use and disposal (Carbon Trust et al., 2008). Carbon footprint studies have been widely applied in various economic sectors, including the food sector, which is responsible for a third of global anthropogenic GHG emissions (Crippa et al., 2021; Xu et al., 2021). Despite the advances, marine fisheries products have historically been neglected, with management recommendations being made based on studies that do not capture the large variability in emissions between fisheries that target different species using different fishing gear (Parker et al., 2018).

While GHG analyses highlight the relevance of emissions from capture fisheries, recent research points to the relevance of considering all stages of the product life cycle, such as processing, packaging, and transportation (Crippa et al., 2021; Xu et al., 2021). In fact, transport takes on particular importance in the current context of globalisation, characterised by a growing demand for seafood, longer supply chains, and a greater dependence on food imports. In a scenario where, (i) fuel represent a crucial variable for the profitability of fishing operations, (ii) fishing plays a key role in providing essential nutrients for the human diet, and
(iii) the urgency of transitioning to low-emission means of production to achieve more sustainable diets; reducing emissions has become one of the main goals of governments around the world, a commitment reinforced by international agreements such as the Paris Climate Agreement (IPCC, 2018; Hicks et al., 2019; Robinson et al., 2022). This dynamic highlight the importance of mapping the commercial networks of fisheries products, their weaknesses, opportunities and associated environmental impacts. Essential information to ensure the resilience of the fisheries sector, and to promote global food and nutrition security in the long term (P'erez-Neira et al., 2016).

1.3 Global Seafood Trade

Economic, technological, and cultural factors resulting from globalisation have boosted international trade in aquatic products in recent decades. The liberalization of trade policies and advances in logistics and communication technology have helped to promote economic interdependence and cultural diffusion, including the diversification of food habits. In addition to playing an important role in global food security, the expansion of trade in aquatic products has a significant impact on the world economy, generating export revenue, employment and added value (FAO, 2022). In 2020, trade activities involving fisheries and aquaculture products were reported by 225 states and territories. The volume of global exports of these products, excluding algae, reached 59.8 million tons, with a market value of US$151 billion. In comparison, this amount was approximately 20 times higher than that recorded in 1976, showing significant growth in international trade in aquatic products over the decades. In that same year, approximately 38 million people were directly employed in the fishing sector and, including workers in secondary and subsistence sectors, together with their dependents, it is estimated that around 600 million people depend on activities related to fishing and aquaculture for their livelihoods (FAO, 2022). Trade in aquatic products also reflects global economic disparities, with a general pattern where developing countries supply products to developed countries, which have more disposable income and insufficient domestic supply to meet demand. Another factor contributing to this trend is linked to trade tariffs, with the main importing markets, such as the EU, the US and Japan, benefiting from reduced or exempted tariffs for countries eligible for the General System of Preferences. This facilitates the rapid growth of exports from emerging countries (World Trade Organization, 2021, 2023). In 2020, the United States led the way as the largest importer of aquatic products, accounting for 15% of the global total, followed by China (10%), Japan (9%), Spain (5%) and France (4%). It is worth noting that China also stood out for the volume of imports both for domestic consumption and for processing and subsequent re-export (World Trade Organization, 2021).

However, international trade in aquatic products and its complex networks are not without their challenges, including geopolitical changes, currency fluctuations, logistical costs and delays, as well as the impacts of disease outbreaks and extreme weather events (Gephart and Pace 2015). The COVID-19 pandemic exemplifies such challenges, causing an estimated 7% reduction in the value of global exports of aquatic products (FAO, 2022), highlighting the vulnerability of international trade in fisheries products to global shocks. Declining fish stocks, overexploitation and changes in the distribution and abundance of commercially valuable species driven by climate change have far-reaching implications for global food security, but also have profound consequences for producers and consequently for international trade networks (Gephart et al. 2017). Mapping these complex networks is vital for effective fisheries management that ensures the benefits of trade without compromising the long-term sustainability of marine resources (Giron-Nava et al. 2021).

1.4 WHY SPAIN, AND WHY HAKE?

With a coastline of approximately 8,000 km and 340 registered fishing ports (EUMOFA, 2020), Spain is among the 25 largest producers of fish products and is home to the largest fishing sector in the EU, accounting for 21% of all active companies and 25% of the revenue generated by the sector (STECF, 2019a). Data from the Scientific, Technical and Economic Committee for Fisheries (STECF) indicate that in 2017, total employment in the Spanish fishing fleet was estimated at 34,326 jobs, and Spain produced around 1 million tons of seafood, representing 18% of the total landings of the entire EU fleet, amounting to almost 2 billion euros in landing value (STECF, 2019b). In 2020, Spain was the fourth largest importer of fish and seafood in the world and the largest importer in the European Union, which in turn was the largest import market, accounting for 34% of the global value of imports of aquatic products (FAO, 2022). With a large domestic market demand for fish and seafood and a high consumption rate, Spain depends heavily on imports, but the country is also a major exporter and connecting link, especially for the EU, which absorbs more than three quarters of its exports (EUMOFA, 2023). Hake, a demersal fish that inhabits depths between 150 and 600 meters, is widely consumed around the world and stands out as a crucial species for the fishing industry. Its importance goes beyond nutrition; it is a symbol of gastronomic cultural heritage for the population of Western Europe, especially in countries like Spain, where it has great importance in its market, and a significant weight for the economy of the fishing sector and international trade (MAPA, 2017). Hake landings in the EU in 2021 totaled 143,065 tons worth 439 million euros, with Spain accounting for more than two-thirds of these total landings. In terms of value, Spanish hake landings in 2021 were worth 262 million euros, an increase of 21% compared to 2020.

In this context, the different species of hake have historically been targeted by demersal fisheries, and their populations are subject to intense pressure due, in part, to the high volume of catches (GFCM, 2017; ICES, 2018). In 2018, Argentine hake (Merluccius hubbsi) was the second most caught species by the Spanish fleet, reaching a live weight of approximately 70,000 tons, while European hake (Merluccius merluccius) ranked seventh with approximately 34,000 tons caught. The rest of the hake species caught make a much smaller contribution to the catch (MAPA, 2018). Each stage of the hake value chain involves different actors, such as fishermen, sellers and/or intermediaries, traditional markets, transporters, wholesale and retail companies, restaurant owners, department stores, until it reaches the consumer's table. And this value chain differs both in its economic relevance for Spanish regions and in its fishing, distribution, post-harvest transportation and foreign trade. This thesis is therefore justified in a scenario characterized by i) the importance of the fisheries sector for subsistence and food security; ii) the relevance of hake for the fisheries sector; iii) the increase in global per capita consumption of fisheries products; and iv) the need for sustainable exploitation of fisheries resources. Countries need to be more responsible in managing the fisheries sector to ensure environmental sustainability and nutritional quality for a growing global population (FAO, 2020).

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1.5 HYPOTHESES, OBJETIVES AND RESEARCH QUESTIONS

In this context, using demersal fishing in Spain and hake as a case study, the general objective of this thesis is to provide insight into the challenges and dynamics of the fishing sector, from the impact of climate change on regional fisheries to the environmental sustainability of fishing practices and the influences of global trade, aiming to contribute to the development of effective strategies for fisheries management and the future resilience of the sector, for the benefit of its workers and the involved communities. To this end, we seek to i) understand how we can develop customised fishery adaptation planning at the regional scale that addresses the specific vulnerabilities of fisheries to climate change (Chapter 2), ii) investigate the implications of the carbon footprint of the fishery supply chain for sustainability and environmental policy (Chapter 3), and iii) delve into the challenges and opportunities of sustainable fisheries management in the context of global commercial market trends (Chapter 4). In this regard, we hypothesize that the sustainable management of hake fisheries, considering regional vulnerability to climate change and the carbon footprint of the supply chain, can mitigate environmental impacts and ensure global food security and the resilience of international seafood trade. Thus, we explore how fisheries can be managed to be resilient to climate change, ensure food security, and address climate justice issues.

The questions we intend to answer to explore and contribute to the creation of scientific knowledge on the socio-ecology of fisheries in the face of climate change are:

1. What is the relevance of the regional vulnerability of Spanish demersal fisheries to climate change, and what management strategies can be applied to ensure the long-term viability of marine resources? (Chapter 2)
2. What is the carbon footprint of fishing, international transport, and national distribution on the carbon footprint of the hake supply chain, and its implications for sustainability and environmental policy? (Chapter 3).
3. How do different countries and regions participate in the commercial market, and what are the challenges and opportunities for the sustainable management of hake fisheries in the context of global commercial market trends? (Chapter 4).

1.6 METHODOLOGICAL APPROACH

This thesis comprises three chapters in the form of scientific articles, Chapters 2, 3, and 4. In Chapter 2, entitled "The Importance of Regional Differences in Vulnerability to Climate Change for Demersal Fisheries," we endeavor to expose and illuminate the significance of regional differences in vulnerability to climate change for fisheries and coastal communities. Utilizing the Spanish demersal fleet as a case study, we develop a Climate Vulnerability Assessment (CVA) within a framework that considers vulnerability as a function of sensitivity, exposure, and adaptive capacity. Relying on a robust set of indicators, we evaluate nine coastal regions of the country (Autonomous Communities), contrasting them with each other and with the Mediterranean and Atlantic zones. The chapter applies this framework to demersal fishing to identify the coastal regions of Spain most exposed to climate change, as well as to identify potential management strategies that ensure the long-term resilience of communities and fishery resources. We begin the chapter by highlighting the crucial role of the ocean in food security and the livelihoods of millions of people worldwide. We then examine the impact of climate change on the marine environment and its potential consequences for fishery landings, the economy, and food security. We underscore that the effects of climate change are not felt uniformly across the globe and depend on the environmental and socioeconomic characteristics of each region. Therefore, it is essential to develop customized fishery adaptation planning at the regional scale to address the specific vulnerabilities of fisheries to climate change. Our results highlight significant differences in the climate change vulnerability index among the Autonomous Communities as well as between the Mediterranean and Atlantic zones, largely supported by exposure and adaptive capacity

factors.

In Chapter 3 of the thesis, "The Carbon Footprint of the Hake Supply Chain in Spain: Accounting for Fisheries, International Transportation, and Domestic Distribution," we reconstruct, for the first time, the supply chain of hake marine products in Spain to understand the environmental impacts of the sector related to greenhouse gas emissions, as well as to identify opportunities for sustainability, fishery management, and environmental policies. The chapter reinforces the importance of reducing GHG emissions to mitigate climate change and highlights the role of the fishing sector in contributing to these emissions. Using a life cycle assessment (LCA) approach, we present a comprehensive analysis of the carbon footprint of the hake supply chain in Spain, including fishing operations, international transport, and domestic distribution, considering air, land, and maritime modes and their specificities. The LCA approach allows for a robust analysis of the environmental impact of the supply chain. Our results indicate a significantly greater contribution of fishing operations to the carbon footprint of the hake supply chain compared to transport. We also identify opportunities to reduce the carbon footprint of the hake supply chain, such as improving fuel efficiency in fishing operations, reducing food waste, and promoting more sustainable consumption patterns. In Chapter 4, "Global Production and Trade of Hake: Considerations for Food Security and Supply Chain Resilience," through a complex methodology of network analysis and graph visualization tools, we decode the International Hake Global Trade Network (HGTN) by analyzing the position of various countries to shed light on the susceptibility of the global seafood market to economic, political, and ecological changes, highlighting the need for resilient, adaptable, and specific trade practices to sustainably manage global seafood trade. Our findings underline the importance of managing resources and maintaining market balance to support global food security and reflect the dynamism of the fishing sector. We examine temporal trends in hake landings to understand the main hake species exploited and the dominant fishing countries. Then, to better understand the global trade network, we focus on determining where the highest apparent consumption of hake occurs. Furthermore, we present the imports and exports of frozen hake from 193 countries over the period 2016 to 2020, exploring different network centrality measures to identify the most relevant participants. The chapter also analyzes the effect of overexploitation of traditional fishing zones in developed countries, which has prompted significant reforms in fishery management, reducing fishing pressure and rebuilding populations. This has led to a reduction in domestic seafood production and self-sufficiency, resulting in an increase in seafood product imports through international trade, mainly from developing countries. We emphasize the interdependence of nations in the modern era and the role that international trade plays in connecting diverse populations with a wide range of food sources.

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2 THE IMPORTANCE OF REGIONAL DIFFERENCES IN VULNERABILITY TO CLIMATE CHANGE FOR DEMERSAL FISHERIES[1]

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Original Article

The importance of regional differences in vulnerability to climate change for demersal fisheries

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Regional differences in climate vulnerability are particularly important in many countries with socio-ecological gradients or geographical and environmental spatial segregation. Many studies are regularly performed at the national level, but regional assessments can provide more detailed information and important insights into intra-national vulnerabilities. They require detailed information of many socio-ecological components that are often neglected at the regional scale but are meaningful and operational at national and international levels. In this work, we developed a climate vulnerability assessment (CVA) to investigate the vulnerability of demersal fisheries based on 19 indicators covering exposure, fisheries sensitivity, species sensitivity (SS) and adaptive capacity (AC) for nine coastal regions of Spain, contrasting the Mediterranean to Atlantic areas. Exposure was consistently larger in the Mediterranean than Atlantic regions, while AC showed the opposite trend. While fisheries and SS did not display a clear Atlantic-Mediterranean pattern, they were critical for capturing regional differences that have an impact on fisheries vulnerability. Our results highlight the generally higher vulnerability of Mediterranean demersal fisheries, mainly due to the lower AC and higher exposure of Mediterranean regions, while providing key regional elements for guiding national and international actions for adaptation. This study demonstrates that the spatial scale considered in the development of CVAs must recognise the spatial heterogeneity in the socio-ecological system within its unit of analysis in order to be a relevant tool for management and policy makers.

Keywords: climate change, climate risk, climate vulnerability assessment, demersal fisheries, fisheries, regional vulnerability, Spain, vulnerability

Introduction

The ocean plays a crucial role in the food security and livelihoods of millions of people worldwide. From 1961 human fish consumption has grown at a rate almost twice that of the world population, and higher than all other animal protein foods, fuelling a sector that currently creates almost 40 million direct employment positions worldwide (Barange *et al.*, 2018; FAO, 2020). Nevertheless, numerous studies suggest that fisheries production is being compromised by climate change impacts on the marine environment (Hollowed *et al.*, 2013; Barange *et al.*, 2018; Moore *et al.*, 2018). Among the most studied effects are the shifts in species distribution and marine productivity, with potential consequences for fisheries landings, the economy and food security (e.g. Hollowed *et al.*, 2013;

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IPCC, 2014a; Gattuso *et al.*, 2015; Barange *et al.*, 2018; Pinsky *et al.*, 2018; Free *et al.*, 2019). However, these effects are not experienced homogeneously at a global scale, and the impacts of climate change depend on the environmental and socio-economic characteristics of each region (Alison *et al.*, 2009; IPCC, 2014a; Payne *et al.* 2020).

Climate vulnerability assessment (CVA) is an analytical framework developed to understand, quantify and synthesize climate change impacts on socio-ecological systems (IPCC, 2001). In it, "vulnerability" is given as a function of the "sensitivity" of a system to climate change, the degree of "exposure" to climate hazards, and "adaptive capacity," as the community's ability to prevent or compensate potential impacts of climate damage (IPCC, 2001). The CVA approach has recently been revised, and its focus has shifted from "vulnerability" to "risk," partly intending to use terms that embrace uncertainties in simulations of future climate impacts (IPCC, 2014a). Despite these changes in nomenclature, the core of the CRA and CVA analysis framework remains essentially unchanged.

To date, several studies have used CVAs and CRAs to investigate the impacts of climate change on the fisheries sector to prioritise where to allocate adaptations funds and provide policy-makers with sufficient knowledge to undertake practical decisions. (e.g. Alison *et al.* 2009; Cinner *et al.*, 2012; Colburn *et al.*, 2016; Pinnegar *et al.* 2019; Payne *et al.*, 2020). This approach has recently been applied at a sub-national level, achieving more detailed information and leading to more accurate analyses of regional vulnerability (Pinnegar *et al.*, 2019; Barnes *et al.*, 2020; Payne *et al.*, 2020). It follows that regional differences are particularly important in many countries with socio-ecological gradients or geographical (and environmental) spatial segregation, for which differences should be expected in the combined effects of (i) the impacts of climate change (Exposure); (ii) the relevance of fisheries to their economies and diets (Sensitivity); and (iii) the limited capacity for social adaptation (Adaptive capacity) (Cinner *et al.*, 2012; Pinnegar *et al.* 2019; Payne *et al.* 2020). However, quantifying these spatial differences poses the challenge of searching for a more diverse set of socio-ecological indicators that capture these important differences at the regional scale, while being meaningful and operational at the national level.

Spain is a paradigmatic example regarding all these characteristics, with two large contrasting areas associated to the Atlantic Ocean and the Mediterranean Sea, and clear gradients and spatial heterogeneity in the ecological, fisheries and socio-ecological contexts (e.g. Hidalgo *et al.*, 2017; Punzón *et al.*, 2020). Indeed, the characteristics of the biological communities and the fisheries that depend on them are also markedly different (FAO, 2018, 2020). Among the common characteristics, demersal fishing plays an important role in both the Atlantic and Mediterranean areas with over one-third of the fleet and more than half the total Spanish fleet's power and gross tonnage (MAPA, 2019). To highlight the importance of regional differences in vulnerability to climate change, we use the demersal fishery to apply a vulnerability assessment framework and identify the Spanish coastal regions that are more threatened by climate change.

Material and methods

Spain is among the 25 largest seafood producers globally and hosts the largest fishing industry in the EU, representing 21% of the total of active companies and 25% of its turnover (STECF, 2019a). In 2017, Spain produced around 1 million tons of seafood, 18% of the total EU fleet landings, with an estimated revenue of 2000 million euros (STECF, 2019b). The Spanish demersal fleet accounted in 2017 for more than 70% of the total revenue with an estimated value of 1500 million euros (STECF, 2019b). With approximately 8000 km of coastline of and 340 registered fishing ports), Spanish coastal regions have distinct characteristics in terms of the relative contribution of different fleets, their dependence on fishing and their socio-economic realities. There are also marked differences between the Atlantic and Mediterranean regions, each having its own fisheries governance structures, with the International Council for the Exploration of the Sea (ICES) active in the Atlantic and the General Fisheries Commission for the Mediterranean (GFCM) in the Mediterranean, developing the fisheries assessment of fisheries resources (e.g. GFCM, 2019; ICES, 2019, for demersal species).

In this context, taking into account: (i) the importance of demersal fishing in Spain; (ii) the heterogeneity of its coastal regions; (iii) and the importance of the fishing sector for livelihood and food security, we investigated the regional vulnerability of demersal fisheries based on 19 indicators covering exposure (E), fisheries sensitivity (FS), species sensitivity (SS), and adaptive capacity (AC) for nine coastal regions of Spain: Galicia, Asturias, Cantabria, Basque Country, Catalonia, Valencia, Balearic Islands, Murcia, and Andalusia. This spatial coverage allowed us to assess differences among these administrative areas and, more generally, between the Atlantic and Mediterranean domains to measure the impact of climate change on fisheries, contrasting these two large areas. Note that Andalusia was considered a Mediterranean region, although part of its coast (the Gulf of Cádiz) is within the Atlantic domain. We made this assumption in order to maintain this region in our analyses, as most indicators could not be partitioned for the Atlantic and Mediterranean regions. The Macaronesian region (i.e. Canary Islands) has not been included in the study due to the minor role played by demersal fishing on its insular shelf and also, in order to maintain the comparability between the Atlantic and Mediterranean areas.

Exposure (E) is defined as the nature and degree to which a system is subjected to significant climatic variations such as temperature anomalies, extreme weather events, or other climate change effects (Füssel & Klein, 2006; IPCC, 2007). The analysis of physical variables is widely considered in vulnerability analysis studies to determine the degree of exposure of the fisheries sector, affecting its operational capacity, economic benefits and food security (Alison *et al.*, 2009; Pinnegar *et al.*, 2019). In this study, we focused on the sea surface temperature trends and the continental shelf area of each region, which was included as a proxy of the probability of exposure to other climate impacts (IPCC, 2014b; Barange *et al.*, 2018; Maxwell *et al.*, 2019) (Table 1). The continental shelf contains an important part of the fishing resources and the effects of climate change on the species that inhabit this area directly threaten the fishing activity and economic productivity. With this in mind, we assume that the regions with the largest shelf areas will tend to have a greater number of impacts associated with climate change, as well as the occasional and/or extreme impact of some of them. FS is defined as the component of total sensitivity that refers to the socio-economic sub-system: employment, food security, among others (Colburn *et al.*, 2016; Pinnegar *et al.*, 2019; Table 1). We used four indicators to assess the FS in each of the nine coastal regions: fleet power, fleet age, fish consumption, and employment (Table 1). Among the characteristics of the fleet, fleet power is highly correlated with tonnage and indicates larger vessels, which are less flexible regarding fishing areas and fishing gear. Larger vessels are expected to be able to move over longer distances and cover larger areas and consequently

Table 1. Summary of variables and data sources used to calculate E, FS and SS and AC of the coastal regions to vulnerabilities associated with climate change impacts on marine demersal fisheries.

Component	Indicator	Variable	Interpretation	Data sources
E	Sea surface temperature	Mean projected sea surface temperature increase (°C at 0.5 m depth) by 2050	Projected trends in the regionalization of the IPCC climate scenarios indicate future exposure of the region to water temperature changes.	COPERNICUS, 2020
	Continental shelf area	Surface of the continental shelf (km^2) between 0 and 200 m	A larger extension of continental shelves (0–200 m) makes fishing regions more exposed to the impacts of climate change as extreme weather events.	EMODNET, 2019
FS	Employment	People working in marine fisheries as % of the total economically active population	Employment in the sector is a direct indicator of its size. In this case, the number of registrations in the sea regime quantifies the fisheries sector capture component. The larger the size, the greater the sensitivity to change.	INE, 2018
	Fleet power	Mean average power of demersal fleet (kW) (2016–2018)	Average vessel power is a measure of fleet capacity; the more powerful fleets are considered the most sensitive and possibly the least adaptive.	STECF, 2019
	Fleet age	Average vessel age (2016–2018)	Older and therefore less efficient fleets are considered to be more sensitive to the effects of climate change.	STECF, 2018
	Fish consumption	Per capita consumption of fishery products (kg/year).	High consumption of seafood is directly related to dependence on this source of protein and, consequently, to sensitivity to climate change.	MAPA, 2019
SS	Price	Price of the main commercial species	The species with the highest market value typically are subject to the greatest fishing pressure, which is why it is estimated that they are more sensitive to climate change.	STECF, 2017
	CPUE stability	Coefficient of variation of the CPUE for the main commercial species by region (2015–2018)	Species with the most variable CPUE are generally those most dependent on environmental conditions and are therefore considered the most sensitive to climate change.	MAPA, unpublished data
	Temperature sensitivity	Preferred temperature range of a species (i.e. range between the 10th and 90th percentile, T10 and T90) divided by its preferred mean temperature.	The species most sensitive to temperature changes will have to withstand narrower temperature ranges and have an affinity for lower temperatures.	AQUAMAPS, 2020

Table 1. Continued

Component	Indicator	Variable	Interpretation	Data sources
	Depth range	Bathymetric range (quantile-10 (D10) of the depth distribution and the quantile-90 (D90)	Inhabiting narrower depth ranges increases species' sensitivity to climate change by limiting their ability to migrate at higher depths.	MAPA, unpublished data
	Spawning period	Spawning season of each species (months/year)	Species with shorter spawning periods will be more sensitive to the seasonal temperature changes expected due to climate change.	FishBase; SeaLife, 2020
AC	Low value species landings	(CPUE of species with low commercial value/total CPUE) × 100 (2016–2018)	The percentage of landings of species with low commercial interest indicates less dependence on resources of high commercial value and is considered an indicator of greater adaptability.	MAPA, unpublished data
	Landings outside the base port	Mean number of ports where each vessel landed (2016–2018)	Landings outside the main port can be considered as indicators of the fleet's ability to adapt, for example to adverse weather conditions or market opportunities.	MAPA, unpublished data.
	Per capita GDP	Per capita GDP	Higher GDP per capita allows for less economic dependence on any single activity, including fisheries, and therefore indicates greater ability to adapt to change.	INE, 2019
	Education	% of the population that complete non-university studies	The percentage of education is an indicator of the population's empowerment, allowing greater adaptation to changing conditions.	MEFP, 2019
	Small scale fisheries	Number of boats using small-scale fishing gear	A larger small-scale fleet represents more opportunities for workers to move within the fishing sector from large-scale to artisanal fishing in order to guarantee their profits and livelihoods.	MAPA, 2019
	Recreational fisheries	Number of recreational fishers	Recreational fishing emerges as an option for migrating boats and fishing crews to the tourist market, an opportunity for adaptation since climate change affects fishing yields and viability.	Gordoa *et al.*, 2019
	Associations	Number of Local Fisheries Action Groups (GALPs) added to the number of Associative Entities of Autonomous Scope (AAS) of the fishing sector	The associative capacity of the sector is related to a greater capacity to adapt to climate change.	REGP, 2019
	Gear diversity	Shannon diversity index of main fishing gear (2016–2018)	A greater diversity of fishing gear within the fleet is related to a greater diversity of target species. Diversification increases the capacity to adapt.	STECF, 2019

COPERNICUS—European Union Earth Observation Programme; EMODNET—European Marine Observation and Data Network; INE—National Statistical Institute of Spain; STECF—Scientific, Technical and Economic Committee for Fisheries; MAPA—Ministry of Agriculture, Fisheries and Food of Spain; MEFP—Spanish Ministry of Education and Vocational Training; REGP—Spanish Network of Fisheries Groups.

be more flexible in terms of spatial distribution. However, this is not the case for the Spanish demersal fleet that even the larger vessels do not spend long periods out of the port.

AC is the degree of adjustment that ecological, social or economic systems can achieve to balance the actual or projected climate and its impacts, including actions that moderate, prevent damage or exploit beneficial opportunities (Noble *et al.*, 2014; UNFCCC, 2018). It includes elements such as the level of social capital, human capital, and the adequacy and effectiveness of governance structures, and it presupposes an indissoluble relationship between climate change actions and the central imperatives of reducing poverty, increasing food security and ending hunger (Haddad, 2005; Yohe *et al.*, 2006; Tol & Yohe 2007; Vincent, 2007). In this study, in addition to these elements that are widely used in climate vulnerability analysis studies, we considered factors of AC related to: the mean number of landing ports per fishing vessel, or the potential of small scale and recreational fishing (Table 1). The possibility of landing outside the base port offers the fishing fleet options for avoiding extreme weather events and seeking a higher economic return on sea voyages. Artisanal fishing is generally more adaptive than industrial fishing regarding target species, fishing gear and fishing locations. Recreational fishing could emerge in this scenario as an option for migrating boats and fishing crews to the tourist market, an opportunity for adaptation since climate change affects fishing yields and viability. Note that some of these factors could serve as either sensitivity or AC indicators. To assess the species sensitivity (SS) to climate change, we collected information on relevant biological traits of the most landed species in both the Atlantic and Mediterranean areas between 2016 and 2018. These traits included temperature preferences (mean and range), spawning duration (months), and depth range, in addition to landing stability and market data (Alison *et al.*, 2009; Hare *et al.*, 2016). These indicators were calculated at the species level and subsequently weighted by the mean CPUE of each species in each region during the period 2016–2018, to represent the sensitivity of the biological communities (Table 1).

Construction of the vulnerability index

A consistent application of weighting criteria has been suggested as an important step to avoid an arbitrary classification of the indicators (Johnson *et al.*, 2016). Because each indicator has its own units, we rescaled the indicators between 0 and 1 to make them unitless and comparable. However, by doing so, we artificially equalled the range of variability of all the indicators. To compensate for this, we use the Coefficient of Variation of each indicator (CV) as a weighting factor, and thus we ended up with a set of unitless and comparable indicators ranked according to their original variability. Following this approach, we computed the E, FS, SS, and AC indices which varied between 0 and 1. The final vulnerability was calculated by adding E, FS, SS, and subtracting –AC.

$$V = E + FS + SS - AC$$

The final vulnerability scores were higher for the most vulnerable regions (i.e. high exposure, high sensitivity and low AC), and lower for the least vulnerable ones. These final index scores were normalized between 0 to 1, with 0 being the lowest vulnerability and 1 the highest vulnerability.

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Results

Exposure (E)

The increase sea surface temperature marked the difference in exposure between the Atlantic and Mediterranean (Wilcoxon W = 20, $p = 0.019$). The Mediterranean regions presented higher warming trends (between 0.023°C/year and 0.028°C/year) than the Atlantic regions (between 0.014°C/year to 0.04°C/year). Note that the highest sea surface temperature increases in the Mediterranean are twice the highest increases in the Atlantic (Figure 1a). The continental shelf indicator was characterised by high interregional variability (Figure 1b). However, no significant difference was found between the Atlantic and Mediterranean areas (Wilcoxon W = 13, $p = 0.054$).

FS

In terms of FS, the indicator with the greatest inter-regional variability was the fisheries employment. The result in the Atlantic region of Galicia (2.1%) was by far the largest, while this indicator ranged between 0.2 and 0.5% in the other regions (Figure 1c). The difference between Atlantic and Mediterranean areas was significant (Wilcoxon W = 1.5, $p = 0.049$). The per capita consumption of fishery products was between 21 and 30 kg/year throughout Spain, with higher consumption in the Atlantic than in the Mediterranean area (Wilcoxon W = 0, $p = 0.019$; Figure 1d). The demersal fleet was generally older in Mediterranean regions (Mean ≈ 38 years) than the Atlantic ones (Mean ≈ 27 years), while this difference was not significant (Wilcoxon W = 17, $p = 0.109$; Figure 1e). Fleet power, used as a proxy for the demersal fleet catch capacity, showed high interregional variability, but no distinct pattern between Atlantic and Mediterranean areas was identified (Wilcoxon W = 10.5, $p = 0.902$; Figure 1f).

AC

Our results showed that three out of the five largest artisanal fleets belong to Mediterranean regions and two to Atlantic ones (Figure 1g). Although there was no clear pattern between these two major areas (Wilcoxon W = 10, $p = 0.903$), the inter-regional scale differences were high. Gear diversity was generally higher in the Mediterranean regions, although no significant difference was revealed between the two areas (Wilcoxon W = 15.5, $p = 0.208$; Figure 1h). Regarding the mean number of ports for landing, there were more for the Atlantic than for the Mediterranean, showing a clear difference (Wilcoxon W = 1.5, $p = 0.048$; Figure 1i). The inter-regional variability was also pronounced for this indicator. In terms of low commercial value species landings, we also found significant differences between the Atlantic and Mediterranean areas (Wilcoxon W = 0, $p = 0.019$), with the Mediterranean regions showing a lower percentage of catches of low commercial value than the Atlantic (Figure 1j).

The Gross domestic product (GDP) ranged between 19.000 and 33.000€ throughout Spain, with the highest GDP belonging to the Atlantic Basque Country region, while Andalusia and Murcia, both located in the Mediterranean were the regions with the lowest GDP (Figure 1k). No significant difference was found between the Atlantic and Mediterranean areas (Wilcoxon W = 6, $p = 0.389$). The rate of non-university education was higher for the Atlantic than for the Mediterranean (Wilcoxon W = 0.5, $p = 0.023$; Figure 1l). In terms of civil participation in fisheries management organizations,

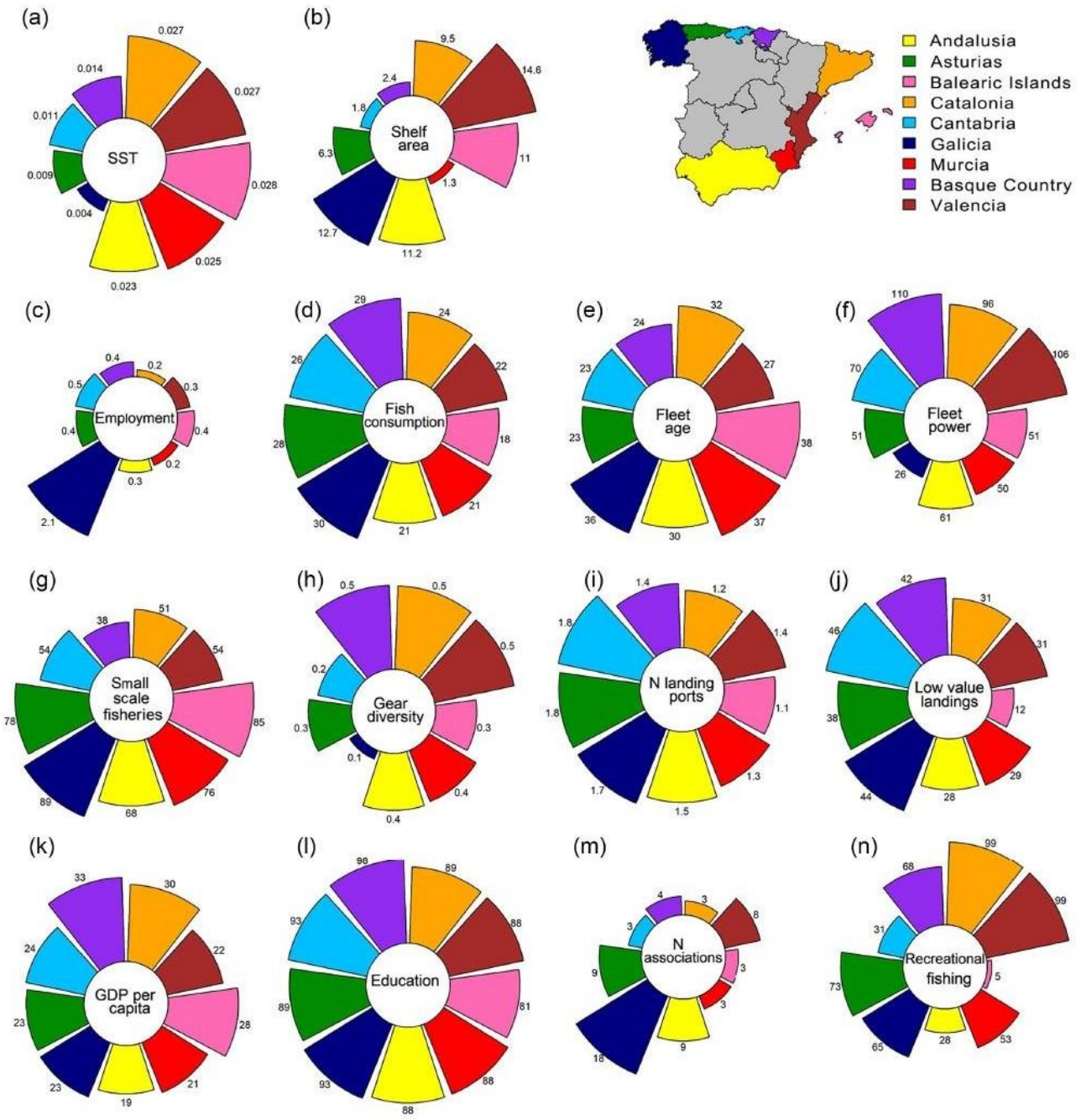

Figure 1. The figure shows the indicators of *Exposure*: (a) continental shelf area, (b) sea surface temperature trend; *FS*, (c) fisheries employment, (d) fish consumption per capita, (e) fleet age, (f) demersal fleet power; and AC (g) small scale fisheries, (h) gear diversity, (l) landings outside the base port, (j) low-value species landings, (k) per capita GDP, (l) non-university education, (m) autonomous community associations, and (n) recreational fisheries. The map shows the colours designated for each coastal region that follow the same pattern in the presentation of the indicator results.

the Atlantic region of Galicia was noteworthy for having the largest number of associations, including Local Support Groups (GALP`s) and Associative Entities of Autonomous Scope for the fishing sector (Figure 1m). Apart from this region, no pattern emerged between the Mediterranean and Atlantic areas (Wilcoxon $W = 6$, $p = 0.368$). Regarding the number of recreational fishers, the largest numbers belonged to Mediterranean regions but still, inter-regional variability was high and no generalised pattern between Atlantic and Mediterranean areas could be recognised (Wilcoxon $W = 9$, $p = 0.902$; Figure 1n).

SS

In terms of the economic value of commercial species, our results showed major price variations with the Mediterranean showing a higher price for most of the species investigated (5.48 ± 5.71€ in the

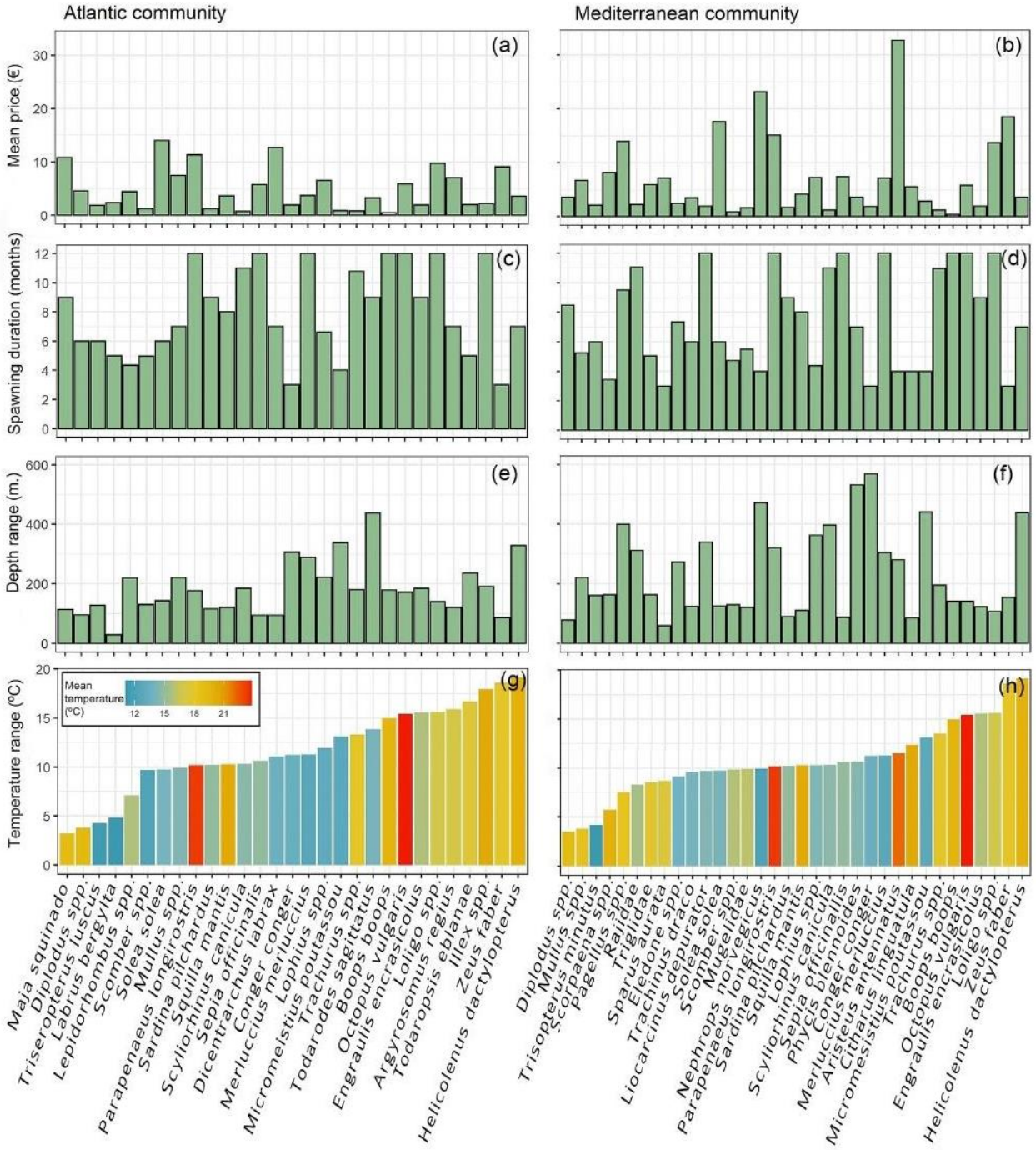

Figure 2. Species sensitivity indicators for the Atlantic and Mediterranean main commercial species targeted by demersal fisheries. Mean price of the main commercial species (a, b); spawning period (c, d); depth range (e, f); and temperature range (g, h).

Atlantic and 6.49 ± 6.71€ in the Mediterranean; Figure 2a, b). Despite major price variations not significant differences between the Atlantic and Mediterranean areas was found (Wilcoxon W = 555, p = 0.389). In terms of life history traits, the spawning period showed similar patterns between the Atlantic and Mediterranean biological communities (Wilcoxon W = 441, p = 0.474; Figure 2c, d). Regarding the species depth ranges, we found differences between the species when contrasting Atlantic and Mediterranean populations, such as for *Conger conger*, *Scyliorhinus canicula* and *Lophius spp.*, with generally wider ranges in the Mediterranean populations (181.78 ± 90.08 m. in the Atlantic and 235.59 ± 145.38 m. in the Mediterranean; Figure 2e and f). No significant difference was found between the two major areas (Wilcoxon W = 514, p = 0.777). In terms of temperature, the Mediterranean and Atlantic areas showed a similar temperature range (11.71 ± 4.27°C in the Atlantic and 10.67 ± 3.65°C in the Mediterranean; Figure 2g and

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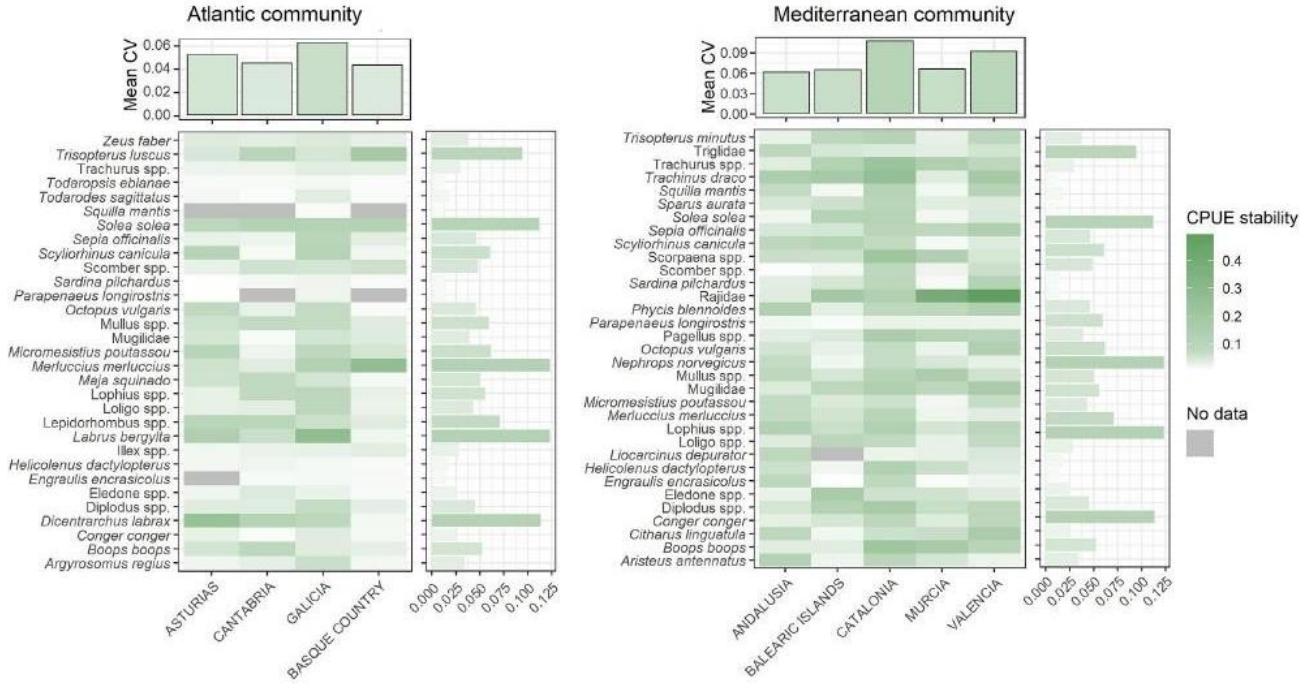

Figure 3. Indicator of stability of landings for Atlantic (left-hand panel) and Mediterranean (right-hand panel) species based on the mean CPUE stability (1/CV). Differences between species and regions are shown for both large areas.

h). Species that require low mean temperatures displayed intermediate temperature ranges (except for *Parapenaeus longirostris*), and species requiring higher mean temperatures displayed both high- and low-temperature ranges. This interaction translated into temperature sensitivity showed a similar pattern between Atlantic and Mediterranean areas (Wilcoxon W = 483.5, $p = 0.620$), being slightly higher in the Mediterranean community (1.7 ± 1.23 in the Atlantic and 1.81 ± 1.16 in the Mediterranean).

The stability of landings showed high inter-regional variability. In general terms, stability was lower in the Atlantic area than in the Mediterranean (Wilcoxon W = 19, $p = 0.037$; 0.051 ± 0.047 and 0.078 ± 0.064, respectively; Figure 3). The mean species sensitivity was similar in the Atlantic and Mediterranean areas (Wilcoxon W = 0.493, $p < 0.05$; 0.46 ± 0.24 and 0.44 ± 0.22 respectively; Figure 4). Some species were particularly sensitive in the Atlantic (e.g. *Zeus faber* and *Maja squinado*) and in the Mediterranean (e.g. *Aristeus antennatus* and *Sparus aurata*), but generally, the species present in both areas had similar sensitivity values; e.g. *Diplodus spp*. And *Solea solea* were among the most sensitive while *Boops boops* and *Scyliorhinus canicula* were among the least sensitive.

Integrative indicators and overall vulnerability index

The integrative exposure index showed that the regions with the highest degree of exposure were: Valencia, Catalonia, Balearic Islands, and Andalusia (Figure 5a), marking a clear distinction between the Atlantic and Mediterranean areas (Wilcoxon W = 19, $p = 0.037$). The regions with the greatest FS were Galicia and the Basque Country (Figure 5b). The result in Galicia was driven mainly by the large number of jobs in the fishing sector, which was the indicator ranking highest regarding inter-regional variability and thus had the largest contribution to the FS index (Figure 5b). The Basque Country had the largest demersal fleet power among all the regions studied, which justifies its position as the second most sensitive region in terms of its fishing fleet. As these two regions are located in the Atlantic, the mean FS of the Atlantic area was generally higher than that of the Mediterranean area (Figure 5b). However, no significant difference was found between Atlantic and Mediterranean areas (Wilcoxon W = 5, $p = 0.2703$).

In terms of species sensitivity Murcia, Valencia and Andalusia were the most sensitive regions, pointing to a more sensitive pattern for the Mediterranean area (Wilcoxon W = 16, $p = 0.172$; Figure 5c) mostly due to the differences in the mean price of the main commercial species. Our analyses have shown that the regions with the least adaptive capacities were the Balearic Islands and Murcia (Figure 5d). The results showed a distinct pattern between the Atlantic and Mediterranean regions (Wilcoxon W = 1, $p = 0.037$), with a lower AC in the Mediterranean region mainly due to the lower number of landing ports, and the lower landings of species of low commercial value (Figure 5d), both indicators being relatively higher than in the Atlantic regions.

In the Mediterranean area Valencia, Balearic Islands, Catalonia and Andalusia emerged as the most vulnerable regions, while the less vulnerable regions were in the Atlantic, i.e. Cantabria, Asturias and Basque Country (Figure 6). These results highlight the generally higher vulnerability of Mediterranean demersal fisheries (Wilcoxon W = 19, $p = 0.037$), partly due to the lower AC of Mediterranean regions and their higher exposure. Galicia was an exception in the Atlantic, with intermediate vulnerability values associated with relative higher exposure (a broad continental shelf) and high FS (Figure 6).

Discussion

Our study conducted a CVA at the regional level based on 19 indicators of exposure, AC, and demersal fisheries and species

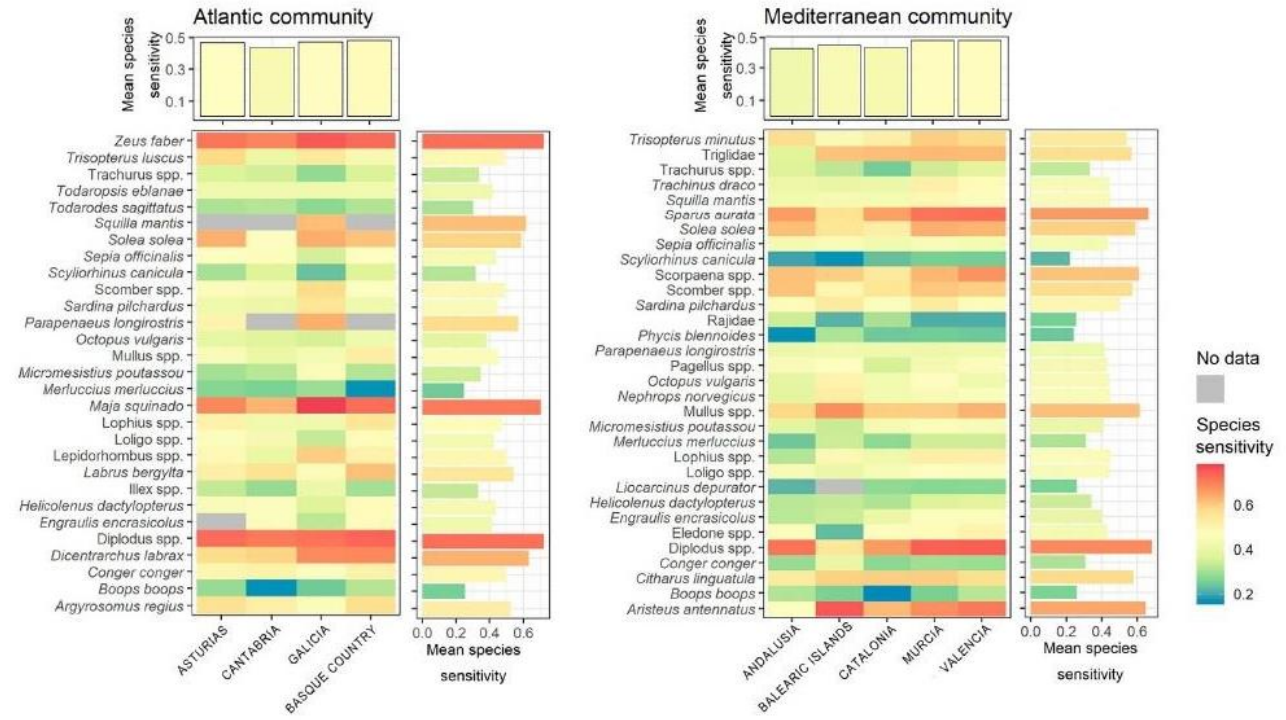

Figure 4. General species sensitivity for Atlantic (left-hand panel) and Mediterranean (right-hand panel) based on the combination of the species sensitivity indicators. Differences between species and coastal regions are shown for both large regions.

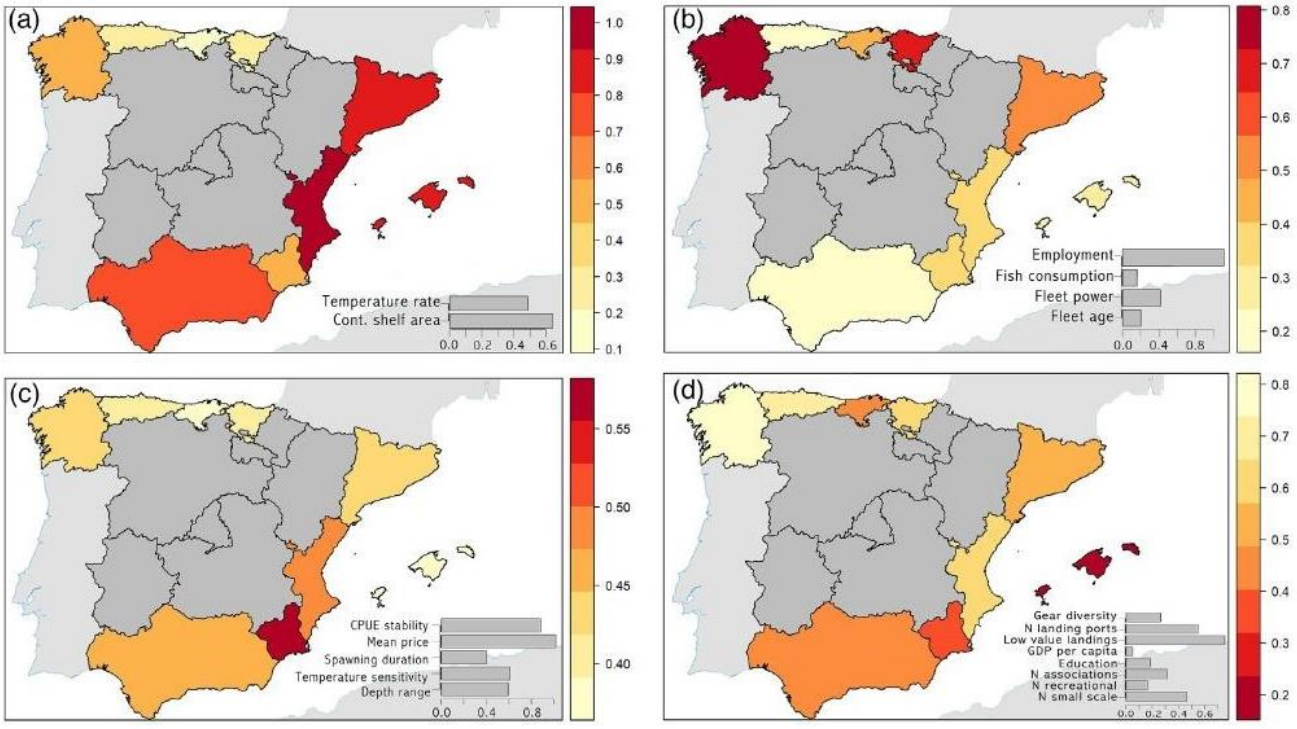

Figure 5. Thematic maps illustrating E (a), FS (b), SS (c), and reverse AC (d) of the Spanish coastal regions (see scale bar; darker colours indicate higher scores associated with higher sensitivity, higher exposure, and lower AC). The grey bars indicate the weight of each indicator in constructing the indexes considering their respective Coefficients of Variation.

sensitivity. Despite the increasing number of CVAs (and CRAs), there is a general lack of assessments specifically considering socio-economic and ecological uniqueness at regional scales, particularly in the European regions. This research gap could be related to the results of previous CVAs performed at the national level, which indicated a generally low vulnerability of the European continent to the risks of climate change, mostly due to its greater AC, when compared to less economically developed regions (Allison *et al.*,

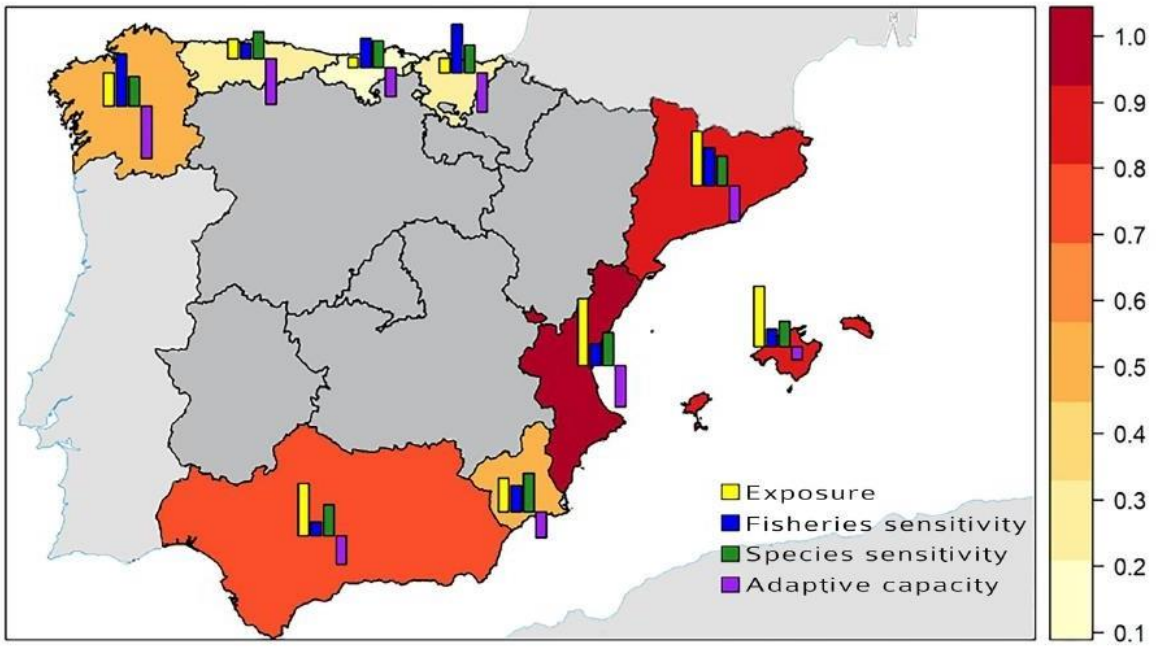

Figure 6. Map illustrating climate vulnerability for each Spanish coastal region based on combined scores for all four attributes (E, FS, SS, AC). The vulnerability index is rated between 0 and 1 (see scale bar; darker colours indicate higher scores associated with higher vulnerability).

2009; Ding *et al.*, 2017). However, recent examples show the need to downscale CVAs (e.g. Pinnegar *et al.*, 2019), mainly when designing effective management approaches (Holsman et al., 2019, 2020).

Beyond clear Atlantic-Mediterranean differences, our study also revealed and characterised previously unknown spatial differences in demersal fisheries vulnerability. Our results point to a generally higher exposure of the Mediterranean coastal regions to climate change risk, than is the case for the Atlantic regions. Indeed, sea surface warming has been more rapid in the Mediterranean Sea than in the Atlantic in the last decades (e.g. Belkin, 2009) and these contrasting warming rates are predicted to persist (Adloff *et al.*, 2015; Aznar *et al.*, 2016). Other climate change-related factors such as acidification, changes in rainfall and, frequency and intensity of extreme meteorological events such as hurricanes or cyclones are not so ubiquitous in the CVA literature, even though they can have clear effects on fisheries vulnerability (; Metcalf *et al.*, 2015; Wabnitz *et al.*, 2018; Pinnegar *et al.*, 2019). This is a limitation for most CVA, which fail to incorporate additional climate factors as these often lack regionalised projections under climate change scenarios. Thus, in addition to the predicted temperature trends, we considered the continental shelf area of each coastal region to account for other climate change-related factors. Indeed, the relatively broader shelf areas in most Mediterranean regions leave their demersal biological communities and fisheries more exposed and thus more vulnerable to the diversity of impacts expected to increase in the Mediterranean, such as the increase of extreme events and heatwaves, changes in vertical mixing and productivity regimes, or changes in the regional circulation and population connectivity (Hidalgo *et al.*, 2018; Darmaraki *et al.*, 2019; Ser-Giacomi *et al.*, 2020; MedECC, 2020). In contrast, CVAs published on European fisheries do not capture this difference, since the exposure indicators considered were different and mainly focused on the diversity of the portfolio of species captured as an indicator of fishery resilience (Payne *et al.*, 2020). This metric is highly relevant over large geographic scales (i.e. broad Europe) as it captures the differences between regions with low diversity of fish in the catches. However, within the national scale, the number of species captured in different regions would generally be more similar, as is the case in Spain (Punzón *et al.*, 2020).

FS proved to be mostly related to the number of jobs in the extractive sector, with Galicia being the most sensitive region in this regard at the national level (STECF, 2019a). The important fishing tradition in Galicia has led to the development of maritime industry that includes activities such as processing and manufacture of canned fish, crustaceans and molluscs. The relevance and socio-economic impact of these activities have made the fishing sector one of Galicia's main economic drivers. Indeed, employment dependency, is the most widely used attribute for exploring FS (Allison *et al.*, 2009; Morzaria-Luna *et al.*, 2014; Ding *et al.*, 2017; Wabnitz *et al.*, 2018; Pinnegar *et al.*, 2019). However, it is also important to notice the high spatial heterogeneity in other factors beyond employment that contribute to FS. Fleet age can be considered a proxy for efficiency in fishing and fuel consumption. The demersal fishing fleet in Spain is generally above 20 years mean age, with several Mediterranean regions approaching 40 years mean age, double the life expectancy for this kind of fishing vessel (Knittweis *et al.*, 2016). An old fishing fleet will suffer from physical deterioration and normal obsolescence, decreasing its capacity to cope with change because it is technologically outdated. Fishing power is highly correlated with tonnage and depicts how much a vessel can fish. While the variability in fleet age is moderate, there is high variability in fishing power, with few coastal regions having a larger share of more powerful industrial vessels, both in the Atlantic and Mediterranean (i.e. Basque Country, Catalonia and Valencia). On the other end, Galicia shows the lowest fishing power, as a large percentage of its fishing fleet is composed of small-scale fishing vessels (MAPA, 2019).

Regarding species sensitivity, the Atlantic-Mediterranean pattern was not as evident. Species sensitivity was the least variable index, pointing to the crucial role of socio-economic differences

in explaining fisheries vulnerability patterns among regions. While about 15% of species in both Atlantic and Mediterranean regions showed high sensitivity (>0.6), their contribution to the overall community sensitivity was low, as they were not among the most abundant species captured by demersal fisheries. The species captured in higher abundances ranked as having low or moderate sensitivities, which reduced species sensitivity index variability among regions. In contrast, to the most used temperature statistics (i.e. maximum preferred temperature ranges [TP90]) (as in Sunday *et al.*, 2015; Hare *et al.*, 2016; Pinnegar *et al.*, 2019), we combined mean and temperature range attributes in an easily computed and broadly applicable indicator of temperature sensitivity. This allowed us to identify species-specific sensitivities within the Atlantic and Mediterranean regions, though not differences between regions. It is important to highlight the difference in species-specific responses to climate change impacts on the marine environment. This reinforces the need for regional studies linking species and climate change all over different ontogenetic stages in order to produce better and more efficient management plans (Catalán *et al.*, 2019; Holsman *et al.* 2019, Twiname *et al.*, 2020). In addition to the most widely used distribution and phenology parameters such as the depth range and spawning time, which are important as resilience indicators (Sunday *et al.*, 2015; Hare *et al.*, 2016), we also estimated the stability of the stocks through the CV of their landings. Together with landing stability, the price analysis emerged as a tool to highlight the pressure suffered by each fish stock, considering that the species with the highest commercial value are therefore subject to higher exploitation rates and will be more vulnerable to climate change risks (Pinnegar *et al.*, 2019; Hiddink *et al.*, 2019).

Another important factor that marked the difference in the vulnerability index between Atlantic and Mediterranean areas was AC, driven partially by lower levels of landings of species of low commercial value in the Mediterranean regions. This could be explained due to the combination of a lower availability of these species and the fact that they are mostly consumed as a proximity fisheries product, as opposed to what occurs in the Atlantic, where there is a higher availability of these species, a higher contribution of catches from other European fishing areas and a higher contribution and supply to the national market (STECF, 2019a). A larger catch of low commercial value species can be related to a greater capacity to adapt, since the fishery is less dependent on a small group of high commercial value species that are under greater fishing pressure. The capture of species of lower commercial value emerges as an alternative when the species of higher value may suffer from the impacts of climate change such as change in distribution and changes in biological patterns. Other indicator that provides flexibility is the possibility of landing part of the catch in different ports, which allows the fleet to adapt in the face of difficulties and impacts associated with climate change, such as adverse weather (e.g. extreme events), but also providing the possibility of taking advantage of better market opportunities. The combination of these two indicators also explains the lower AC in Mediterranean area and particularly the Balearic Islands region, indicating a great dependency of a local and more constrained market (UE, 2011). The transition of fishing crews from large-scale fishing to artisanal fishing and the recreational fishing sector has also been considered an important indicator of adaptation capacity. In this context, the Atlantic region of Galicia shows an adaptative advantage over the other regions with a much larger artisanal fishing fleet that provides more opportunities for the workers to move around within the fishing sector in order to guarantee their profits and livelihood (Gordoa *et al.*, 2019). Note that some indicators could benefit from scaling up by making their values relative to size of other indicators improving the perception of the size to the opportunity (e.g. ratio between recreational and small-scale fishery). However, with the methodological approach taken, this would increase correlation with other indicators affecting the interpretation of our results.

The overall vulnerability index showed a clear pattern between the Atlantic and Mediterranean areas and regions within these two areas. The results for each region are unique in the combination of their dependence on the fishing sector, socio-economic development, and exposure to climate risks regionally. Nevertheless, some regions demand more specific studies due to their biogeographic complexity. For example, Andalusia presents a more pronounced geographical heterogeneity than other regions with part of its territory on the Mediterranean and part on the Atlantic, calling for more specific vulnerability studies for this region which consider its uniqueness. Using demersal fishing on the Spanish coast as an example, the present study highlights the importance of regional scale analyses to achieve more refined diagnoses in CVAs. These studies may be instrumental in supporting decision-making at both national and international levels, as the design of efficient adaptation management strategies requires cross-scale risks (including exposure, sensitivities and differences in adaptive capacities) (Holsman *et al.*, 2020). Future analyses should be conducted to explore the complexity of natural and socio-economic systems, their interactions and their trade-offs. This shows that customised fisheries adaptation planning is urgently needed at the regional level, given that the expected large-scale policies may limit flexibility and compromise their effectiveness (Holsman et al., 2019, 2020). Management results can be more effective when they adopt dynamic measures that locally consider social and environmental variability (Levin *et al.*, 2013). Besides the possibility of not achieving the expected results, the adoption of large-scale adaptation planning can lead to a lack of confidence in fisheries management even within well-managed systems (Levin *et al.*, 2013; Mumby *et al.*, 2017). While the spatial scale for CVA should minimize the complexity and variability (spatial heterogeneity) in the socio-ecological system within its analysis unit, it must be relevant and operational for management purposes. With this in mind, our study calls for a more detailed consideration of the intranational vulnerabilities in other countries to reveal additional and important socio-ecological sources of fisheries vulnerability to climate change.

Data availability

The data underlying this article will be shared on a reasonable request to the corresponding author.

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3 THE CARBON FOOTPRINT OF THE HAKE SUPPLY CHAIN IN SPAIN: ACCOUNTING FOR FISHERIES, INTERNATIONAL TRANSPORTATION, AND DOMESTIC DISTRIBUTION[2]

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The carbon footprint of the hake supply chain in Spain: Accounting for fisheries, international transportation and domestic distribution

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ABSTRACT

Climate change mitigation depends to a large extent on economic sectors modifying their production processes to significantly reduce their greenhouse gas emissions, particularly CO_2. However, greenhouse gas emission assessments are usually excluded from management of capture fisheries. Traditionally, hake (*Merluccius* ssp.) has been an important food for the population of Western Europe, and remains one of the most consumed fish in Spain's gastronomic culture. This paper reconstructs, for the first time, the hake seafood chain in Spain with the aim of estimating the carbon footprint of its extraction (fishing), transport and distribution. Our results show that total greenhouse gas emissions from the hake production and value chain in 2017 were 681 kt CO_2e, with an emission intensity of 4.42 $kgCO_2e\ kg^{-1}$ of whole fish. From these total emissions, those related to fishing operations represent 67% (456 kt CO_2e), with the remaining 33% (225 kt CO_2e) associated with transport (maritime, air or road). Air transport was the highest in terms of emission intensity per kilogram of hake transported (15.85 $kgCO_2e\ kg^{-1}$), and contributed to the largest share (72%) of transport emissions. Maritime transport presented the least emission intensity (0.33 $kgCO_2e\ kg^{-1}$) and predominated for hake caught outside the EU (e.g., Argentina, Namibia), offsetting the long distances the hake had to travel with greater transport efficiency. Our study highlights the importance of including greenhouse gas emissions analysis in the operationalization of the ecosystem-based fisheries management in the European Common Fisheries Policy as well as other regulations such as the Marine Strategy Framework Directive as a key tool for decision makers to appropriately address climate change impacts. The evidence provided by our study highlights the importance of finding a balance between healthy fish consumption patterns and their associated environmental impacts.

1. Introduction

The current globalization of the economy has led to an increasing volume of international trade. An interconnected network of suppliers, producers, traders and consumers across the globe has increased the distances between the production and consumption sites (Kastner and Haberl, 2014; Watson et al., 2015, Farmery et al., 2015). This global supply chain may raise living standards and help alleviate poverty, but it also places great demands on ecosystems and natural resources (Wible et al., 2014; Tilman and Clark, 2014). Reducing greenhouse gas (GHG) emissions to mitigate climate change (CC) requires increasing our knowledge about which sectors generate the largest contributions to GHG emissions and where and how reduction strategies can be effectively implemented. In particular, offshoring processes should be taken into consideration, as they lessen impact indicators in consumer countries at the expense of natural resources from all over the world (Barrett et al., 2013).

Recent studies point out that food system emissions, from production to consumption, including processing, transport and packaging, represent a third of global anthropogenic GHG emissions (Crippa et al., 2021;

[2] This chapter previously appeared as an article in the ICES Journal of Marine Science. The original quote is as follows: Aragao, G. M., Saralegui-Díez, P., Villasante, S., López-López, L., Aguilera, E., & Moranta, J. (2022). *The carbon footprint of the hake supply chain in Spain: Accounting for fisheries, international transportation, and domestic distribution.* **Journal of Cleaner Production**, 360, 131979. https://doi.org/10.1016/j.jclepro.2022.131979

Xu et al., 2021). This indicates a clear difference in GHG emissions between food categories, with grains, fruit and vegetables having the lowest impact and meat from ruminants having the highest impact (Clune et al., 2017; Poore and Nemecek, 2018). Some examples are the impacts related to feed production in the European meat sector (e.g., Weiss and Leip, 2012), or emissions related to synthetic nitrogen fertilizers in Spanish agriculture (e.g., Aguilera et al., 2021). Even more, transport impacts should also be taken into consideration, particularly in countries such as Spain, where dependence on food imports has increased in the last decades (Pérez-Neira et al., 2016). Overall, the emissions of the Spanish population account for 3.5 Mg CO_2e cap^{-1} yr^{-1} related to their consumption patterns, 45% of which is related to animal food (Aguilera et al., 2020).

Previous studies found that the fisheries sector emits between 112 and 179 million tonnes of CO_2 into the atmosphere annually, which accounts for ca 0.5% of total GHG emissions and represents about 4% of global emissions from food production (Tyedmers et al., 2005; Parker et al., 2018; Greer et al., 2019). Despite recent advances, marine capture fisheries are often excluded from global GHG assessments or, in the best of cases, policy recommendations are usually made based on a limited number of case studies, thus not taking into account the large variability in emissions among fisheries that target a wide range of species using different fishing gears (Parker et al., 2018). GHG assessments applied to fisheries show that transport and fuel consumption of the fishing activity commonly constitute the most important impacts (Hospido and Tyedmers, 2005; Vázquez-Rowe et al., 2010, 2011).

Under this context, Spain is among the 25 largest seafood producers in the world and hosts the largest fishing industry in the European Union (EU) (STECF, 2021). In 2019, Spain produced around 850,000 tons of seafood, 29% of the total EU fleet landings, and accounted for nearly 1700 million euros in landing value (STECF, 2021). In Spain, Iribarren et al. (2011) were the first scholars who assessed the carbon footprint of fishing activities, reporting GHG emissions of 888,620 t CO_2e $year^{-1}$ by the Galician fleet. Vázquez-Rowe et al. (2011) also evaluated the environmental impacts related to the extraction, processing and consumption of the northern stock hake in European waters caught by Galician trawlers and longliners, showing considerably lower environmental impacts for fresh fillets of European hake from longline vessels compared to trawlers, mainly due to the high energy demand of the trawlers analysed.

Hake has been an important food for the people of Western Europe throughout history, and it remains as one of the most consumed seafood products in Spain. It is also important for the domestic market and particularly relevant for the economy of the fishing sector and food security, accounting in 2017 for 15% of the total value caught by the Spanish fleet (MAPAMA, 2017a; STECF, 2021). However, there is no evidence available on the carbon footprint of the hake supply chain in Spain as a whole. Therefore, by using the life cycle-oriented indicator of the carbon footprint (Finkbeiner, 2009; Vázques-Rowe et al., 2016), we have assessed, for the first time, the GHG emissions for: (a) Spanish vessels targeting hake landed at domestic ports; b) Spanish vessels targeting hake landed at international ports; (c) hake imports destined for Spain, including GHG emissions from fishing vessels in the countries of origin; and (d) the transport modes and routes (sea, air and land) used for transport to Spain and distribution routes (roads) within the Spanish territory. We also compared the carbon footprint for fresh or chilled hake and frozen hake, which includes only frozen fillets and meat.

2. Material and methods

The system analysed includes extraction (fishing), international transport to Spain, and domestic distribution within Spanish territory for the year 2017. The fleet consumption of fuel included all fishing operations (Supplementary Material, Figure SM1), while imports included international transport as well as emissions from fishing fleet operations in the countries of origin. We accounted for the different types of transport (land, sea and air) and the diverse routes that landings follow from ports to retailers distributed in Spain, following intermodal transport supply chains from abroad up to the final distribution in each Spanish province. The domestic distribution included the recirculation[1] of hake within the national territory and between the logistics centres of the different provinces in order to cover the demand for domestic consumption (Supplementary Material, Figures SM2, SM4, SM5, SM6 and Table SM5).

Some components of the supply chain have been excluded from the analysis: a) all post-retail emissions, including transport, storage, cooking and waste, b) the volume of hake marketed as "canned and processed", because it represents a minimal amount of the total hake marketed in Spain, c) carbon emissions during trawling operations due to the resuspension of seabed sediments, although recent studies suggest that this remineralisation could be an important source of CO_2 emissions (Sala et al., 2021), d) GHG emissions related to the transport and distribution of exports to third countries, because our aim is to understand the emission intensity and impacts of the food chain supply associated with hake consumption in Spain (It should be noted that exports have only been considered for calculating the net availability of hake for consumption in Spain), and e) emissions from cooling agents in fishing operations (Iribarren et al., 2011).

The hake landings of the Spanish fleet were obtained from the vessels' logbook records (Data Collection Framework, Regulation (EU) N° 2017/1004). These records include information on the number of landings, fishing zones and sub-zones according to the codes used by the Food and Agriculture Organization of the United Nations (FAO), the port and country of landing, and the vessels' engine power. International seafood trade flows of hake were obtained from the official database of the Spanish Secretary of State for Foreign Trade Statistics (DataComex, 2017), which includes information on countries of origin, Spanish provinces of destination, volume transported and types of transport (road, maritime and air). We assumed that landings of the Spanish fleet in international ports followed the same transport routes as imports, using the same cargo areas and logistics centres. We also assumed that hake landed at Spanish ports followed the same supply chain transport routes as other foods.

The difference between the net availability of hake for human consumption within each Spanish province, i. e., the difference between landings, plus imports minus exports, and the volume of consumption in each province allowed us to identify the existence of recirculation of a product between them, from those provinces with a production surplus to those with a deficit, to cover their domestic consumption (Supplementary Material). The volume of hake consumption in each Spanish province was obtained from the Food Consumption Panel data (MAPAMA, 2017c). To compute the volume of hake received by the provinces with deficits, we assumed that they received a proportional contribution of the aggregate total national surplus from provinces with surplus, according to the market shares of large distributing wholesalers in Spain (Supplementary Material, Table SM1). After estimating the hake flows a proportional contribution of the aggregate domestic total from the fishing zones and the net imports to retail in each province, we computed the international transport and the domestic distribution routes with the associated means of transport in each case, as well as the distances travelled.

2.1. Calculating the carbon footprint

To obtain the carbon footprint we converted the fleet fuel consumption and the distances covered by the different types of transport at the different stages of the entire hake supply chain into GHG emissions. In this study we considered a functional unit (FU) as the amount of CO_2

[1] Transport of hake between provinces with a surplus to provinces with a deficit.

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equivalent (CO_2e) emitted per kilogram of whole hake, and we applied a series of converters widely used in this type of studies following the ReCiPe (H) 2016 v.1.04 methodology (Huijbregts et al., 2016) (Supplementary Material, Figure SM3).

2.2. Greenhouse gas emissions from fishing

The GHG emissions from hake catches were calculated based on fuel consumption by fishing vessels, including fishing, transport from the fishing zone to the landing port and the outward journey with an empty vessel, assuming it represents the vast majority of GHG emissions (Vázquez-Rowe et al., 2011). Data on fuel consumption were extracted from the Scientific, Technical and Economic Committee for Fisheries (STECF, 2019), which provides a detailed consumption profile for each fleet segment of different fishing areas. As fleet segments catch more than one species, it was necessary to allocate fuel consumption in a weighted manner between the volumes of the different species caught, using a mass allocation approach[2] (see the Supplementary Material). Finally, GHG emissions related to fuel consumption ($KgCO_2$ eq. t^{-1}. km^{-1}) were calculated following the methodology and converters developed by Aguilera et al. (2019) (Eq. (1), and Supplementary Material, Table SM2):

$$GHG_{fishing} = \frac{V_{diesel}}{M_{hake}} x\ M_{hake}\ x\ GCV\ x\ GHG_{diesel} \quad (1)$$

where *Vdiesel/MHake denotes* the volume of diesel consumption per tonne of hake caught, *Mhake* means the mass of hake caught, *GCV* (gross calorific value) is the energy contained in each unit of mass or volume of diesel, and *GHG* diesel denotes the value of GHG emissions per MJ of diesel for the year 2010, including fuel production and direct emissions from fuel combustion.

2.3. Greenhouse gas emissions from transport

The GHG emissions associated with the different transport types were calculated using converters for each of the types of transport used in the hake supply chain in Spain obtained through a literature review (Supplementary Material, Table SM3). We complemented this information with the Ecoinvent 3.7.1 database (Ecoinvent, 2019). The choice of a particular transport type and the use of refrigeration was made based on the information available in the scientific literature and on expert knowledge (Fitzgerald et al., 2011; Meneghetti and Ceschia, 2020; Parajuli et al., 2021). Measuring the emissions from these transports in Kg CO_2e per tonne per kilometre (Kg CO_2 eq.t^{-1}.km^{-1}), makes it possible to estimate the emissions derived from transport by multiplying the distance travelled and the volume transported by the values of the converters (Supplementary Material). Transport routes of the net volume of hake marketed were reconstructed by breaking down the distances travelled for each of the transport types. The application of the selected converters allowed us to calculate the impact of each of the routes from the volume transported and the distance travelled between the origin and the destination (Eq. (2)):

$$GHG_{transp} = \sum (GHG_{md} x\ distance\ x M_{Hake}) \quad (2)$$

Emissions from transport (*GHGtransp*) are calculated through the converters (Supplementary Material, Table SM3) for each mode of transport (*GHGmd*), multiplied by the estimated distance and the mass of hake transported (*Mhake*).

[2] The application of efficiency to the volume captured in each sub-zone allows us to estimate the amount of diesel attributable to the hake captures for each segment.

3. Results

3.1. Total supply, net availability and origin of hake

The term 'hake' encompasses a group of demersal fish species (genus *Merluccius*) that inhabit all seas and oceans, usually at depths between 150 and 600 m and close to the bottom. Of the 12 different species belonging to this genus worldwide, 8 are marketed in Spain (Supplementary Material, Table SM4) (MAPAMA, 2017b). Among them, European hake (*Merluccius merluccius)* and Argentine hake (*Merluccius hubbsi*) were responsible for 83% of the total catches of hake of the Spanish fleet (STECF, 2017). Regarding imports, the main species of hake marketed in Spain are Cape hake (*Merluccius capensis*), Argentine hake and Southern hake (*Merluccius australis*). Henceforth in this paper, references 'hake' include the 8 species marketed in Spain.

The Spanish fleet caught 98,206 t of hake in 2017. Of this total 30,134 t came from Spanish vessels landing their catch in domestic ports, of which 12,789 t were caught in national fishing zones and 17,345 t in international fishing zones (Fig. 1). The remaining 68,072 t came from Spanish vessels fishing exclusively in international fishing zones, and landing their catches at international ports. Imports reached a volume of 121,032 t, which when added to the catch yield produced a total availability of 219,239 t. From this total availability we deducted the volume of hake exported (65,305 t), resulting in a net availability of 153,934 t of hake, which is the volume that ultimately reached the retail sector for consumption in Spain (Fig. 1). It is worth highlighting that of all the hake available for consumption in Spain, only 8% is caught by the Spanish fleet in national fishing zones.

Spanish vessels harvesting hake operate regularly in 5 major FAO fishing zones. The FAO 41 (Southwest Atlantic) is the fishing zone with the highest volume of catches (46,000 t; 47%); 93% of these catches were landed at international ports (mainly Argentina and Uruguay) while only 7% were landed at Spanish ports (Fig. 2). The second FAO zone with the highest catches was FAO 27 (North-East Atlantic) (more than 33,000 t; 33%), 76% of the volume was landed at Spanish ports, while the remaining 24% was landed at international ports (Ireland and France), and then transported to Spain. These two zones (41 and 27) together account for 80% of the total hake caught by the Spanish fleet (Fig. 2a; Supplementary Material, Table SM4).

Most of the hake available in Spain (55%) relies on imports, with Namibia being the country from which the most hake was imported (40,000 t), representing 30% of the total volume of imports. Of the hake imported from Namibia, 96% was transported to Spain frozen. The second most important country was France (24,000 t), representing 17% of the total. Unlike Namibia, almost all of the hake imported from France arrived in Spain fresh (98%). Argentina was the third country, with more than 15,000 t of hake, all of which was marketed frozen (Fig. 2b).

The hake imported and landed by Spanish vessels in international ports travels long distances to be sold in Spain. Fig. 3 shows the weighted average distance (km) of hake transported by each country of origin. South American countries (Chile, Argentina, Uruguay) and the Islas Malvinas/Falkland Islands led the ranking of weighted average distances. Chile was the country with the longest journey per ton of hake caught and transported to Spain, while in the opposite position ranked Portugal, with a weighted average distance of less than 850 km. France, the United Kingdom, Ireland and Denmark also showed very similar figures when comparing the weighted average distance travelled for landings of catches in international ports and imports. Hake transported from Germany, Denmark, South Africa, the United States, Canada and Chile came mainly from imports, while hake transported from Uruguay, Mauritania, Senegal, Morocco, Portugal, Guinea, Italy and Angola came exclusively from catches landed by Spanish vessels in international ports (Fig. 3).

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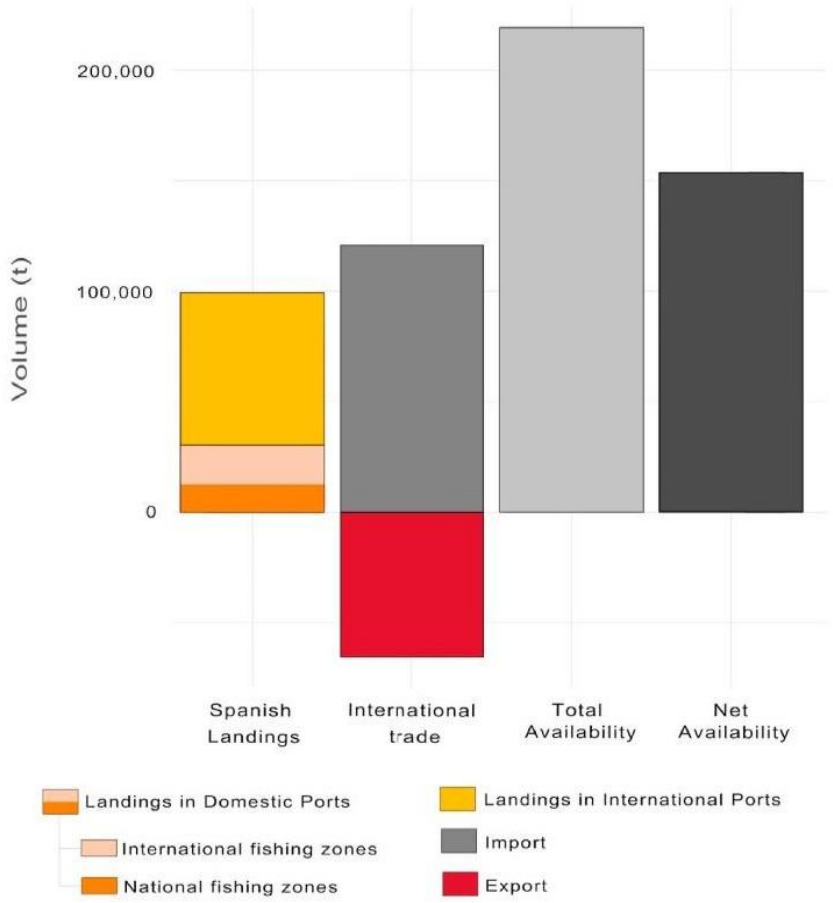

Fig. 1. Availability of hake in the Spanish supply chain. Total availability includes the sum of all hake entering Spanish territory, and Net availability refers to the hake actually available to consumers in Spain after subtracting exports from total availability.

3.2. Greenhouse gas emissions (GHG) of the hake supply chain

The total GHG emissions of the hake supply chain were 681 kt CO_2e, with fishing accounting for 456 kt CO_2e (67%), and transport accounting for 225 kt CO_2e (33%) (Fig. 4; Supplementary material, Table SM6). Emissions associated with imported hake were 356 kt CO_2e, accounting for more than half of total emissions (52%), with fishing being responsible for 231 kt CO_2e (65%), and transport for 124 kt CO_2e (35%). In the second place, we found hake from vessels landing their catches at international ports, with an amount of 216 kt CO_2e, and representing 32% of total GHG emissions. In this case, fishing was responsible for emissions estimated at 119 kt CO_2e (65%), and transport for 97 kt CO_2e (55%). Finally, hake from vessels landing their catches at domestic ports emitted 109 kt CO_2e, representing 16% of total emissions, with fishing accounting for 97% and transport for the remaining 3%. Of landings made at domestic ports, hake caught in national fishing zones presented an emission of 57 kt CO_2e, while hake caught in international fishing zones reached 52 kt CO_2e. In both cases, emissions associated with fishing accounted for more than 95% (Fig. 4; Supplementary Material, Table SM6). All hake landed at international ports and from imports was caught in international fishing zones.

Considering only emissions by product presentation (fresh and frozen), emissions from fresh hake accounted for 541 kt CO_2e, 79.5% of total GHG emissions, with fishing accounting for 337 kt CO_2e (62% of emissions from this presentation), and transportation represented 204 kt CO_2e (38% of emissions from fresh hake) (Fig. 4; Supplementary Material, Table SM6). Our results also indicate that frozen hake was responsible for lower emissions than fresh hake due to the lower volume caught and transported, reaching a total amount of emissions estimated at 139 kt CO_2e. Emissions related to the fishing of frozen hake were 118 kt CO_2e (85%), and those from transportation were 21 kt CO_2e (15%) (Fig. 4; Supplementary Material, Table SM6).

The Emission Intensity (EI) of hake in Spain was 4.42 kg CO_2e/kg of whole fish (Fig. 5). The imported hake showed the highest EI (4.88 kg CO_2e/kg), followed by the hake landed at international ports (4.09 kg CO_2e/kg), while hake landed at domestic ports presented the lowest emission intensity ratio (3.86 kg CO_2e/kg). It is important to highlight that hake landed at domestic ports are caught in both national and international fishing zones: while hake caught in international zones showed an EI of 3.22 kgCO_2e kg^{-1}, hake caught in national zones showed a higher EI, with a value of 4.74 kgCO_2e kg^{-1} (Fig. 5). Fresh hake also showed a higher EI when compared to frozen hake, reaching an amount of 4.62 kgCO_2e kg^{-1}, while the EI for frozen hake was 3.78 kg CO_2e/kg (Fig. 5).

The associated emissions from international and domestic hake transport alone amounted to 225 kt CO_2e (Fig. 6; Supplementary Material, Table SM6). The transport mode with the highest volume of emissions was air transport, with a volume of 165 kt CO_2e, representing 73% of emissions related to hake transport, despite only accounting for 14% of the total volume transported. In second place we found sea transport, with 34 kt CO_2e, 15% of the total emissions, and 45% of the total volume transported and finally road transport which presented 26 kt CO_2e, 10% of transport-related emissions being responsible for 41% of the total volume transported (Fig. 6; Supplementary Material, Table SM6). Air transport also showed the highest emissions intensity, valuing 7.70 kgCO_2e kg^{-1}, far above the other modes of transport, sea

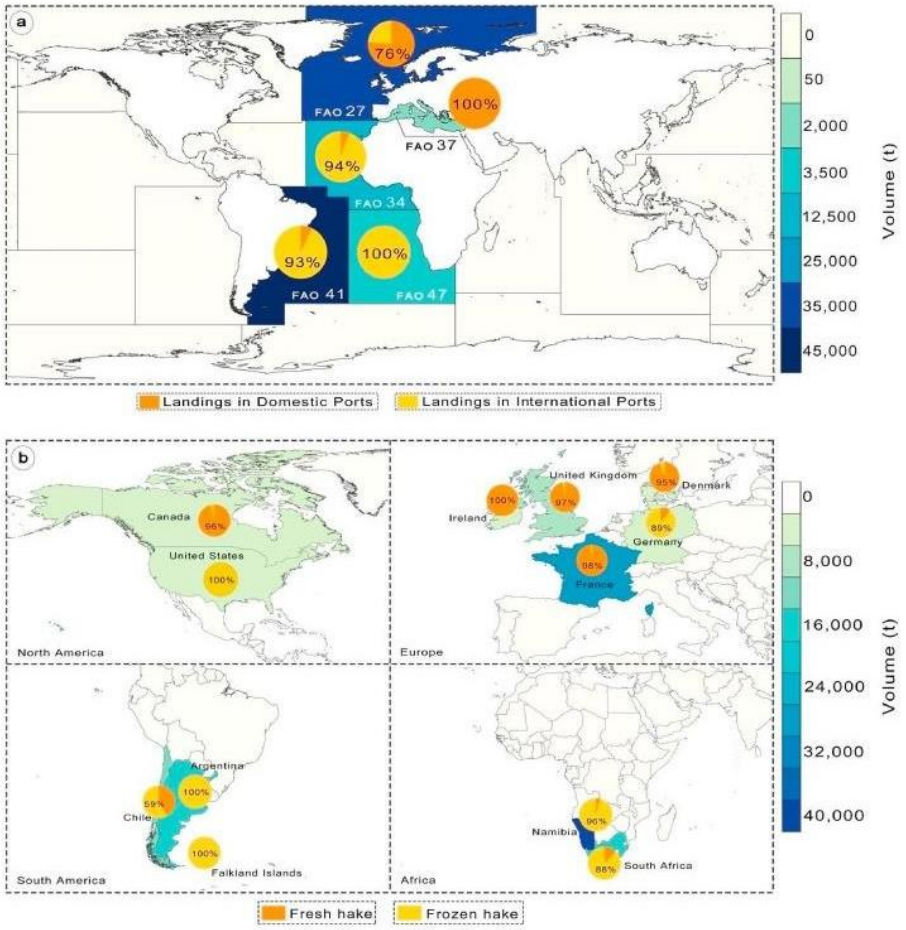

Fig. 2. a) Volume of hake catches in tonnes (t, colour scale) and percentage of catches landed on Spanish territory and in third countries by FAO area. Catches landed by Spanish vessels in Spanish ports are differentiated from those catches landed by Spanish vessels in international ports. b) Volume of hake imports in tonnes (t, colour scale) and percentage of imports of fresh and frozen hake.

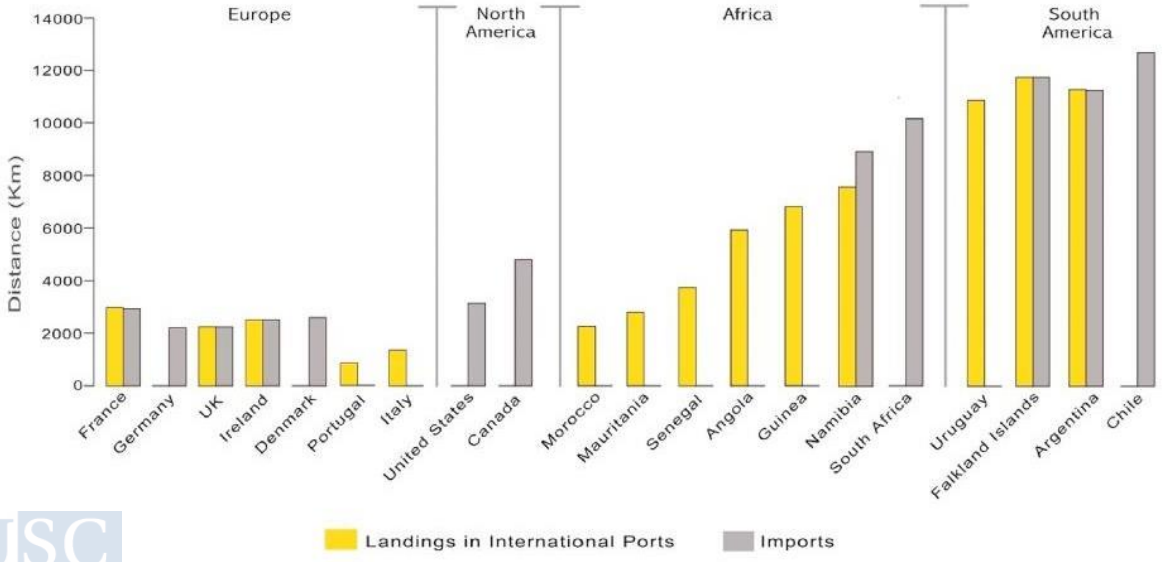

Fig. 3. Weighted average distance (in km) per tonne transported by country of origin. The yellow bars refer to hake caught by Spanish vessels and landed at international ports. The grey bars refer to hake caught by vessels from third countries and imported to Spain as international seafood trade flows. The distances include the transport routes from the country of landing to retail in Spanish provinces.

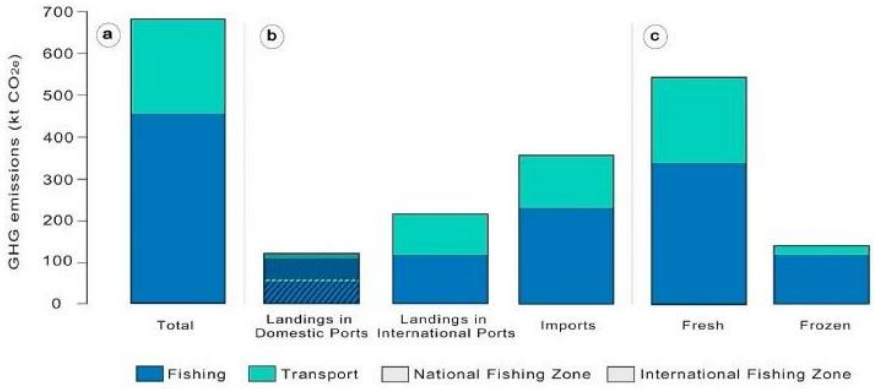

Fig. 4. Total Greenhouse gas emissions (GHG) (kt CO_2e) for: **a)** the hake supply chain with breakdown of emissions between fishing and transport to retail, **b)** by origin of hake considering the catches landed by Spanish vessels in Spanish ports, the catches landed by Spanish vessels in international ports and imports, as well as transportation associated with these categories (the catches landed by Spanish vessels in Spanish ports are divided into catches made in "National fishing zones" and in "International fishing zones"), **c)** by presentation of hake (fresh and frozen) with breakdown of emissions between fishing and transport to retail.

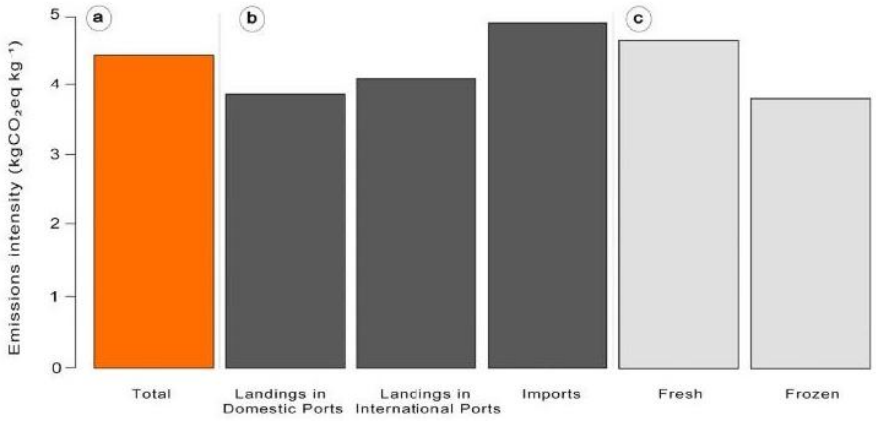

Fig. 5. The Emission Intensity ($kgCO_2e\ kg^{-1}$): **a)** of the hake supply chain; **b)** by origin of hake considering the catches landed by Spanish vessels at Spanish ports, the catches landed by Spanish vessels at international ports and imports; **c)** by presentation of hake (fresh and frozen).

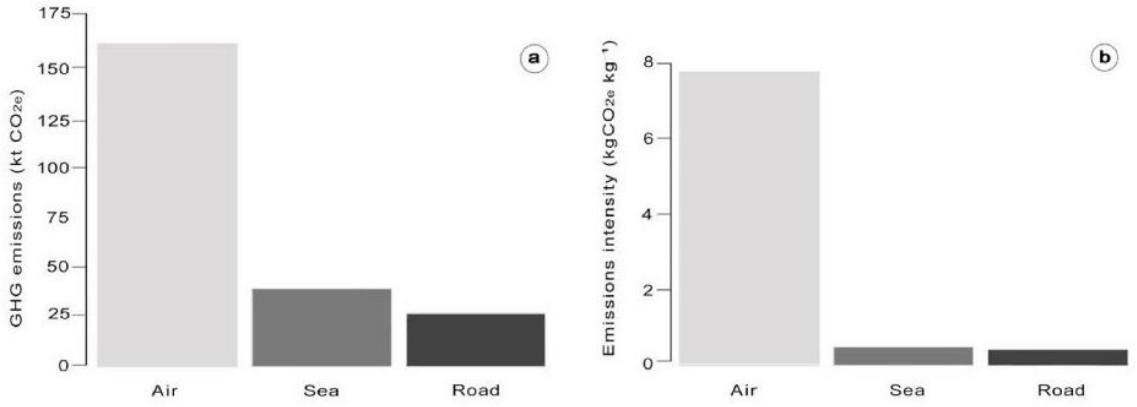

Fig. 6. **a)** GHG emissions (kt CO_2e) by transport mode for the hake food chain, **b)** Emission intensity ($kgCO_2e\ kg^{-1}$) by transport mode for the hake food chain. Neither penal includes emissions from fishing operations.

transport presented an EI 0.50 $kgCO_2e\ kg^{-1}$, and road transport was the most efficient compared to air and road transport, with an EI 0.42 $kgCO_2e\ kg^{-1}$.

4. Discussion

The fishing industry has become increasingly interconnected on a global scale (Hilborn, 2013). Travelling to the deepest waters of the oceans is now a common practice (Swartz et al., 2010), and subsequent transport to the final destination market may require hundreds or thousands of miles of travel by sea and air (Madin and Macreadie, 2015). The dependence on consumption of hake from international sources fuels the debate on the environmental impacts that transport has on the seafood supply chain. This debate exists for a wide range of food products, which is based precisely on the dependence of food chains on various factors such as the location of logistical distribution nodes, the means of transport used or the production systems, with production systems being the factor that generally has the greatest environmental

impact (Infante-Amate et al., 2018; Pérez Neira et al., 2020). As mentioned earlier (section material and methods), this study did not include the emissions related to leakage of cooling agents in the production system (fishing), although some studies indicate that this source can increase the total value of GHG. For example, according to Iribarren et al. (2011) GHG emissions increased by 13% due to refrigerant leakage. However, the *R22* refrigerant used at the time has been gradually replaced by other less harmful materials and if we were to count the GHG emissions associated with *R22*, we would overestimate the weight of the GHG emission in our calculations.

From the science-policy interface, the results of this study have implications in terms of fisheries management in several key directions, contributing to: (a) advancing the management of hake fisheries, (b) advancing the reduction of environmental impacts from fishing in order to mitigate the effects of climate change, and (c) articulating innovative actions with the potential to foster sustainability transformations of the Spanish food system in general and for the consumption of hake in particular.

The latest reform of the EU's Common Fisheries Policy (CFP) highlighted the need to move away from traditional single-stock fisheries management and towards operationalising the ecosystem approach to fisheries (EAF) (Prellezo and Curtin, 2015). Within the CFP, achieving the Maximum Sustainable Yield (MSY) does not require considering the climate change impacts through the incorporation of GHG emissions and the retained carbon sequestration of catches (Mariani et al., 2020). While recent findings indicate that marine resources throughout their life cycle contribute to processes that sequester considerable amounts of carbon (Blue Carbon Initiative, 2021), the MSY-based management objective does not take that into account, as it is limited only to promoting optimal commercial fish harvest. Thus, although the new CFP advocates the implementation of some form of EAF, it is still unclear how to implement conservation objectives within the management measures such as the GHG emissions and carbon sequestration of species.

In terms of fisheries management, taking actions towards GHG emissions and climate change considerations would require reconsidering the current MSY reference point moving towards ocean management instead of fisheries management, thus promoting climate services from the oceans (Aragão et al., 2021). Indeed, Mariani et al. (2020) recently showed that commercial fishing activities reduced the carbon sequestration of the oceans by decreasing the biomass of fish stocks, particularly regarding top predators (i.e., adult hake), and highlighted the importance of measures to promote the rebuilding of fish stocks, thus increasing their capacity for sequestering blue carbon.

In terms of mitigating environmental and climate change, it is worth noting that the fishing industry has a significant carbon footprint (Chassot et al., 2021; Hilborn et al., 2018; Ziegler et al., 2013). However, seafood carbon footprints are rarely integrated into sustainability assessments in commercial fisheries management, either through eco-labels or through sustainability certification or sustainability guides for consumer seafood products. Thus, environmental analyses of fishing activity generally focus on certain biological concerns such as resource availability and stock conservation, while underestimating other impacts caused by fishing activities (Hospido and Tyedmers, 2005; Vázquez-Rowe et al., 2010). Energy and material use by fishing vessels can generate significant environmental impacts, mainly related to fuel consumption (Hospido and Tyedmers, 2005). These analyses, however, generally do not consider the impacts associated with the entire food chain, thus preventing a holistic understanding of the environmental footprint associated with a population's food consumption patterns. Therefore, improving fisheries management should not only be linked to efforts to reduce overfishing, bycatch and discards, the disturbances created in benthic communities by trawling and other types of gear, or altered trophic dynamics (Fonseca et al., 2005), but also to the analysis and mitigation of the impacts of fisheries and the organization of their food chain on GHG emissions and the resulting global warming.

From the consumer perspective, including the carbon footprint in seafood awareness campaigns could also generate a number of key benefits for both the consumer and the seafood producer (Madin and Macreadie, 2015). Providing consumers and businesses (e.g., restaurants) with information on the relative contribution to climate change associated with one product compared to another can promote products with a lower carbon footprint (e.g., by shifting purchases to locally produced seafood), or serve as an indicator for improving the steps in the food chain with the greatest impacts in order to move towards more sustainable scenarios (Altiok et al., 2021). Therefore, a more powerful effort is needed to increase the social acceptance of low-carbon products by consumers (Bryant, 2019).

The limited evidence suggests that giving stakeholders access to information on other aspects of seafood sustainability may lead to preferential purchase of products with lower environmental impact (Teisl et al., 2002). The existence of legislation linked to ecosocial transition may also contribute to the consumption of products with lower environmental impacts, but other factors such as the price of the labelled product influence consumer choice (Aoki and Akai, 2013; Grebitus et al., 2013; Elofsson et al., 2016). Another approach could be directed at limiting consumer choice by distributing seafood products that fulfil specific environmental criteria (Panzone et al., 2011). To our knowledge, there are few initiatives at an international level to raise awareness about sustainable seafood. One example would be Friend of the Sea, which explicitly incorporates carbon footprint into its selection criteria, or the Swedish national eco-label KRAV for small-scale seafood products (Ziegler et al., 2013). Thus, both the generation of legislative frameworks capable of promoting the adoption of practices that mitigate climate change in this context, and the promotion and awareness-raising of consumers and operators in the food chain through labelling should be options to combine for achieving the sustainability objectives in the global action frameworks.

Unhealthy diets represent a serious challenge for Spanish society, given that the country has one of the highest rates of obesity in adults and young people among OECD countries (OECD, 2019). In addition, today's consumers are also increasingly concerned about the origin and environmental impact of the food they eat and value the good quality of the natural environments. In terms of seafood, there is strong evidence of the benefits of fish consumption for human health, such as contributing to reducing cardiovascular problems (Whelton et al., 2004), improving neurodevelopment in pregnant women and children during pregnancy, improving mental health, and helping with stress, depression and anxiety while preventing cancer, autoimmune diseases, asthma, multiple sclerosis and diabetes (EUPHA, 2017). There is also robust scientific evidence linking diets to human health and environmental sustainability (MacDiarmid, 2013).

However, the absence of scientific studies conducted at global and national levels for simultaneously assessing healthy and sustainable diets has hampered coordinated efforts to transform the food system (Willett et al., 2019). In this sense, this paper on GHG emissions from the hake supply chain provides new evidence to link sustainability issues to other studies addressing the health effects derived from fish consumption by the Spanish population. The high dependence on imports and catches in international fishing zones, while only 8% of the hake consumed in Spain comes from national fishing zones, and the entire carbon footprint associated with intensive fishing and its associated international transport make the current volumes of hake consumption by the Spanish population alarming. Furthermore, neither simplistic approaches based on large-scale fishing efficiency in international fisheries, nor the human health of diets based on current hake consumption volumes should underpin decision-making and legislative frameworks. A combination of recommendations for sustainable and healthy fish consumption should take both aspects into account on an equal footing, i.e., encouraging the transformation of the food supply chain by moving to more efficient and sustainable practices without undermining the positive nature of hake consumption in Spanish diets. For this same

reason, the fishing industry, policy makers and society at large must work together to achieve significant transformative changes in sustainable and healthy food production and consumption patterns.

To build a new narrative for ocean healing (Lubchenco and Gaines, 2019) and align with the UN Decade of Oceans for Sustainable Development from 2021 (Claudet et al., 2020), new nature-based solutions are needed to reduce the impact on oceans. Unlocking current barriers to transformative change towards sustainable oceans and healthy diets in line with the UN Sustainable Development Goals for 2030 requires innovative solutions (Rosa, 2017). This highlights the importance of educating society through effective communication efforts about the real value of food for human health and to promote environmental sustainability (Medawar et al., 2019; Nelson et al., 2016; Tomova et al., 2019).

5. Conclusions

This study provides scientific evidence and new insights that can be helpful for the design of possible solutions to help managing hake exploitation at sustainable production levels (both outside and within the European Union), thus supporting climate change mitigation and healthy diets. The framework of this study presents a sound proposal on how to consider the ecosystem impacts not only of fisheries, but also of the entire food chain supplying a country, which would contribute to improving the approach to be adopted in the forthcoming review of the CFP regulatory framework, as well as other regulations such as the Marine Strategy Framework Directive. Evidence suggests the need for striking a balance between healthy fish consumption patterns and associated environmental impacts.

There are great opportunities available for promoting the transformation of food systems towards a shared vision of the Planet's health and people's health. The scientific targets set by the EAT-Lancet Commission on dietary change, sustainable production and food loss and waste will enable Spanish companies to create science-based solutions that can support food system transformation (Willett et al., 2019). To lead this transformation and ensure the success and continuity of the fisheries sector, we advocate for business leadership and public policies aimed at adopting innovative solutions along the entire value chain, such as (a) reducing GHG emissions in operations and supply chains using nature-based climate solutions, (b) extending and standardising food labelling to include information on the health and sustainability implications of food products, (c) supporting the fisheries sector in this transition with training and development, assistance and recognition, (d) encouraging transparent marketing practices that promote healthy and sustainable food consumption, (e) helping consumers reduce food waste with ideas for leftovers and portion sizes, and (f) adopting a diverse and sustainable protein mix by increasing diverse plant-based protein sources. The future of current and future generations depends on our ability to create a food system that supports healthy people and a healthy Planet.

Data availability

The data underlying this article will be shared upon reasonable requests to the corresponding author.

CRediT authorship contribution statement

Guilherme Martins Aragão: Conceptualization, Writing – original draft, Data curation, Writing – review & editing. **Pablo Saralegui-Díez:** Methodology, Validation. **Sebastián Villasante:** Conceptualization, Writing – review & editing, Validation. **Lucía López-López:** Conceptualization, Validation. **Eduardo Aguilera:** Validation. **Joan Moranta:** Conceptualization, Writing – review & editing, Validation.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.131979.

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4 GLOBAL HAKE PRODUCTION AND TRADE: CONSIDERATIONS FOR FOOD SECURITY AND SUPPLY CHAIN RESILIENCE[3]

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Article

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Global hake production and trade: Insights for food security and supply chain resilience

Check for updates

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Hake, a key species in global seafood trade, substantially influences market dynamics and consumption patterns. This study delves into the global hake trade network (HGTN), spotlighting the roles and connections of key countries such as Spain, Namibia, Argentina, South Africa, the USA, and Italy, with Spain being the primary importer and countries like Namibia and South Africa notable exporters. Our findings unveil a multifaceted trade network, with Spain and Namibia as central nodes, and reveal growth in trade volume and value, signifying an evolving marketplace. The network's susceptibility to economic, political, and ecological shifts underscores the necessity for resilient, adaptable trading practices to sustainably manage hake trade. Our findings emphasise the importance of managing resources and maintaining market balance to support global food security and reflect the dynamic seafood industry.

The role of international food trade in supporting food and nutrition security worldwide is increasingly acknowledged. While trade optimises food distribution, diversifies diets, and stabilises prices[1,2], disparities in governance, infrastructure, and market access often skew these benefits[3–5]. Low-income and vulnerable countries are particularly exposed to negative shocks in the food trade system, making equitable distribution of food a significant challenge[6–8].

Within the intricate web of global trade, hake emerges as a species of significant economic and nutritional value, impacting international market dynamics and dietary preferences worldwide. Primarily belonging to the genera *Merluccius* and *Urophycis*, hake is extensively traded on the international stage and is a critical component of the global white fish market. Its trade volumes and values, which between 2016 and 2022 accounted for 2.23% and 2.19% respectively of the global trade in frozen fish, underscore its significant commercial role relative to other major seafood commodities such as yellowfin tuna, which represented 4.3% by weight and 5.43% by value[9]. This study aims to explore the intricacies of the global hake trade network (HGTN), emphasizing its pivotal role in the broader context of global fisheries and trade policies.

Food security, as defined by the Food and Agriculture Organization (FAO), is a condition that exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life. The international trade of aquatic products is crucial for enhancing global food security, expanding consumer choices, and driving economic growth, particularly in lower-income countries[10]. This sector not only generates significant export revenue and employment but also addresses nutritional needs, especially in regions like Africa, where the import of nutrient-rich small pelagic species plays a pivotal role in enhancing food security and providing access to essential micronutrients[9]. Seafood, one of the most globally traded food commodities, is susceptible to various negative shocks such as fishery collapses, natural disasters, oil spills, policy shifts, and disease outbreaks in aquaculture, which threaten its stability and availability[11]. Moreover, as the global population is projected to reach nearly 9.8 billion by 2050, the escalating demand for nutritious food sources such as seafood further exacerbates these challenges (United Nations).

Global trade agreements and organisations such as the World Trade Organisation (WTO) have significantly broadened the reach of the seafood trade by reducing barriers and promoting interregional exchange. While

[3] This chapter previously appeared as an article in the ICES Journal of Marine Science. The original quote is as follows: Ospina-Alvarez, A., Aragão, G. M., López-López, L., Villasante, S., & Moranta, J. (2024). Global Hake Production and trade: Insights for food security and supply chain resilience. npj Ocean Sustainability, 3(1), 52 https://doi.org/10.1038/s44183-024-00083-5

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these developments have been crucial for economic growth and market access[9,12], they also present challenges for resource management and the traceability of fisheries. The liberalization of trade has the potential to complicate the tracking of seafood products, making mechanisms like traceability and catch documentation even more essential. These mechanisms are the cornerstone of food safety regulations and key initiatives in the fight against illegal, unreported, and unregulated fishing. Alongside these, certification schemes and ecolabels play a critical role in safeguarding consumer protection and ensuring sustainable resource use. They help maintain a balance between the benefits of market access and the imperatives of environmental and consumer safety[9].

The global decline of fish stocks within biologically sustainable levels—from 90 percent in 1974 to 64.6 percent in 2019—highlights the escalating pressures on marine resources, with significant implications for global food security and local economies[13]. The resilience of seafood trade networks, increasingly recognized as fundamental to sustaining global food supplies amid ecological and economic shocks, refers to the capacity of these networks to maintain their functionality and structure in the face of external stresses[4,6]. Such resilience is crucial in the fisheries sector, where sustainability of fish stocks is directly impacted by market demands and regulatory frameworks[14,15].

In the Southwest Atlantic, for example, the Argentine hake (*Merluccius hubbsi*) catch increased significantly by 26 percent from 2017, marking it as a crucial species in terms of catch volumes for the FAO area[9]. This improvement exemplifies how effective fisheries management can enhance sustainable fisheries practices. Conversely, in the Mediterranean and Black Sea, most commercially important stocks, including hake (*Merluccius merluccius*), are fished beyond biologically sustainable limits, with an overall fishing mortality nearly 2.5 times higher than sustainable reference points[9].

Substantial research underscores the multifaceted impact of global trade networks, highlighting both their benefits and vulnerabilities, as well as the complex interdependencies they create among producers, intermediaries, and consumers Stoll et al.[16–19]. For example, analysis of lobster trade routes has revealed that regional market shifts or policy changes can have extensive effects on global markets, affecting stakeholders from producers to consumers across different continents (Stoll et al.[16]). Similarly, studies on the octopus trade demonstrate that the dominant exporters and importers may not necessarily control the market; often, it is the entities within expansive and diversified commercial networks that bridge major economies or regions, effectively directing the flow of goods[19]. Employing network analysis to explore these complex trade dynamics allows for a deeper understanding of how distant feedback loops and trade dependencies influence global markets[17,18]. This methodological approach is essential for developing strategies that promote effective and sustainable fisheries management and inform sound policy decisions[19–23]. Hake, being a major commodity in the seafood market, is subjected to varying fishing pressures and regulatory environments across its range. The species' trade patterns provide critical insights into overexploitation risks and opportunities for implementing sustainable practices. By analysing these networks, stakeholders can identify key countries and links that are crucial for the flow of hake, pinpointing where interventions might be most effective. This analysis helps in understanding how disruptions in one part of the network, such as overfishing in a primary export region or policy changes in a major import country, can ripple through to affect global supply chains.

This paper, therefore, seeks to address three interconnected objectives. First, it aims to delineate the structure and characteristics of the global hake trade network, highlighting the interplay between trade dynamics and fisheries management. Second, it endeavours to assess the resilience of this network, with a particular focus on its capacity to withstand and adapt to ecological and economic shocks. Lastly, it seeks to contribute to the discourse on sustainable fisheries management by examining how trade networks can be leveraged to promote more equitable distribution of resources and enhance global food security.

Through this comprehensive analysis, the paper aspires to provide actionable insights and recommendations that can inform policy decisions and management strategies aimed at sustaining the viability of hake fisheries and ensuring the long-term resilience of global seafood supplies.

Material and methods

Firstly, our study conducts a comprehensive analysis of hake fishery production from 1950 to 2020. We traced the development of hake catches across various species, continents, and subcontinents, highlighting significant trends, shifts in species dominance, and the emergence of key producers. We derived fishery catches statistics from the FAO's FishStatJ global capture production database[24] and integrated these with export and import data from the United Nations Commodity Trade Statistics Database[25] to estimate global per capita hake availability (Table 1). Secondly, we focused the analysis on the HGTN between 2016 and 2020, particularly for the genera *Merluccius* and *Urophycis*, leveraged data from the same UN database[25]. Using network analysis and advanced graph visualisation techniques, our study not only elucidates the complex patterns and dynamics of the HGTN but also identifies its principal players.

Here the concept of food supply, defined as the quantity of food available for human consumption, was central[26]. We focused on understanding primary consumers in the hake trade network to analyse hake market dynamics comprehensively. Given that official databases often lack detailed per capita consumption data for individual hake species, we estimated national food supply by considering production, imports, and exports relative to population size (apparent food supply=production +imports−exports/human population) from 2016 to 2020. This estimation method, adapted from the FAO's approach for food balance sheets, reflects the total quantity of hake produced, imported, and exported[26]. However, unlike the FAO's comprehensive method, our calculation does not account for stock changes and non-food uses[26]. Although our method potentially overestimates average consumption, it provides a necessary balance between data availability and reliability, as outlined in Table 2. It is important to note, as per FAO guidelines, that the actual amount consumed

Table 1 | Summary of the main databases used in this research, including the coverage periods and the species involved

Database	Time period coverage	Genera	Species	Common names	Source
Global capture production 1950-2021 (FishStatJ)	1950–2020 (70 years)	Merluccius *Urophycis*	*M. hubbsi* *M. merluccius* *M. capensis* and *M. paradoxus* *M. productus* *M. bilinearis* *M. gayi* and *M. australis*, other real hakes and hakes of the genus Urophycis	Argentine hake European hake Cape hake N. Pacific hake Silver hake S. Pacific hake other hakes.	24
United Nations Commodity Trade Statistics Database (COMTRADE)	2016–2020 (4 years)	*Merluccius*, *Urophycis*	Not explicitly specified	Not explicitly specified	25

See Fig. 1 to the species included in the "other hakes" categories.

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Table 2 | Top-ranking countries by continent in terms of hake catches contribution, food supply per capita, and trade for the period 2016-2020

2016-2020										
Continent / Country	**ISO3**	**Catches Arithmetic mean (tonnes)**	**Catches Sum (tonnes)**	**%**	**Food Supply (kg/ person-year)**	**%**	**Sum of Exports (tonnes)**	**%**	**Sum of Imports (tonnes)**	**%**
Africa										
Namibia	NAM	149100	745501	10.93%	2.47	0.21%	344213	8.67%	14428	4.57%
South Africa	ZAF	134256	671282	9.84%	43.46	3.61%	191974	15.55%	101236	0.65%
Angola	AGO	9599	47995	0.70%	0.46	0.04%	2907	0.13%	12232	0.55%
Morocco	MAR	5914	29572	0.43%	0.25	0.02%	321	0.01%	7662	0.35%
Nigeria	NGA	3694	18471	0.27%	0.11	0.01%	0	0.00%	99018	4.47%
Senegal	SEN	2285	11425	0.17%	0.22	0.02%	1	0.00%	35328	1.60%
Americas										
USA	USA	296823	1484117	21.76%	6.29	0.52%	300840	13.59%	1624	0.07%
Argentina	ARG	285532	1427659	21.93%	0.77	0.06%	443299	20.02%	27070	1.22%
Canada	CAN	100525	502625	7.37%	1.64	0.14%	267131	12.07%	3665	0.17%
Peru	PER	62879	314397	4.61%	1.96	0.16%	32860	1.48%	86	0.00%
Chile	CHL	41207	206035	3.02%	2.15	0.18%	40869	1.85%	3603	0.16%
Uruguay	URY	15615	78074	1.14%	3.67	0.30%	27591	1.25%	987	0.04%
Mexico	MEX	9977	49884	0.73%	0.43	0.04%	25990	1.17%	314	0.01%
Ecuador	ECU	7975	39876	0.58%	0.09	0.01%	4976	0.22%	94	0.00%
Brazil	BRA	7060	35300	0.52%	0.11	0.01%	420	0.02%	75944	3.43%
Falkland Is. (Malvinas Is.)	FLK	5760	28800	0.42%	1109.13	92.11%	16804	0.76%	22	0.00%
Asia										
Republic of Korea	KOR	5924	29620	0.43%	0.13	0.01%	8447	0.38%	3721	0.17%
Georgia	GEO	725	3623	0.05%	0.09	0.01%	2889	0.13%	58564	2.65%
Syrian Arab Republic	SYR	31	153	0.00%	0.00	0.00%	46905	2.12%	88569	4.00%
Europe										
Spain	ESP	122246	611230	8.96%	3.72	0.31%	322022	14.55%	443008	20.01%
France	FRA	39109	195546	2.87%	0.82	0.07%	3561	0.16%	43256	1.95%
United Kingdom	GBR	12374	61870	0.91%	0.24	0.02%	3242	0.15%	14154	0.64%
Italy	ITA	7228	36140	0.53%	0.72	0.06%	1029	0.05%	173541	7.84%
Norway	NOR	5041	25204	0.37%	0.65	0.05%	504	0.02%	10660	0.48%
Greece	GRC	4088	20442	0.30%	0.96	0.08%	3276	0.15%	71	0.00%
Denmark	DNK	4039	20193	0.30%	0.76	0.06%	2908	0.13%	1484	0.07%
Ireland	IRL	3533	17665	0.26%	0.97	0.08%	420	0.02%	2911	0.13%
Russian Federation	RUS	1373	6863	0.10%	1.45	0.12%	90	0.00%	315984	14.27%
Croatia	HRV	1004	5022	0.07%	2.81	0.23%	17751	0.80%	147745	6.67%
Albania	ALB	848	4242	0.06%	0.48	0.04%	18877	0.85%	58538	2.64%
Germany	DEU	759	3797	0.06%	2.35	0.20%	7212	0.33%	38615	1.74%
Netherlands	NLD	467	2334	0.03%	0.07	0.01%	11096	0.50%	36001	1.63%
Oceania										
New Zealand	NZL	4333	21666	0.32%	0.32	0.03%	16342	0.74%	149	0.01%
Others		11963	63262	0.93%	14.34	1.19%	47069	2.13%	393553	17.78%
TOTAL		**1363286**	**6819885**		**1204.07**		**2213837**		**2213837**	

The food supply, measured in kg per person per day, represents the average availability of food for the entire population of a country or territory, but it does not indicate the actual consumption by individuals (Iceland, Faroe Islands, and the Falklands/Malvinas Islands omitted). The ISO 3166-1 alpha-3 (ISO3) international standard codes for countries are also indicated.

may be lower than our estimated supply due to losses at various stages, including household consumption[26].

Our study uses network analysis and advanced interactive graph visualization techniques to disentangle the complexities of the global hake trade network. We collated data on frozen hake trades, which predominantly constitute the market[27,28], across 193 countries or territories from 2016 to 2020. This was achieved using UN Comtrade commodity codes 030366, 030378, and 030474[25]. To facilitate accessibility and

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comprehension of this trade database, we developed an interactive web application: https://mares-imedea.shinyapps.io/Hake_Global_Trade_Network/. This advanced yet user-friendly spatially-explicit tool displays maps with various centrality measures and allows users to explore and download the clean, processed, and filtered database on hake trade. This platform enables anyone to effectively visualize the quantity, monetary value, and directional flow of hake trades, thereby revealing the network's structure and dynamics.

In conducting our study, network analysis was crucial in identifying essential nodes and clusters within the global hake trade, shedding light on influential players and potential trade flows. To determine the nodes' and edges' significance, we applied centrality measures including degree, strength (weighted degree), betweenness, and Page's Rank, each offering distinct insights[18,29].

Degree centrality was crucial in identifying hubs that if disrupted, could substantially impact the network's coherence, reflecting on the network's resilience. Strength (weighted degree) illuminated the economic throughput within each node, thus informing us of the network's efficiency in terms of trade volume and value. Betweenness centrality allowed us to locate nodes that function as vital bridges in trade pathways. High betweenness scores indicated points of potential vulnerability, where disruptions could wave through the network, emphasizing the network's ability to withstand shocks. Page's Rank identified nodes of influential prominence, often indicative of strong interconnectivity and robust trade links, serving as a metric for resilience through distributed influence and importance within the trade network.

These centrality measures afforded us a comprehensive view of the hake trade network's structure and function, offering fundamental indicators for the network's capability to maintain functionality and facilitate efficient trade under varying conditions[18,30]. The nuanced understanding these metrics provide for assessing the network's resilience and efficiency is elaborated in Table 3.

Hierarchical clustering, employing Ward's method, was used to group traders within the global hake trade network[31]. This approach aimed to minimise within-group dispersion, effectively revealing patterns and relationships that might otherwise be obscured in the complexity of international trade. By focusing on import and export links, quantified as in-degree and out-degree respectively, we gained valuable insights into the network's structural dynamics. This aspect of our analysis was crucial in understanding how hake trade flows are organised and how different countries or regions contribute to the overall network. The statistical significance of these clusters was verified using a similarity profile method (permutations = 999, expected clusters = 1000).

Furthermore, we used a Sankey diagram to effectively communicate the complexities and intricacies of the trade flows within the hake market between countries. Sankey diagrams are adept at depicting such connections and magnitudes, making them an ideal choice for representing the multifaceted nature of international trade flows in a manner that is both informative and accessible to a wide range of audiences.

Analyses were performed using the R language and environment[32]. Network analysis employed the "igraph" package v.1.2.527[33], hierarchical clustering utilised "flashClust" v.1.01-228[34], and network visualisations were created with "ggplot2" v.3.2.1[35], "ggmap" v.3.0.0[36], "ggraph" v.2.0.013[37] and "ggtree" v3.0.2[38]. Figures 1, 2 S1 and S2 were created with Python using Matplotlib[39] and Seaborn libraries[40].

Results

Global hake catches

The analysis of FAO databases reveals that 6 out of 22 hake species, namely Argentine hake (*Merluccius hubbsi*), Cape hake (*Merluccius capensis*), North Pacific hake (*Merluccius productus*), South Pacific hake (*Merluccius gayi*), silver hake (*Merluccius bilinearis*), and European hake (*Merluccius merluccius*), accounted for 94% of total catches from 1950 to 2020. Peak catches occurred in the 1970s, reaching 23 million tonnes in 1973 (Fig. 1).

European and South American fleets dominated hake catches until the late 1970s, after which South American fleets, notably from Argentina and Peru, took the lead, a position they maintain today (Fig. 2a). This shift is evident from the surge in South American catches during the late 1970s and early 2000s (Fig. 2b and Table S1). Argentina and the USA led the American continent in catches for the period 2016-2020 (Table 2, Figure S1), while European catches, despite being stable initially, have shown a decline since the early 1990s (Fig. 2c). Spain recorded the highest volume of hake catches in Europe from 1950 to 2020 (Table 2, Table S1, Figure S1).

The role of Africa, especially the southern region represented primarily by South Africa, is noteworthy. Here, hake catches have increased since the 1950s, with a significant rise in 1990 when Namibia's catches increased (Figure S1). These catches experienced a decline in mid-2005 and have since stabilised, surpassing European catches (Fig. 2). South Africa and Namibia together accounted for 21% of Africa's catches from 2016 to 2020 (Table 2). Asia and Oceania, though smaller in catching volumes, have shown fluctuating trends, with peaks and subsequent falls (Fig. 2e, f). Japan led the catches in Asia until the 1980s, followed by the Republic of Korea, while the leader in Oceania was New Zealand (Table 2, Table S1).

It is important to note, according to the FAO[26] statistics office, that the reported national data encompass all quantities caught by fishing vessels registered under the flag of the reporting country, whether landed domestically or abroad. This data excludes catches by foreign vessels that are landed in domestic ports (Table 2). This delineation helps clarify the ownership and origin of catch data, essential for understanding the dynamics of global fisheries and managing marine resources effectively.

Global hake trade and supply

In terms of international trade from 2016 to 2020, Europe emerged as the dominant importer, outperforming other regions (Figure S2). North America and Africa displayed high export volumes, whereas Asia and Oceania had lower values. Europe is a significant net importer, while Africa and North America are predominantly export-oriented. Asia shows a balanced trade profile, slightly inclined towards imports. In South America, both exports and imports were low and comparable throughout the period.

The GDP, betweenness centrality and hake supply connection

The Falkland/Malvinas Islands, Namibia, Argentina, Saint Kitts and Nevis, Montenegro, Spain, Portugal, and Lithuania stand out for their high per capita hake supply. This supply is also substantial in South Africa, Uruguay, and Chile (Table 2). An interesting correlation emerges between countries with high network intermediation (betweenness), ample hake supply, and Gross Domestic Product (GDP) (Fig. 3). Countries with higher GDPs generally, display greater volumes of hake supply (linear model: GDP ~ food supply, adjusted $R^2 = 0.24$, p-value < 0.001), indicative of a correlation between economic affluence (i.e., GDP) and hake trade network intermediation (linear model: GDP ~ betweenness, adjusted $R^2 = 0.58$, p-value < 0.001). Notably, the USA and China are positioned at the upper end of the GDP spectrum yet demonstrate moderate normalized betweenness, suggesting significant hake supplies but less centrality in the trade network. In fact, there is an overlap between food supply and catches in the USA, except for the periods between 1985 and 1992 and from 2012 onwards, which coincide with increased exports (Figure S1). European countries show varied levels of both GDP and hake supply, with Spain (ESP) exhibiting a high betweenness, underscoring its pivotal role in the hake trade. The case of Spain is noteworthy, as the food supply has consistently exceeded the catches across the data series. From 1976 to 1990, this supply was primarily supported by catches. However, from 1990 onwards, Spanish catches have been significantly lower than imports, with the latter sustaining the supply over the last three decades (Figure S1). African nations, like South Africa (ZAF) and Namibia (NAM), also appear as key nodes, with substantial hake supplies and high betweenness, highlighting their importance in the hake market. Namibia and Argentina are both exporting countries with food supply below the level of catches (Figure S1). In contrast, countries with lower GDPs, such as Senegal (SEN), show lower hake supply but not

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Table 3 | Network metrics and clustering techniques: Definitions and trade contextualization

Metric or technique	Definition	Rationale contextualised for trade networks	Source
Degree	For undirected networks: The total number of connections a node has. For directed networks: the sum of in-degree and out-degree.	Nodes with a high degree act as central hubs within the trade network, signaling key players in market interactions. Their influence on network robustness and competition is significant, reflecting their role in the stability and connectivity of the global trade system.	Freeman[29]
In-degree	The number of incoming connections to a node in a directed network.	A node with a high in-degree functions as a significant destination within the network, often serving as a large market or redistribution hub that shapes regional trade dynamics and dependencies.	Opsahl et al.,[57]
Out-degree	The number of outgoing connections from a node in a directed network.	Nodes with a high out-degree are typically major exporters or producers, influencing the volume of trade and the economic health of the sourcing region. They are critical for the initiation of trade flows.	Opsahl et al.,[57]
Strength	In weighted networks: The sum of weights (e.g., volume or value of trade) of links connected to the node.	The strength of a node indicates the economic weight it carries within the network. Nodes with significant strength are pivotal for the movement of goods and capital, often representing economic powerhouses within the trade network.	Barrat et al.,[58]
In-strength	The sum of inward link weights for a node in a directed network.	High in-strength nodes are key importers or recipients within the network, indicative of large-scale demand and consumption patterns. They can have substantial influence over trade policies and market demands.	Barrat et al.,[58]
Out-strength	The sum of outward link weights for a node in a directed network.	Nodes with high out-strength are notable suppliers, exerting a notable influence on the distribution and flow of goods. Their trading activity can significantly impact global supply chains and price stability.	Barrat et al.,[58]
Betweenness	The extent to which a node lies on paths between other nodes. Calculated based on shortest paths.	Nodes with high betweenness are critical intermediaries in the network. They can act as strategic gatekeepers, controlling the flow of information or goods and thus influencing the network's overall efficiency and security.	Freeman[59]
Edge Betweenness	The importance of an edge based on its presence on the shortest paths between pairs of nodes in the network.	Edges with high betweenness signify crucial trade channels. Their disruption can have extensive repercussions, potentially impacting the network's resilience and the distribution of goods, thereby affecting regional economies and relationships.	Girvan, Newman[60]
Page's Rank	A measure of node importance based on the number and quality of links to the node. Originates from web page ranking algorithms.	A high Page's Rank is indicative of nodes with substantial influence and trust within the network, frequently correlating with market leadership or strategic importance in the trade flow. Nodes with high Page's Rank are often decision-makers in the network, shaping the direction and terms of trade.	Brin, Page[61]
Hierarchical Clustering	A statistical method to group similar objects into clusters, with the goal of achieving high intra-group similarity and low inter-group similarity, often using Ward's method[31].	In the context of trade networks, clustering can identify groups of countries with similar trading patterns, revealing underlying structures and relationships within the market. It is useful for discerning distinct trade blocs or alliances and understanding market segmentation.	Ward[31,62]

necessarily lower betweenness, pointing to strategic niches within the trade network. This visualization underscores the nuanced interplay between a country's economic status, hake supply capacity, and its role within the global trade network of this commodity.

Current trends in hake trade

Our findings indicate a growth in total hake transactions in both volume and value, although the growth transactions rate has declined since 2016 (Figure S3). In 2016, the total volume of hake traded was 319 tonnes, with a value of 908 USD million. This volume increased by 47% in 2017 (469 tonnes), with an estimated value of 1.21 USD billion (33% annual increase). In 2018, there was a modest volume increase by 5%, reaching 497 tonnes and a value of around 1.34 USD billion (11% annual increase). In 2019, the volume continued to grow by only 0.3%, reaching 499 tonnes, while the value suffered a slight decline with a total of 1.32 USD billion. However, in 2020, a decline in the volume of hake trade was observed, falling to 429 tonnes, while the value remained around 1.18 USD billion.

Degree centrality and trade clusters

Cluster analysis, using a degree threshold, has revealed stable and frequent trade relations within the global hake market. We observed a positive correlation between the number of trade connections a country maintains and its total export and import flows (linear model: Degree ~ country exports, adjusted $R^2 = 0.30$, p-value < 0.001; and linear model: Degree ~ imports, adjusted $R^2 = 0.35$, p-value < 0.001). Prominent and stronger links, which signify regular and intense bilateral trade, point to key trade flows and strategic partnerships, or possibly, preferential trade agreements between countries. In the HGTN, which includes 193 diverse traders, we identified 14 distinct clusters (as shown in Fig. 4). The foremost cluster comprises Spain, the USA, Argentina, and China, creating a broad and varied trade sub-network that spans Europe, North America, South America, and Asia. These nations, marked by a higher number of connections, serve as pivotal trade hubs, playing a crucial role in facilitating the exchange of goods and services across multiple regions. Additionally, the second and third most significant clusters include both developed and developing countries, namely Germany, the Netherlands, Canada, France, and Portugal, as well as South Africa, Uruguay, and Namibia. These intricately linked clusters demonstrate specific trading patterns, indicative of either regional trade agreements or the influence of geographical factors on bilateral trade dynamics. Furthermore, the analysis allows for the

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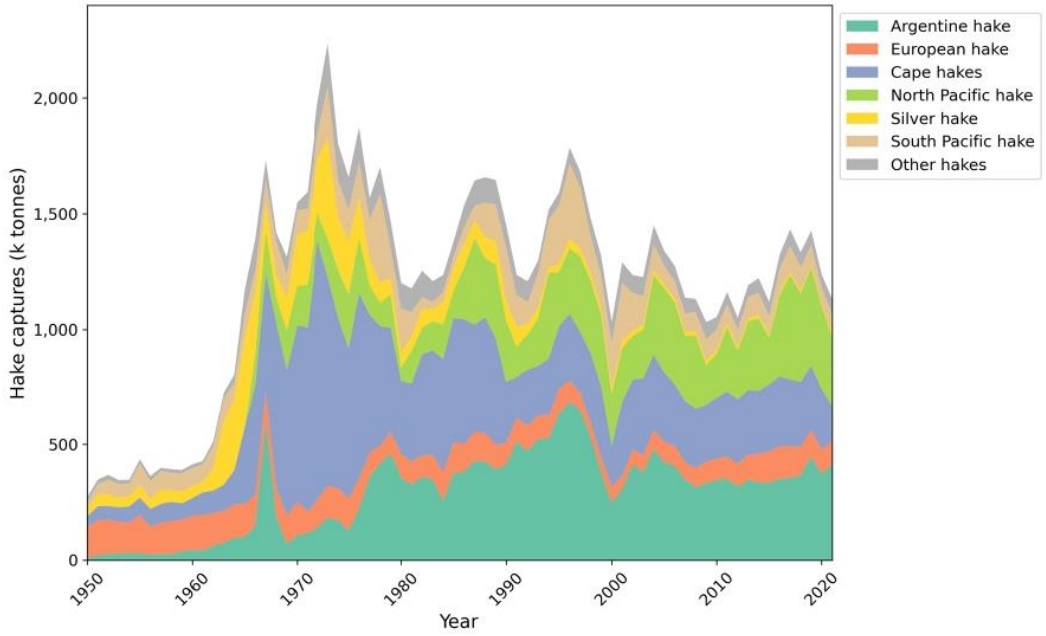

Fig. 1 | Hake catches by species 1950–2020. The "other hakes" group encompasses Benguela hake, Deep-Water Cape hake, Hakes not elsewhere included, Offshore silver hake, Panama hake, Patagonian hake, Senegalese hake, Shallow-water Cape hake, Southern hake, Brazilian codling, Carolina hake, Gulf hake, Red hake, Southern codling, Spotted codling, Urophycis not elsewhere included, and White hake. Values are given in tonnes. Data source: FAO. Created with Python using Matplotlib library.

identification of major export and import pathways, such as the pronounced trade flow from Namibia to Spain, illustrating not only the volume of trade but also the strategic trade relationships between countries.

The most important hake exporters and importers

Analysis of the top 100 trade mass flows in the international hake market reveals significant insights (Fig. 5). Despite its extensive network, China is not a major mover of large hake quantities or currency. In weighted network analyses, China appears as the least significant partner in the main trading cluster, which includes Spain, Argentina, and the United States. Interestingly, China's trade is mostly characterised by hake imports from Canada, a unique aspect of its trade pattern. In contrast, Argentina, Spain, and the United States are prominent as the leading producers and exporters of frozen hake, both in terms of weight and value. They have significant export relationships with each other and with other nations like Ukraine, Portugal, Brazil, and Russia. Namibia also plays a key role as a hake producer and exporter, mainly exporting to Spain. Canada is notable too, exporting frozen hake to Ukraine and China. The United States is particularly active in exporting fish to Ukraine and Nigeria, indicating substantial involvement in these markets. Ukraine emerges as a major importer of hake, with minimal exports, likely due to high domestic consumption. Spain serves as a crucial hub, connecting South American and African hake supplies with European markets. It receives significant hake quantities from Namibia, Argentina, and the Falkland/Malvinas Islands, with a considerable portion re-exported to countries like Ukraine, Portugal, Italy, and Serbia. This highlights Spain's pivotal role in the global hake trade network. Similarly, South Africa acts as a connective node, importing hake from Namibia, Canada, and the US, and predominantly supplying Spain, Portugal, and Italy. The trade dynamics between South Africa and Namibia are noteworthy, with a significant quantity of hake possibly being re-exported after processing or value addition. This analysis underscores the complexity and interconnectedness of the international hake trade, emphasising the crucial roles played by the US, Spain, Canada, and South Africa in shaping the hake trade dynamics.

The combined volume and value of imports and exports serve as robust indicators of a country's engagement and intensity in international trade relations. This is encapsulated by the centrality metric known as 'Strength,' which denotes the extent of a nation's active involvement and its influence in bilateral trade dynamics. Countries with a high strength score are key players in the trade network, exerting significant control over the direction and magnitude of trade flows (Figure S4). This measure often correlates with the country's economic and commercial prominence on a global scale. Key nations in this context include Spain, Namibia, South Africa, the USA, Argentina, and Italy, as detailed in Fig. 6 and Table S2. Spain leads in import volume, with transactions exceeding USD 1.68 billion, while Namibia (USD 1.45 billion), Spain (USD 881 million), and South Africa (USD 800 million) are the top exporters. Other major importers are Italy (USD 739 million), Portugal (USD 553 million), Ukraine (USD 464 million), Brazil (USD 224 million), and South Africa (USD 219 million). The trading relationship between Namibia and Spain was particularly noteworthy, with a total trade volume of USD 826 million from January 2016 to December 2020. Other significant trade flows during this period include Spain to Portugal (USD 338 million), South Africa to Spain (USD 263 million), Argentina to Spain (USD 208 million), the USA to Ukraine (USD 202 million), and Spain to Italy (USD 202 million) (Table S3).

Betweenness centrality: Strategic positioning of countries in trade networks

The network visualisations elucidate the complex structure of the global hake trade from 2016 to 2020. Evaluating the betweenness centrality measure, weighted by the traded mass, the graphic portrays the efficiency of trade connections, accentuating countries that command strategic positions within the network (Figure S5). Spain, the USA, South Africa, Portugal, China, and Italy facilitate cost-effective transactions and maintain competitive market access, irrespective of their trade volume. When the centrality is weighted by trade value instead of mass, a distinct set of countries come to the fore (Figure S6). Spain, South Africa, the USA, Portugal, China, and

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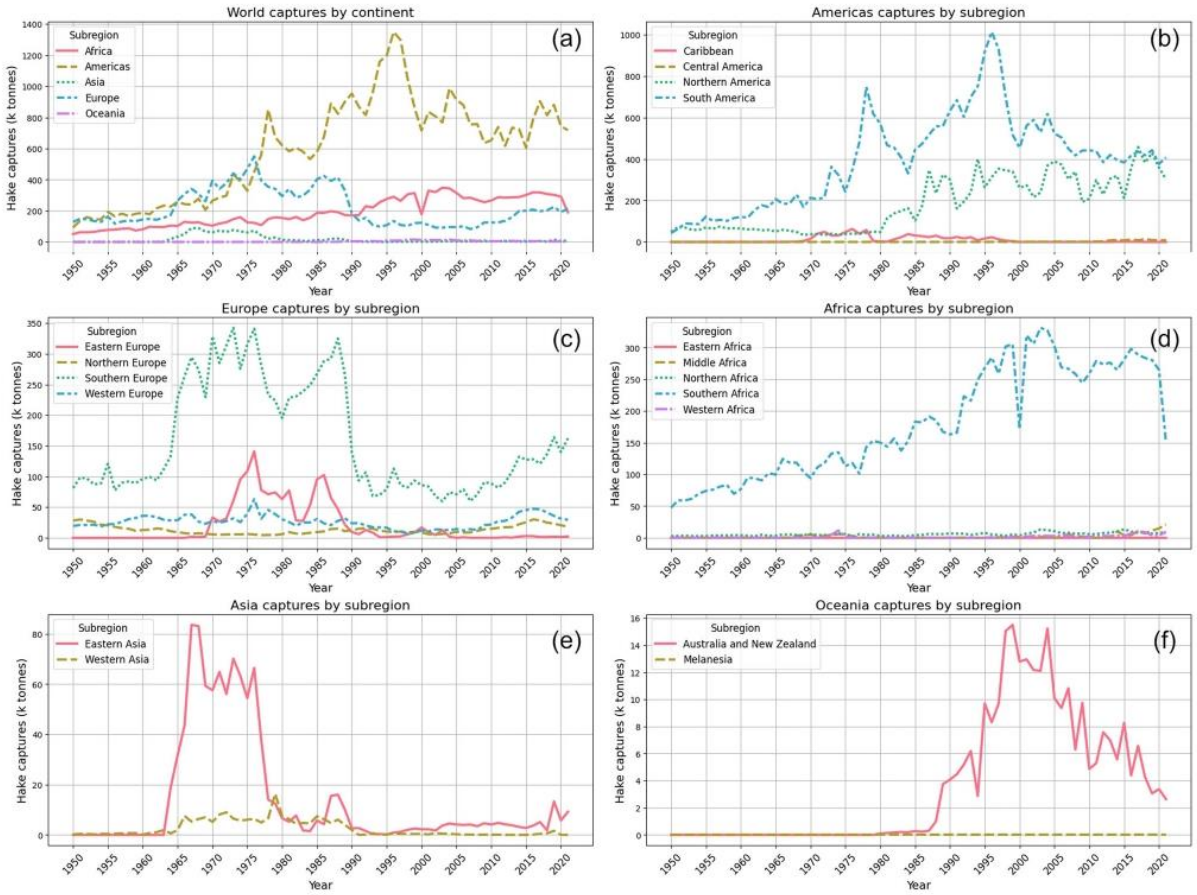

Fig. 2 | Global hake catch trends: 1950-2020. Hake catches over time by region—(**a**) global overview by continent and (**b**–**f**) detailed breakdown by continent and subcontinent (unit: kilo tonnes). Note that Y-axis scales vary between subplots. Data source: FAO. Created with Python using Matplotlib and Seaborn libraries.

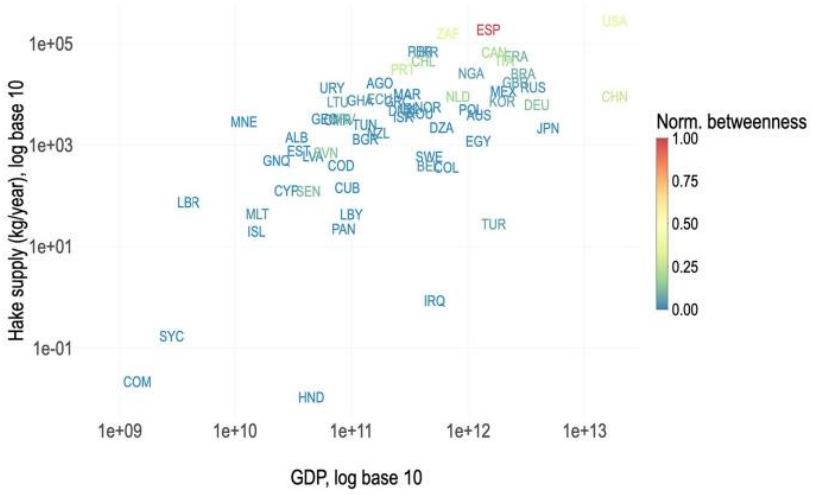

Fig. 3 | Betweenness centrality and hake supply versus GDP: An analysis of hake trade volume and country economic influence from 2016 to 2020. This figure illustrates two significant correlations: (1) between higher GDP and greater hake supply (linear model: GDP ~ food supply, adjusted $R^2 = 0.24$, $p < 0.001$); and (2) between higher GDP and increased network centrality (betweenness) (linear model: GDP ~ betweenness, adjusted $R^2 = 0.58$, $p < 0.001$). The hake supply (catches and imports minus exports) and Gross Domestic Product (GDP) are displayed on a logarithmic scale. The normalised betweenness centrality is weighted by hake trade volume (tonnes). Each country is represented by its ISO3 code, as listed in Table 1. The figure was generated using the R package 'ggplot2' v.3.2.113.

Canada are particularly prominent, denoting their significant roles in the network by facilitating high-value trade flows. In this refined analysis based on trade value, Spain remains a key intermediary, while South Africa's position is reinforced, reflecting their enhanced role in high-value trade. Canada's prominence is more pronounced, indicating their critical involvement in high-value transactions within the global network. These countries' ability to optimise trade costs becomes even more apparent when considering the monetary aspect of trade connections. Canada emerges as influential node that was not as emphasised in the mass-based evaluation, suggesting their strategic importance in the network's financial structure. These insights underline a nuanced landscape where some countries hold strategic economic influence, not immediately apparent when only

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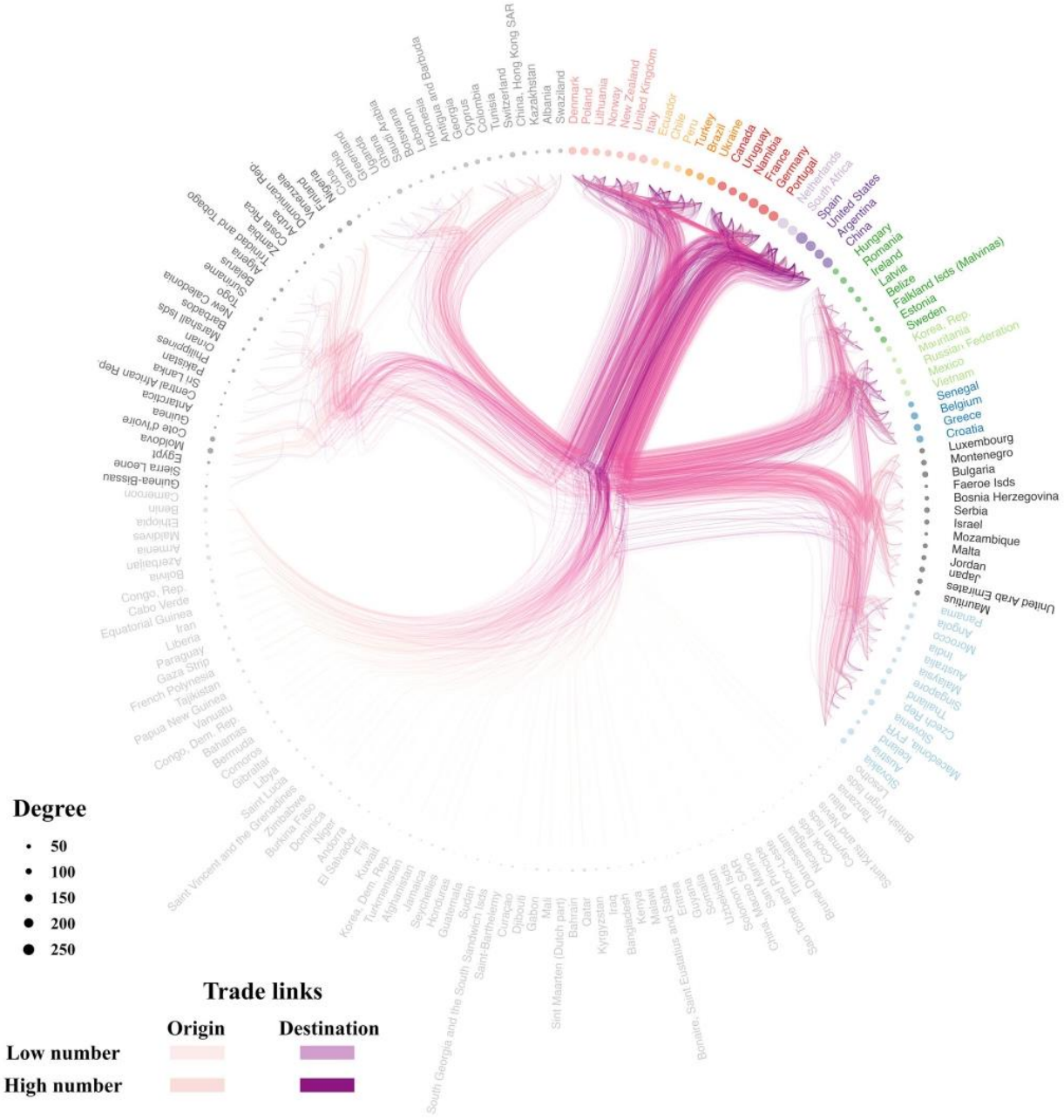

Fig. 4 | The Hake Global Trade Network (HGTN): Country importance and cluster membership in international trade. The 193 traders of the HGTN as nodes (circles) and their trade links as lines. The colour and the size of the nodes represent, respectively, the cluster membership and relative importance of the trader in the HGTN, estimated from the number of trade links with other traders (i.e., degree). The colour of the edges represents the origin, destination, and proportion of trade links for all years between each pair of traders. The clusters were made using Ward's method. The figure was created with R packages: "ggraph" v.2.0.0 and "ggtree" v3.0.2.

considering the physical volume of trade. Their nodes and connecting edges in the visualisation are marked by their relative size and colour intensity, directly correlating with their pivotal role in the hake market's value chain (Figure S5, Figure S6 and Table S2).

Page's Rank as a measure of influence and robustness

Countries with a high Page's Rank typically exhibit a considerable number of inward relationships (imports) from countries that hold a prominent position in global trade, characterised by a substantial flow of exports and imports. This high Page's Rank suggests a resilient trade network as the loss of a connection with a partner would have minimal impact on import volumes, thanks to the country's diversified trade networks (Fig. 7 and Figure S7). Comparative analysis between Page's Rank weighted by mass and by value for the period from 2016 to 2020 reveals a European dominance in the hake trade network. Spain (in-degree = 47), Italy (in-degree = 38), and Germany (in-degree = 43) demonstrate their strategic trade centrality across both metrics. Notably, Portugal emerges as a central player when value is considered, indicating its significant role in higher-value transactions within the network. The consistent high

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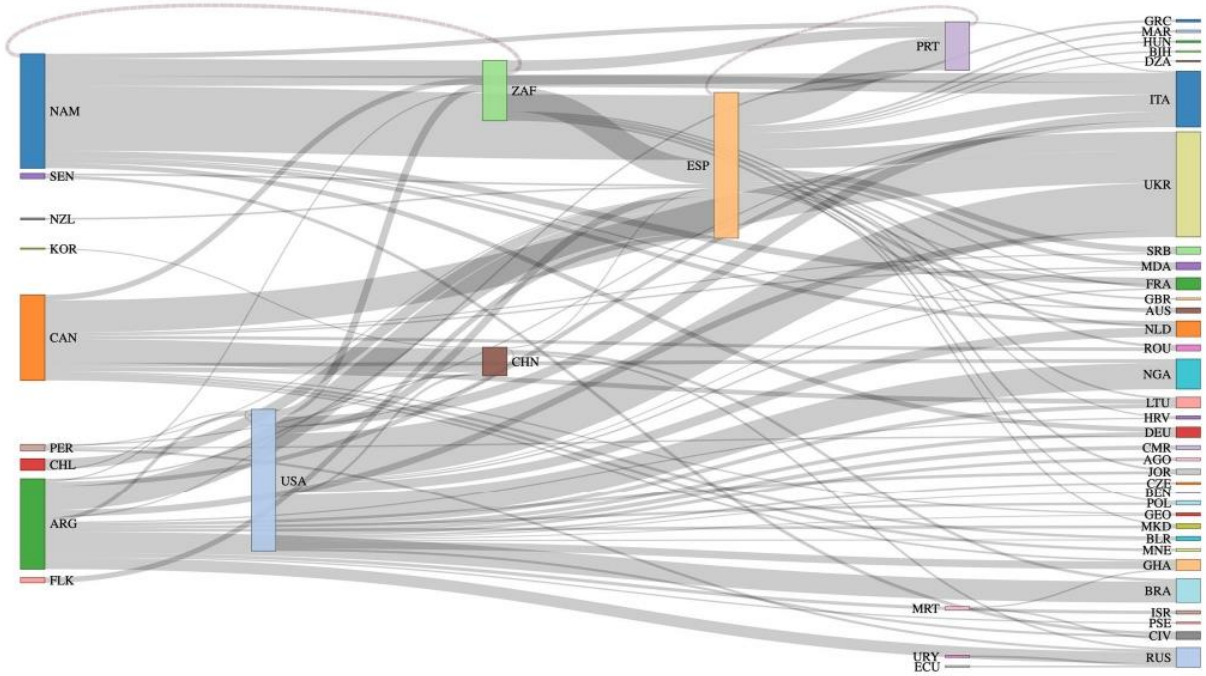

Fig. 5 | Sankey diagram of the Global Hake Trade Network for the period 2016–2020. Countries (nodes) are represented by rectangles or text. The size of the rectangle is proportional to the quantity (mass) of hake traded. Arrows or arcs are used to show the flows between them. The diagram shows the 100 largest flows (tonnes) between countries in the world. Countries are represented with the ISO 3166-1 alpha-3 international standard codes. The interactive diagram can be accessed at: https://mares-imedea.shinyapps.io/Hake_Global_Trade_Network/.

Fig. 6 | Normalised node and edge strengths weighted by monetary value in the Hake Global Trade Network (HGTN). Global Hake Trade Network between Jan. 1, 2016, and Dec. 31, 2020. The numbers correspond to the normalised amount of currency (USD) traded. Each node represents a trader, and each edge represents the relationship between two traders. The size and colour of the node represent the relative importance of the trader in the network in terms of its strength. The width and colour of the edge represent the relative importance of the relationship between two traders in terms of their edge strength. This graph is based on UN Comtrade 030366, 030378, and 030474 commodity codes. The figure was created with R packages: "ggplot2" v.3.2.113, "ggmap" v.3.0.029 and "ggraph" v.2.0.030.

ranking of Spain, Italy, Serbia, and Germany, alongside Montenegro —predominantly EU countries—underscores EU's substantial influence in the hake trade market. Serbia and Montenegro maintain their crucial positions, while Côte d'Ivoire, though influential in terms of mass, is replaced by Portugal in the value-weighted ranking, highlighting the different facets of trade importance. These EU nations, forming a core part of the network, illustrate the region's robust trade architecture, capable of withstanding disruptions and maintaining trade efficiency. Occupying such central positions in the global hake trade network, these countries reinforce the network's

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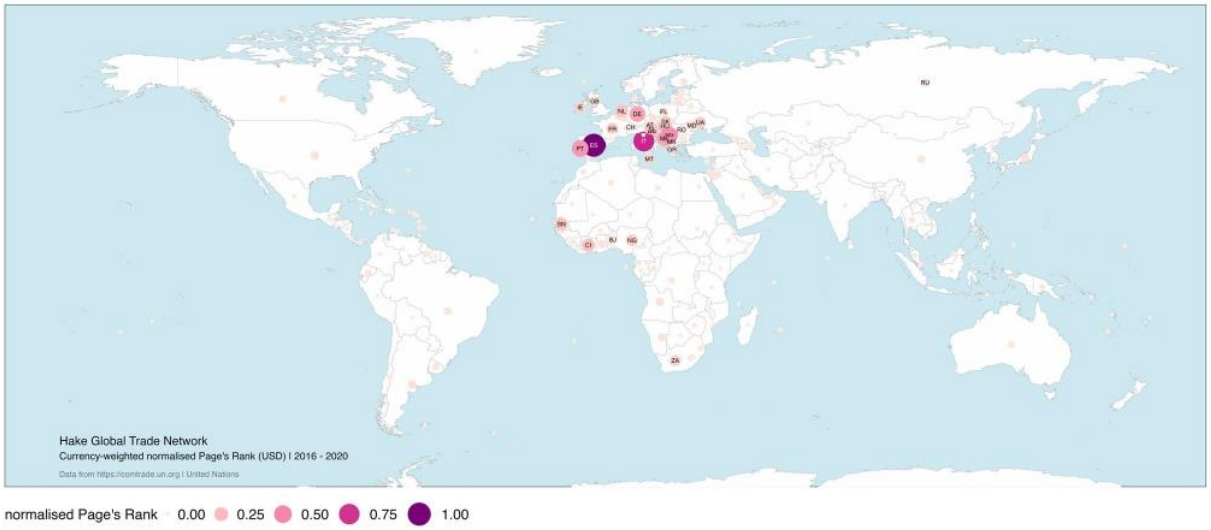

Fig. 7 | Normalised node Page's Rank weighted by monetary value in the Hake Global Trade Network (HGTN). Global Hake Trade Network between Jan. 1, 2016, and Dec. 31, 2020. The numbers correspond to the normalised amount of currency (USD) traded. Each node represents a trader. The size and colour of the node represent the relative importance of the trader in the network in terms of its Page's Rank. This graph is based on UN Comtrade 030366, 030378, and 030474 commodity codes. The figure was created with R packages: "ggplot2" v.3.2.113, "ggmap" v.3.0.029 and "ggraph" v.2.0.030.

resilience and highlight their strategic economic roles (Table S2, Fig. 7 and Figure S7).

Discussion

Global Population Growth and Marine Food Potential

The urgency to meet the nutritional demands of a rapidly increasing global population, expected to reach 9.8 billion by 2050[41], cannot be overstated. In this context, the potential of marine foods, including species like hake, emerges as a pivotal element in addressing global food shortages and malnutrition challenges. Studies like Costello et al.[42] have highlighted the significant opportunities marine resources offer for supporting food security, particularly in regions facing acute nutritional deficiencies. Marine ecosystems, once thought to be an endless source of resources, have the inherent capacity to augment global food supplies. Specifically, hake species, due to their widespread distribution and significant biomass, have the potential to be a key contributor to this endeavour. Our analysis revealed that 6 out of 22 hake species (including the genus *Urophycis*) accounted for 94% of total catches from 1950 to 2020, underlining the species' global significance in fisheries (Fig. 1). However, the contribution of hake to the increase in aquatic food production may be constrained due to the overexploitation and full exploitation of most hake stocks. These species, typically large and long-lived top predators within marine demersal ecosystems, have exploitation rates that are heavily influenced by the historical fishing practices and the health of the ecosystems. Our results showed a notable growth in total hake transactions in both volume and value, although the growth rate has stabilized since 2016 (Figure S3). This scenario raises concerns about the sustainable management of hake fisheries to support future food security.

The contribution of marine foods like hake to global nutrition is also underscored by their high protein content and essential fatty acids, which are crucial for human health. These nutritional attributes make them an ideal candidate for addressing the protein requirements of a growing population. Yet, the declining trend in global hake catches since their peak in the 1970s (Fig. 1) highlight a critical challenge in harnessing this potential. The decline in hake catches is juxtaposed with the increasing demand for protein-rich foods globally. As human diets evolve with growing economic prosperity in various regions, the demand for seafood is expected to rise, further straining the already overexploited marine resources[43]. This scenario presents a complex challenge: balancing the need for increased marine food production with sustainable fishing practices to ensure the long-term viability of these resources.

As we move towards a future where food security becomes increasingly critical, it is imperative to adopt sustainable marine resource management strategies. These strategies should not only focus on optimising yield but also on preserving marine biodiversity and ecosystem health. The sustainable management of hake fisheries, therefore, becomes a case study within of the broader challenge facing global marine food resources. Efforts to increase aquatic food production through advances in fisheries, aquaculture, and mariculture are promising[43]. However, these need to be coupled with stringent conservation measures and effective management policies to address the dual challenges of food security and environmental sustainability.

Hake Overexploitation and Sustainability Challenges

The sustainability of hake populations is a critical concern in the face of escalating global demand for seafood. A simple visual examination of hake fisheries production data reveals that despite their considerable contribution to marine food resources, hake species contend with the dual challenges of overexploitation and catch fluctuation (Fig. 2). Significant spikes and subsequent declines in hake catches are observed across various regions, including South America in the early 2000s (Fig. 2b), Southern Europe in the late 1990s (Fig. 2c), Southern Africa in the late 1960s (Fig. 2d), Eastern Asia in the 1960s and 1970s (Fig. 2e), and the Australia and New Zealand subregion around 2006 (Fig. 2f). These shifts could suggest overfishing but also warrant consideration of additional potential factors, such as changes in regulations, enforcement of quotas, conservation efforts, and ecological dynamics that could influence these trends. These patterns are concerning as they directly impact the species' demography and, consequently, their reproductive viability and population health[9]. For instance, in 2019, South Pacific hake (*Merluccius gayi*) and Southern hake (*Merluccius australis*) were identified as overfished. Additionally, silver hake (*Merluccius bilinearis*) and white hake (*Urophycis tenuis*) failed to show a significant recovery in the Northwest Atlantic. Moreover, European hake (*Merluccius merluccius*) in the Mediterranean and Black Sea exceeded biologically sustainable limits[9].

The patterns observed in hake fisheries mirror a broader trend in global fisheries, where overexploitation often results in reduced catches and jeopardises long-term sustainability[44]. This is particularly evident in the EU

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context, where our analysis shows a consistent decline in hake catches since the early 1990s, with Spain recording the highest volume of catches (Table 1, Fig. 2c). Such trends point to the need for re-evaluating current fishing practices and implementing more sustainable approaches. In addition to the ecological impacts, overexploitation has significant economic ramifications. The stability of hake catches has led to fluctuations in market prices and supply uncertainties, affecting the livelihoods of those dependent on these fisheries. The observed stability and subsequent decline in hake catches, particularly in regions like Europe, have economic implications that extend beyond the fishing industry, impacting food security and trade dynamics globally[45].

The ecological consequences of overfishing are not limited to the species targeted. The removal of top predators like hake can lead to trophic cascades and imbalance in marine ecosystems[46,47]. This highlights the interconnectedness of marine species and the importance of maintaining ecological balance to ensure the sustainability of fisheries. Addressing these challenges requires a comprehensive approach that encompasses both regulatory measures and community engagement. Effective fishery management policies, including catch limits, size restrictions, and closed seasons, are essential to prevent overfishing and allow stock recovery[48]. Additionally, promoting responsible fishing practices and raising awareness about the importance of sustainable seafood consumption are vital steps towards mitigating the overexploitation of hake and other marine resources[49].

In this context, the concept of "sustainable commoditization" as proposed by Belton, Reardon, and Zilberman[50] becomes particularly relevant. They advocate for a model where seafood production not only meets the growing global demand but does so sustainably by integrating efficient production processes with sustainability principles. This approach aims to balance food security needs with environmental conservation, emphasizing the development of robust supply chains and regulatory frameworks that support sustainable practices across the Global North and South. Such strategies are vital to ensuring that seafood commoditization contributes to economic growth while minimizing negative environmental impacts.

Global Trade Dynamics and Dependency

The global trade dynamics of hake have evolved significantly over the past decades, reflecting broader changes in the seafood industry and international market dependencies. Our study indicates that Europe, particularly Spain, has emerged as a dominant importer in the hake market, underscoring a major shift in global seafood trade (Figure S1 and Figure S2). Furthermore, hake are often harvested in multispecies fisheries utilizing non-selective methods like bottom trawling. This shift highlights the growing dependence of developed countries on seafood imports to satisfy domestic demand, a trend that has been steadily increasing due to declining local catches and heightened consumer preferences for diverse seafood products[45]. In the case of Spain, only 8% of the hake consumed in this country is caught in its territorial waters[27].

The intensification of international trade, especially in hake, has been driven by a range of factors, including overfishing in traditional fishing grounds, regulatory changes in fisheries management, and the globalisation of food systems. The effect of overexploitation in developed countries has led to reforms aimed at reducing fishing pressure and rebuilding fish stocks. This globalisation of food commodities creates opportunities for the import of essential nutrients, especially in developing countries where domestic resources may be limited[1,2]. However, as our findings show, these reforms have also resulted in a reduced domestic seafood production, thereby increasing the reliance on imports from other regions, especially from countries like Namibia, Argentina, and South Africa (Table 2, Figs. 2c and 4). Additionally, nutrient flows do not always align from countries with surplus nutrient production to those with deficits. In low and lower-middle-income countries, the role of trade in filling nutrient gaps is generally marginal and cannot reliably compensate for domestic shortfalls[51].

This increased dependency on imports has significant implications for global trade dynamics. The rise in import and export activities across all regions from 2016 to 2018, followed by a decrease from 2019, reflects not only the fluctuations in hake availability but also the impact of global events such as the COVID-19 pandemic (Figure S2, Figure S3). Developed countries, in their quest to maintain high seafood consumption levels, have thus turned to developing nations to bridge the gap in domestic supply. This trend is particularly evident in Europe, where imports have far outnumbered exports, creating a heavy reliance on hake sourced from other parts of the world.

The transition from domestic production to increased imports in developed countries has created a complex network of trade relationships. As our cluster analysis reveals, countries like Spain, Argentina, and the USA have become central nodes in this network, facilitating significant trade flows across continents (Fig. 4). These countries, due to their strategic geographical locations and historical trade links, play a crucial role in the global hake market, influencing both the supply and pricing of hake internationally.

Moreover, the global trade in hake is not merely an economic transaction but also a reflection of geopolitical relationships and regional alliances. Countries with a high degree of network intermediation, such as Spain, have been able to leverage their trade relationships to secure a steady supply of hake, thereby influencing global market dynamics (Fig. 3 and Figure S5). This scenario underscores the interdependence of nations in the modern era, where international trade acts as a critical facilitator connecting diverse regions and influencing food and nutrition security[1,2]. However, this increased interdependence also raises concerns about the resilience of global food systems to shocks, such as ecological disruptions or political changes. The fluctuations in trade volumes and the uneven distribution of trade benefits highlight the vulnerability of countries, particularly those heavily reliant on seafood imports, to external factors.

Economic Disparities and Trade Benefits

The global hake trade exhibits significant economic disparities, manifesting an uneven distribution of benefits among nations. Our analysis reveals a clear correlation between a country's economic status, as measured by GDP, and its role within the hake trade network, influencing the distribution of trade benefits (Fig. 3). This pattern underscores a broader dynamic in global trade, where wealthier nations frequently secure superior positions, enabling them to access resources and maximize trade opportunities effectively. Developed countries, particularly those with robust economic and trade infrastructures such as Spain, have substantially benefited from the hake trade. Their prominent role as major importers in the global market (Figure S1 and S4) not only ensures a consistent seafood supply but also grants them considerable influence over global market prices and trade policies.

Conversely, developing nations, despite their significant contributions to the global hake supply, often occupy a less favourable position. For example, Watson et al.[10] highlight that lower-income countries export high-value seafood to alleviate poverty and ensure food security by importing lower-value seafood. This strategy reflects deliberate trade adjustments aimed at achieving broader economic and social goals, such as poverty alleviation and enhancing food security. However, this exchange of nutrients between nations presents challenges, particularly for low and lower-middle-income countries. They struggle to offset domestic nutrient deficits through imports, a dilemma that frequently results in irreversible nutritional shortfalls[51].

Countries like Namibia and Argentina, which are key hake exporters, face the challenge of balancing their economic growth with the sustainability of their natural resources. The export-driven approach of these nations, while beneficial in the short term, raises concerns about the long-term impacts on their fisheries and local economies (Table 2, Fig. 3, Figure S1). Moreover, the reliance of developing countries on export revenues from hake trade can make them vulnerable to market fluctuations and external economic pressures. The disparities in the hake trade network also reflect a broader issue of inequitable resource distribution in global trade. While some countries reap significant economic benefits, others struggle to gain equitable access to resources and markets. This imbalance poses a challenge to achieving sustainable and inclusive growth in the global seafood industry.

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Moreover, the socio-economic impacts of the seafood trade, especially on small-scale fisheries, highlight significant inequities in benefit distribution. Drury O'Neill et al.[52] have shown that although the seafood trade generates considerable economic value, the benefits are disproportionately skewed towards actors higher up in the value chain, such as processors and retailers, rather than local fishers. This disparity underscores the need for market structures that foster fair trade practices and bolster the livelihoods of small-scale fishers, who play a vital role in the sustainability of marine resources.

Trade resilience and food security

The resilience of global trade networks, especially in the realm of hake trade, is integral to sustaining food security. Our study highlights those countries like Spain, which have diversified their trade networks, exhibit greater resilience against disruptions in the seafood market (Fig. 7). This resilience is vital in ensuring a consistent supply of food, particularly in areas heavily reliant on seafood imports for nutrition. The relationship between trade resilience and food security is intricate, influenced by geopolitical, ecological, and economic factors that impact trade stability.

The COVID-19 pandemic, for instance, presented significant challenges but also catalysed innovative adaptations in the seafood industry. Love et al.[53] documented how disruptions, while causing substantial losses, also fostered innovative responses such as the adoption of direct-to-consumer sales platforms. These innovations not only buffered against global disruptions but also opened new opportunities for market expansion. Stoll et al.[54] further observed the effectiveness of alternative seafood networks during the pandemic, proposing them as models for a more resilient seafood trade system. In response to these challenges, developed regions are expected to shift towards more self-reliant seafood trade models, while developing regions might struggle due to their dependence on seafood exports, a scenario discussed by Wei et al.[55].

Our findings indicate that countries with prominent roles in the hake trade network, such as Spain, Italy, and Germany, demonstrate strategic trade centrality crucial for a stable food supply (Table S2, Fig. 7, Fig. S7). Their capacity to maintain steady import volumes despite potential trade disruptions underlines the importance of establishing robust and varied trade connections.

Moreover, our analysis of the hake trade network underscores the importance of regional trade clusters and mutual trade agreements in enhancing food security. Countries within these clusters, often bound by cultural ties and historical trade relationships, benefit from a fairer distribution of resources and improved self-reliance. This aspect is particularly important for low or lower-middle-income countries facing acute food security challenges. Yet, the global hake trade is not immune to shocks, such as ecological disturbances or political shifts. These events can cause ripple effects on food prices and availability, impacting both exporters and importers. The vulnerability of global trade to such disruptions emphasises the necessity for adaptive and resilient trading systems capable of responding to and mitigating potential impacts on global food security[3,4,8,20]. Additionally, there is a growing need to re-evaluate international trade rules and shift towards shorter-distance trade, which emphasizes exports and imports between proximate countries within the same continent. Intra-regional trade remains vital for low and lower-middle-income countries. Enhancing regional integration through bilateral and regional trade agreements and investments in regional connectivity could improve nutrient adequacy at the regional level[51].

Adapting Hake Fisheries to Global Shifts: Challenges and Strategies

The global hake market, deeply impacted by shifting dynamics such as the COVID-19 pandemic, has seen significant trade volume fluctuations[27]. This volatility highlights the fragility of international seafood markets and underscores the need for resilient supply chains. In developing countries, particularly in regions like Namibia, the challenge extends to balancing lucrative international trade with addressing local nutrient deficiencies, as emphasised by Hicks et al.[56]. The sustainable exploitation of local hake populations could significantly contribute to meeting the nutritional needs of coastal communities reducing the dependency of local food security from global markets stability.

Moreover, the complexity of global hake trade is magnified by bilateral and private fisheries agreements, which often dictate seafood transfer patterns, influencing both global and local market dynamics[45]. These agreements, along with the broader trade policies, play a significant role in shaping the accessibility and sustainability of hake fisheries.

Considering these challenges, aligning hake fisheries management with the Sustainable Development Goals, particularly the Zero Hunger Goal, becomes crucial. This alignment necessitates a balanced approach, ensuring that the exploitation of hake stocks for international trade does not compromise the ecological sustainability and food security of local populations.

Conclusions

This study has elucidated the multifaceted nature of the global hake trade and its implications for food security and sustainability. Our analysis underscores that while the hake trade offers significant opportunities for addressing global food shortages, it is fraught with challenges related to overexploitation, sustainability, and economic disparities. The increasing global population and the rising demand for nutritious food sources make the sustainable management of hake fisheries more critical than ever[41–43].

The findings reveal a complex interplay between global trade dynamics, economic disparities, and trade resilience, each contributing to the broader narrative of food security. Developed countries, especially those like Spain, have emerged as significant players in the hake market, influencing trade patterns and resource distribution globally ([45; Fig. 5). Meanwhile, the dependence on hake imports in these countries underscores the need for diversified and resilient trade networks to mitigate the risks associated with market and ecological disruptions.

In conclusion, the hake trade exemplifies the challenges and opportunities inherent in global seafood markets. Sustainable management practices, equitable trade policies, and resilient trade networks are imperative for ensuring the long-term viability of hake fisheries and contributing to global food security. This study highlights the need for a collaborative approach to address these challenges, involving stakeholders across the spectrum, from fishers to policymakers.

Data availability

The data supporting the findings of this study are available from two primary sources. The first source is the FAO Fishery and Aquaculture Statistics, which covers global capture production from 1950 to 2021, and can be accessed at https://www.fao.org/fishery/en/collection/capture. Access to these data may be subject to certain restrictions as outlined in the FAO's Open Data Licensing Policy and governed by the Statistical Databases Terms of Use, detailed at https://www.fao.org/contact-us/terms/en/. The second source is the United Nations Commodity Trade Statistics Database (UN Comtrade), available at https://comtradeplus.un.org. The use of these data is restricted under the United Nations On-line Usage Agreement, which can be reviewed at https://comtrade.un.org/licenseagreement.html. The data were used under license for this study. Additionally, processed data are available through the authors' interactive Shiny web application, which facilitates data exploration and visualization, accessible at https://mares-imedea.shinyapps.io/Hake_Global_Trade_Network/.

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Conceptualization: A.O.-A., J.M., S.V., Methodology: A.O.-A., G.A., S.V., J.M., Data curation: A.O.-A., G.A., Analysis of data: A.O.-A., G.A., L.L., S.V., J.M., Writing draft paper: A.O.-A., G.A., L.L., S.V., J.M. Review and editing: A.O.-A., G.A., L.L., S.V., J.M.

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The authors declare no competing interests.

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5 GENERAL DISCUSSION

5.1 CONTEXTUALIZATION AND UNITY OF THE CHAPTERS

The three main chapters of this thesis offer interconnected and complementary perspectives on the global challenges currently faced by demersal fisheries which are essential for understanding the challenges of long-term fisheries sustainability. The work focuses on Spanish demersal fisheries and particularly on hake, one of the most valuable resources for these fleets, and as such, on how global challenges affect the fisheries sector of a country with a well-developed economy. As climate continues to increase the vulnerability of the fisheries sector (chapter 2), maintaining or increasing the exploitation of depleted fishery resources increases the climate feedback through higher carbon footprints (chapter 3), being however insufficient to meet the consumer demand. In this regard, Spain has positioned itself as an international commercial hub for fisheries products (chapter 4; Ospina- Alvarez et al., 2022), with e.g. hake imports largely exceeding the national catch, which also increases the carbon footprint of the fishery products having strong implications for global food security and supply chain resilience, but also negatively impacting the adaptation capacity of the fleet operating in national waters. Additionally, dependence on imports could make Spain more susceptible to fluctuations in international markets, increasing economic and geopolitical vulnerabilities related to global trade.

The common theme of all the chapters is the complex nature of the challenges currently facing marine ecosystems around the world, especially regarding fish stocks. Climate change, characterised by rising temperatures, sea level changes and an increase in the frequency of extreme weather events, directly affects marine life and fisheries; it also affects the fishing sector, indirectly altering its accessibility to fish stocks. The results of this thesis highlight different aspects of fishing that can be related to its vulnerability to climate change and its adaptive capacity, which need to be promoted to increase the resilience of the fishing sector and the environmental health of its biological resources. However, the managerial implications of climate change cannot be interpreted in isolation but also require a careful examination of the sector's feedback on climate change through its carbon emissions.

Beyond the direct emissions from fuel consumption, another critical but often overlooked factor is the role of bottom trawling in disturbing long-stored carbon in seabed sediments. This practice, widely used in demersal fisheries, resuspends carbon that has accumulated over millennia, releasing it into the water column where it can eventually enter the atmosphere as CO_2. Recent estimates suggest that between 1996 and 2020, bottom trawling could have contributed up to 0.34–0.37 Pg CO_2 yr^{-1} at the global scale, highlighting its potential as a significant but unregulated source of anthropogenic carbon emissions. Additionally, in heavily trawled and semi-enclosed seas, this disturbance not only alters local water pH but also disrupts benthic ecosystems, impacting the productivity and biodiversity of demersal fish stocks (Atwood et al., 2024). In the European context, seabed habitats are under significant pressure from the cumulative impacts of demersal fishing, coastal developments, and other anthropogenic activities. A European Commission report from the year 2020 indicated that approximately 43% of Europe's shelf and slope areas and 79% of its coastal seabed are considered physically disturbed, with bottom trawling identified as the main factor in this degradation. This widespread impact concerns not only for biodiversity conservation, but also for the long-term sustainability of fisheries, as habitat loss and degradation can reduce the

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productivity of commercial fish stocks (European Commission, 2020).

Greenhouse gas (GHG) emissions in the hake fishery are deeply linked to the efficiency of the Spanish demersal fleet, standing out as a crucial factor in assessing climate vulnerability. Older fleets with reduced energy efficiency tend to consume more fuel, resulting in high GHG emissions, which in turn contributes to the acceleration of climate change (Knittweis et al., 2016). In 2020, the EU had a fishing fleet of 73,716 vessels that landed 3.9 million tonnes of seafood worth €5.8 billion (STECF, 2022). Europe's fishing fleet consumes almost 2 billion litres of fuel a year, roughly equivalent to the annual emissions from 1 million cars, highlighting the sector's significant carbon footprint and the urgent need for energy efficiency improvements. Fuel savings are beneficial both for reducing environmental impact and for improving the economic resilience of the sector (STECF, 2022). The price of fuel, being a significant determinant of economic income from fishing, is impacted by high consumption, influencing the prices of commercial species and, consequently, the sales volumes and income of the sector (Parker et al., 2018; Sala et al., 2022). Additionally, ecological imbalances caused by climate change, such as changes in fish population dynamics, are identified as key influences on the sustainability of fishing practices (FAO, 2018; FAO, 2022). Changes in the availability of commercial species can lead to an increase in fishing efforts, affecting catch per unit effort (CPUE) coefficients and exacerbating GHG emissions from vessels, which increases the carbon footprint of fish products, influencing the consumption choice of a population that seeks not only healthy but also sustainable food (Nelson et al., 2016; FAO, 2018; EUPHA, 2017).

In the study on climate vulnerability, fleet power was highlighted as an important variable, with regions such as the Basque Country, Catalonia and Valencia having the largest vessels in Spain. These vessels, due to their greater power, have the ability to sail over long distances and access wide areas,
which makes them more adaptable in their catches (Vázquez-Rowe and Tyedmers 2013). However, this advantage is accompanied by an increase in fuel consumption and, consequently, greenhouse gas emissions (Basurko et al., 2013; Olmer et al., 2017). In contrast, Galicia, which has a mostly small- scale fleet (MAPA, 2019), faces greater sensitivity to the effects of climate change, but with a lower intensity of emissions per vessel. This situation illustrates the challenge of balancing climate resilience and adaptive capacity with fishing efficiency and environmental sustainability.

In this sense, management measures and conservation policies can help with the resilience of marine species and the mitigation of environmental impacts in the short term, but these actions alone are not enough to balance the need for growth in fishing productivity with a reduction in emissions (FAO, 2022; United Nations, 2022). The indicators used in this thesis to calculate climate vulnerability, some of them widely used in the literature and others developed ad-hoc for Spanish fishing, give an idea of the lines of action, for example, the age of the fleet and the efficiency of catches is directly related to innovation in the sector, requiring the modernization of fleets and the increase in innovations towards improved fishing performance and a low-carbon industry (Lucchetti et al., 2023). Fishing vessels with alternative propulsion, sensors, buoys and smart traps, and the digitization of fishing operations using machine learning are some of the recent innovations with great potential to have a positive impact on both catch efficiency and the decarbonization of fleets (European Commission, 2020).

Fishing vessels with alternative propulsion, sensors, buoys, and smart traps, along with the digitization of fishing operations using machine learning, are some of the recent innovations with great potential to enhance both catch efficiency and fleet decarbonization

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(European Commission, 2020). The integration of artificial intelligence and big data analytics into fisheries management offers a significant opportunity to improve data acquisition, processing, and application. Machine learning techniques have been successfully employed in fisheries forecasting, species classification, marine spatial planning, and the monitoring of fishing activities (Uriondo et al., 2024). Despite these advancements, the fishing industry has been slow to incorporate digital technologies compared to other maritime sectors. This delay is primarily attributed to high initial investment costs, regulatory and bureaucratic constraints, inconsistent data collection methodologies, and limited stakeholder engagement. Overcoming these barriers requires the establishment of a harmonized digital infrastructure that facilitates real-time data analysis and enhances decision-making processes. By leveraging AI-driven insights, the sector can achieve greater operational efficiency, improved sustainability, and enhanced economic viability, thereby aligning with broader environmental and resource management objectives (Uriondo et al., 2024)

The ecological imbalances induced by climate change, together with the overexploitation of stocks, have direct consequences for both food security in developing nations and the nutritional quality of diets in developed countries. Fishery products are fundamental components of a healthy diet (FAO, 2022). In addition to being an excellent source of high-quality protein, aquatic foods provide essential micronutrients that are often scarce in other dietary sources, such as iodine, selenium, calcium, iron, and zinc. They are also rich in long-chain omega-3 fatty acids, which are crucial for brain development in children and play a protective role against coronary heart diseases (FAO, 2024). The consumption of whole fish, rather than just fillets, further enhances dietary intake of vitamins and minerals, making aquatic foods particularly valuable for low-income populations with limited access to diverse nutrition sources (FAO, 2024).

Although global demand for fish products is increasing (FAO, 2022), consumption in Spanish households has been falling alarmingly in recent years. In fact, the volume of fish consumed in the country in 2022 fell by 15.6% compared to 2021, the lowest in any historical series, and has fallen by 32.8% since 2008 (MAPA, 2020; 2021, 2022, 2023). Spain is characterised by being a nation with a long history of production and consumption of fish products, with a stable supply and a population with a GDP that stands out in the global context (MAPA, 2023; Han et al., 2022). Many factors may be related to the decline in consumption of fish products in Spain, but recent studies highlight a potential trend towards consumer preference for convenience food products (Brunner et al., 2010; Peltner & Thiele, 2018; Saidi et al., 2022). In addition, the globalisation of food markets and supply chains has played a significant role in changing people's eating habits, leading to a transition in consumer demand from local to global products (FAO 2020; Hanus, 2018). This indicates a potential shift in Spanish society away from the Mediterranean and Atlantic diets, diets that have historically held sway in terms of longevity and quality of life (Serra- Majem et al., 2006; Harmon et al., 2015; Carballo et al., 2023). This trend poses the challenges of maintaining fishery resources as a fundamental part of the nutritional quality of a complete diet and preserving the jobs and socio-economic networks associated with this traditional sector.

Employment dependency is the attribute most widely used to explore the sensitivity of fisheries in CVA studies (Allison et al., 2009; Morzaria-Luna et al., 2014; Ding et al., 2017; Wabnitz et al., 2018; Pinnegar et al., 2019). The results of this thesis show that the main variable that amplifies the sensitivity of fisheries is precisely the number of jobs in the extractive sector, with Galicia being the most sensitive region in this regard at national level (Chapter 2, STECF, 2019a). In this sense, it is imperative that strategies are drawn up to reverse these consumption trends and support the sustainability of the sector. Spreading

knowledge of the health benefits of fisheries products, innovation in new product lines and in the implementation of certification and traceability systems related to safety for quality, as well as the promotion of exports are strategies that can effectively contribute to winning over Spanish consumers, guaranteeing income and increasing the resilience of the Spanish fisheries sector (Giacomarra et al., 2021; Han et al., 2022; Fiorile et al., 2023).

On the other hand, diversifying regional seafood preferences has the potential to reduce pressure on marine ecosystems and, at the same time, support local fishing economies by reducing their vulnerabilities. Campaigns that induce changes in consumer behavior by encouraging the consumption of a greater variety of local fish and seafood species can be important tools in reducing the ecological footprint of seafood products, contributing to the resilience of the sector and the sustainability of fisheries, as well as maintaining fish resources as a fundamental part of the nutritional quality of a complete diet and preserving the jobs and socio-economic networks associated with this traditional sector (Altiok et al., 2021; European Commission, 2023; United Nations, 2023). In the Mediterranean region, a strong preference for a limited number of fish and seafood species has led to excessive pressure on certain stocks, highlighting the need for a broader and more diversified seafood basket. Expanding consumer choices to include species that are often discarded due to perceived low commercial value can not only alleviate overexploitation of popular species but also contribute to reducing food waste and improving economic opportunities for local fishers (Altiok et al., 2021. Additionally, while diversification can play a key role, it is also necessary to reassess overall seafood consumption levels, as the production of seafood generally entails higher land displacement and CO_2 emissions compared to plant-based food sources (Clune et al., 2017; Galli et al., 2020a; Kim et al., 2019).

Fishing is also closely linked to tradition, natural heritage and cultural heritage, this historical context is strongly connected to the fishing tradition in Spain, which has driven the development of its maritime sector and its privileged position in international fisheries policies that guarantee the exploitation and management of marine resources (Maza et al., 2019; Kopela, 2019). In reality, the global allocation of fishing catches is determined by the flag state (nationality) of the vessel and not by the location of the catch (Lobach, 2003). This system, which generally relies on historical catch data to allocate quotas, tends to benefit nations that have historically had the resources to invest in and expand their fishing fleets, and can disadvantage coastal states of developing nations seeking to expand their maritime sectors (Davis et al., 2022). Factors such as its fishing culture, together with its great expertise, productive capacity and strategic geographical location, position Spain in a strategic position in the hake production chain, both as a producer and as an important player in the international trade network.

International trade plays a significant role in global food security and in the availability and diversification of food sources. It also has a significant impact on the global economy, guaranteeing export revenue, employment and reducing local vulnerabilities (FAO, 2022). In the case of hake, the direct benefit for Spain in terms of international trade is noteworthy, as it plays a central role in the network and imports account for most of the fish available in the country (55%). However, the same international trade that guarantees the nutritional quality of diets in Spanish homes contributes to an increase in GHG emissions and the carbon footprint associated with hake. The results of this thesis confirm this trend since hake imported into Spain had the highest relative emissions intensity (4.88 kg CO_2e/kg), while the mode of transport with the highest volume of emissions was air transport, accounting for 73% of the emissions related to hake transportation, despite representing only 14% of the total volume transported.

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Our results reveal an interesting correlation between countries with high international trade network intermediation, ample hake supply and Gross Domestic Product (GDP), where countries with higher GDPs generally have higher volumes of hake supply, indicating a correlation between economic affluence (i.e. GDP) and hake trade network intermediation. A pattern that connects with a global seafood market context with developing countries concentrating the largest exports, while developed countries concentrate the largest volumes of imports (OECD, 2015). The impacts of climate change on marine species, overexploitation and stock preservation policies in developed countries prevent them from meeting their domestic demand for seafood and boost imports, but this high dependence poses significant risks to the stability of supply and access to these resources (FAO, 2022). Fishing in regions with lower GDP is strongly associated with a low capacity to adapt to climate change, leaving trade networks vulnerable to shocks that can compromise their resilience and consequently access to resources (Allison et al., 2009; Brugère & De Young, 2015; Blasiak et al., 2017; Ding et al., 2017). In addition, long transportation distances considerably increase GHG emissions, amplifying climate change and the carbon footprint of fishery products.

The lessons learned and strategies developed for Spain and hake can be adapted and applied to other contexts, as long as their specificities are taken into account. This exchange of knowledge and experience is fundamental for more effective global management of marine resources. In summary, the holistic analysis of the challenges faced by the hake fishery is a small sample of the complexity and work that lies ahead to achieve sustainable management of marine resources. This integrated approach, which takes into account the interdependence of various factors and feedback loops, is fundamental to the development of effective global strategies aimed not only at the sustainability of the hake fishery, but also at the resilience of the entire fisheries sector in relation to the present and future environmental, economic and social challenges posed by climate change.

The results of this thesis indicate some targets for future efforts to achieve the goal of providing healthy diets and food security, guaranteeing the perpetuity and development of fisheries and their workers in a coherent and sustainable manner from a climate perspective. Using the vulnerability study of demersal fisheries in Spain as a basis, future actions should strive to deepen knowledge about the vulnerability attributed to other Spanish fleets and fishing gear, as well as developing and fostering managerial, technological and market innovation that can mitigate the environmental impacts of fishing and leverage the transition of fisheries to a low-carbon economy. Innovative impact entrepreneurship should be a priority for governments and investors, taking into account that creative businesses can be major drivers of changes in current fishing production patterns, as well as income opportunities and increasing the adaptive capacity of Spain's coastal communities (Asche et al., 2018; Luchetti et al., 2023). In the context of the climate crisis, decarbonization and reducing the carbon footprint of products are priorities, in which case technological innovations can be of great value, but given the need for urgent action, fisheries management strategies and public policies should recognize the physical limits of ocean resources, encourage the consumption of species with lower associated carbon emissions combined with market strategies that can guarantee the income and sustainability of the fishing sector.

Reforms in fisheries management necessarily involve the supply chain, including international trade networks. The vulnerability of the global hake trade described in this thesis emphasizes the need for adaptable and resilient trade systems capable of responding to and mitigating the possible impacts on global food security, the guarantee of nutritious diets and the economy of the fishing sector (Gephart et al. 2017; Blanchard et al. 2017; Grassia et al. 2022; Cao et al. 2023). In this sense, it is of the utmost importance to create broader trade agreements

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and policies on the accessibility and sustainability of fishing. This reform requires a balanced approach, ensuring that the exploitation of hake stocks for international trade does not compromise the ecological sustainability and food security of local populations. In addition, we suggest expanding the scope of the study of fish trade networks to other species of commercial interest, studies that can support equitable policies and efficient management actions.

5.2 WRAPPING UP THE FINDINGS OF THIS THESIS

5.2.1 Vulnerability to Climate Change for Demersal Fisheries

Chapter 2 of the thesis embarks on an exploratory journey to understand the varying effects of climate change on demersal fisheries at a regional scale. This academic exercise stems from the need to identify and analyse how different socioeconomic and ecological factors contribute to the vulnerability of fisheries across various European regions. The study emphasises the lack of detailed assessments that consider these unique regional characteristics, especially when previous evaluations have generally portrayed Europe as having low vulnerability to the risks of climate change, primarily due to its advanced adaptive capacities (Allison et al., 2009; Ding et al., 2017).

A central element of this research is the use of Climate Vulnerability Assessments (CVAs) at the regional level, employing 19 indicators of species exposure and sensitivity. This approach is distinguished by its effort to downscale CVAs, which allows for the design of more effective management strategies (Holsman et al., 2019; Holsman et al., 2020). The study uncovers significant differences between the Atlantic and Mediterranean in terms of vulnerability, with particular attention to the greater exposure of Mediterranean coastal regions to climate change risks. This finding is supported by data indicating a faster warming of the sea surface in the Mediterranean compared to the Atlantic over recent decades (Belkin, 2009; Adloff et al., 2015; Aznar et al., 2016).

The research also highlights the limitations of existing CVAs, such as the underrepresentation of climate change-related factors like acidification, changes in precipitation, and the frequency of extreme weather events, all of which have a profound impact on fishing vulnerability (Metcalf et al., 2015; Wabnitz et al., 2018; Pinnegar et al., 2019). In addressing these gaps, the study considers the continental shelf area of each coastal region, recognizing its relevance in assessing the various predicted impacts in the Mediterranean, such as the increase in extreme events and changes in marine ecosystems (Hidalgo et al., 2018; Darmaraki et al., 2019; Ser-Giacomi et al., 2020; MedECC, 2020).

A crucial aspect of this study is its investigation into the socioeconomic sensitivity of fisheries, using factors such as employment dependence and fleet characteristics. The study identifies Galicia as a region with high sensitivity, given its significant fishing tradition and the socioeconomic role of the fishing sector (STECF, 2019a; Allison et al., 2009; Morzaria-Luna et al., 2014; Ding et al., 2017; Wabnitz et al., 2018; Pinnegar et al., 2019). Additionally, the research points to the age and efficiency of the fishing fleet as adaptability indicators, observing variations across different Spanish regions (Knittweis et al., 2016; MAPA, 2019).

The sensitivity of species to climate change also emerges as a key aspect, revealing that while a proportion of species in both the Atlantic and Mediterranean regions show high sensitivity, their overall contribution to the community's sensitivity is low due to their limited abundance in fishing catches. This aspect underscores the importance of considering the specific responses of each species to climate change and the need for regional studies linking species to climate impacts at different life stages (Catalán et al., 2019; Holsman et al., 2019; Twiname et al., 2020; Sunday et al., 2015; Hare et al., 2016). Furthermore, the study examines the adaptive capacity (AC) of regions, with Mediterranean areas showing lower AC levels

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partly due to lower landings of low commercial value species. This is attributed to local consumption patterns and the availability of these species, contrasting with the situation in Atlantic regions (STECF, 2019). The ability of fishing crews to transition between large- scale and artisanal fishing, as well as the flexibility to land catches at different ports, are also identified as crucial adaptive indicators (Gordoa et al., 2019).

In conclusion, the study presents a clear pattern of vulnerability between the Atlantic and Mediterranean zones, highlighting the unique combination of factors affecting each region's vulnerability to climate change. It calls for more detailed international studies to uncover additional socio-ecological aspects influencing fisheries' vulnerability. Emphasis is placed on the need for customised fishery adaptation planning at the regional level, highlighting the potential limitations of large-scale policies to address the complex and variable nature of fisheries management (Holsman et al., 2019, 2020; Levin et al., 2013; Mumby et al., 2017).

5.2.2 Carbon Footprint of the Hake Supply Chain

This comprehensive study in Chapter 3 delves into the carbon footprint of the hake supply chain in Spain generated by fishing, international transportation, and national distribution. It highlights the global interconnectedness of the fishing industry and the extensive journeys required to bring seafood products from the depths of the oceans to the final market, emphasising the significant carbon footprint of this process (Hilborn, 2013; Swartz et al., 2010; Madin & Macreadie, 2015). The study identifies the environmental impact of food chains, particularly the fishing sector, as a critical factor, often overshadowed by more visible concerns such as resource availability and population conservation

(Infante-Amate et al., 2018; Pérez Neira et al., 2020; Hospido & Tyedmers, 2005). Notably, the study acknowledges that it did not account for emissions related to refrigerant leaks in the fishing process, which can substantially increase the total GHG emissions (Iribarren et al., 2011).

From a policy perspective, the findings have several implications for fisheries management, such as advancing the management of hake fishing, reducing the environmental impact of fishing to mitigate the effects of climate change, and encouraging sustainability transformations in the Spanish food system (Common Fisheries Policy [CFP] of the EU, Prellezo and Curtin, 2015; Mariani et al., 2020). The paper criticises the CFP's focus on Maximum Sustainable Yield (MSY), arguing that it overlooks the contribution of marine resources to carbon sequestration (Blue Carbon Initiative, 2021; Aragão et al., 2021; Mariani et al., 2020). The study also explores the role of fisheries management in addressing climate change, suggesting a shift towards ocean management that integrates GHG emissions and carbon sequestration considerations (Aragão et al., 2021). It highlights the importance of rebuilding fish populations to increase their capacity for blue carbon sequestration, especially in the case of top predators like adult hake (Mariani et al., 2020).

Regarding the mitigation of environmental impacts and climate change, the paper points out the significant carbon footprint of the fishing industry, often overlooked in sustainability assessments and seafood consumption guides (Chassot et al., 2021; Hilborn et al., 2018; Ziegler et al., 2013). The study advocates for better fisheries management that encompasses not only biological concerns but also the analysis and mitigation of GHG emissions and global warming (Hospido & Tyedmers, 2005; Fonseca et al., 2005). Consumer awareness is highlighted as a critical factor in promoting low-carbon seafood products. The study suggests that providing consumers with information about the carbon footprint of different seafood products can influence purchasing decisions towards more sustainable options (Madin & Macreadie, 2015; Altiok et al., 2021; Bryant, 2019; Teisl et al., 2002; Grebitus et al., 2013;

Elofsson et al., 2016).

The research also addresses the health aspects of fish consumption, noting the multiple health benefits associated with seafood products, such as the reduction of cardiovascular problems and the improvement of mental health (Whelton et al., 2004; EUPHA, 2017; MacDiarmid, 2013; Willett et al., 2019). However, it warns against simplistic approaches that overlook the environmental impacts of intensive fishing and international transportation associated with current consumption volumes of hake in Spain (OECD, 2019). In conclusion, the study advocates for a balanced approach that considers both the environmental sustainability and health benefits of fish consumption. It underscores the need for transformative changes in sustainable and healthy food production and consumption patterns, aligning with global frameworks like the UN Decade of Ocean Science for Sustainable Development (Lubchenco & Gaines, 2019; Claudet et al., 2020; Rosa, 2017; Medawar et al., 2019; Nelson et al., 2016; Tomova et al., 2019).

5.2.3 Global Hake Production and Trade

Chapter 4, presents a detailed analysis of the role of hake in global food security, its production, and trade dynamics. It underscores the urgent need to meet the nutritional demands of the growing global population, expected to reach 9.8 billion by 2050 (United Nations, 2017). In this context, marine foods, particularly hake, emerge as a crucial element in addressing global food shortages and malnutrition challenges (Costello et al., 2020; Golden et al., 2021). The study reveals that six of the 22 hake species account for a significant portion of total catches, highlighting the global importance of these species in fisheries. However, the potential of hake to increase aquatic food production is limited due to overexploitation and the stability of catches, as demonstrated by a notable growth in hake transactions both in volume and value, with a decreasing growth rate since 2016. This scenario raises concerns about the sustainable management of hake fisheries to support future food security.

The contribution of hake to global nutrition is emphasized by its high protein and essential fatty acid content, crucial for human health. The downward trend in global hake catches since the 1970s poses a critical challenge to leveraging this potential, especially in the face of increasing global demand for protein-rich foods. The study calls for a balance between the need to increase marine food production and sustainable fishing practices to ensure the long-term viability of these resources. The sustainability of hake populations is a critical concern given the increasing global demand for seafood products. Overexploitation and the stability of catches have caused ecological and economic impacts, including the reduction in individual size and reproductive potential of hake populations (FAO, 2022). This is particularly evident in species such as the South Pacific hake and European hake, identified as overexploited. The study also highlights the ecological implications of overfishing, such as trophic cascades and imbalances in marine ecosystems. It underscores the need for comprehensive approaches that include regulatory measures and community engagement for effective fisheries management, including catch limits and size restrictions (Kraak et al., 2013; Caddy and Seijo, 2005).

The dynamics of global hake trade have evolved significantly, with Europe, particularly Spain, becoming a dominant importer in the hake market. This shift reflects broader changes in the seafood industry and international market dependencies. The study indicates an increasing dependence of developed countries on seafood imports due to declining local catches and rising consumer preferences for diverse seafood products (Ye and Gutiérrez, 2017; Aragão et al., 2022). The study also addresses economic disparities in hake trade, highlighting the uneven distribution of benefits among different nations. Wealthier nations often have the advantage in securing resources and capitalizing on trade opportunities, while developing countries, major

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contributors to the global hake supply, are in a less advantageous position.

Regarding trade resilience and food security, the study emphasizes the importance of diversified trade networks to ensure a steady food supply, especially in areas highly dependent on seafood imports. The relationship between trade resilience and food security is influenced by geopolitical, ecological, and economic factors affecting trade stability (Gephart et al., 2017; Blanchard et al., 2017; Grassia et al., 2022; Cao et al., 2023). We conclude by highlighting the need to adapt hake fisheries management to global changes and challenges. Aligning hake fisheries management with the Sustainable Development Goals, particularly the Zero Hunger Goal, is crucial to ensure that the exploitation of hake populations for international trade does not compromise ecological sustainability and the food security of local populations. The study offers a comprehensive view of the complexities and challenges associated with hake production and trade, emphasising the need for sustainable and inclusive growth in the global seafood industry.

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6 GENERAL CONCLUSION

6.1.1 Thesis Contribution

The thesis reveals the complex interaction between the demand for fish products, the impacts of climate change on fishing, the dynamics of the global hake trade, and the feedback loop of fishing exacerbating the effects of climate change. All these axes contribute to a broader narrative of the sustainability and resilience of the fishing sector. Our analysis shows that while fisheries offer significant opportunities for addressing global food shortages and ensuring healthy and balanced diets, their management is fraught with challenges related to overexploitation, sustainability and economic disparities. The increase in global population and the growing demand for nutritious food sources make sustainable fisheries management more critical than ever. This thesis provides scientific evidence and new insights that can be useful for designing solutions to help manage hake exploitation at sustainable production levels, supporting climate change mitigation and healthy diets. And knowledge that can serve as inspiration and foundation for a wider context, of other species, geographical areas and fishing gear. We have delivered a solid proposal that goes through the identification of vulnerability to prioritise management and adaptation strategies, following the impacts of the production chain to establish a balance between healthy patterns of fish consumption and the associated environmental impacts, and the complex international trade networks that exemplify the challenges and opportunities inherent in global seafood markets, highlighting the need for sustainable management practices, equitable trade policies and resilient trade networks. In conclusion, this study provides evidence that highlights the need for a collaborative approach at national and international level to address the challenges of fisheries sustainability, involving stakeholders across the spectrum, from fishermen to policymakers.

6.2 RECOMMENDATIONS FOR FISHERY MANAGEMENT AND POLICIES

This thesis offers recommendations for decision-makers and policymakers:

4. We advocate for strategic management actions and fishery policies on a global scale that include local contexts for climate-resilient development. We call for: (a) conducting detailed vulnerability assessments at the local scale to uncover additional and significant socio-ecological sources of vulnerability for fisheries and their populations to climate change; (b) policies that protect human communities, marine ecosystems, and the most vulnerable fisheries; (c) fishery management strategies that address social and economic inequalities and the resulting differences in adaptive capacity, thus ensuring long-term fish production as well as food and income security.

5. We advocate for business leadership and public policies aimed at adopting innovative solutions throughout the value chain, such as (a) reducing GHG emissions in operations and supply chains using nature-based climate solutions; (b) expanding and standardising food labelling to include information about the health and sustainability implications of food products; (c) supporting the fishing sector in this transition with training and development, assistance, and recognition; (d) promoting transparent marketing practices that encourage the consumption of healthy and sustainable foods; (e) assisting consumers in reducing food waste with

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ideas for leftovers and portion sizes; and (f) adopting a diverse and sustainable protein mix by increasing the diversity of plant-based protein sources

6. We recommend conducting complex analyses of the international trade networks of other commercial species and highlight the need for a collaborative approach to promote more efficient networks with respect to environmental sustainability, more resilient to political, economic, and ecological changes, involving stakeholders across the spectrum, from fishermen to policymakers.

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This thesis investigates the intricate dynamics of the Spanish demersal fisheries sector amid a backdrop of global environmental challenges. By examining the vulnerabilities of regional fisheries to climate change, assessing the carbon footprint of the hake supply chain and analyzing the implications of global trade market trends, this study highlights the
importance of developing tailored adaptation strategies, promoting sustainable practices and fostering resilient trade networks to ensure the long-term viability of marine resources. This thesis advocates strategic management actions and policies that address the socio-ecological complexities of fisheries sustainability. The findings presented serve as a basis for increasing the resilience and sustainability of fisheries not only in Spain, but also on a global scale.