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Towards transdisciplinary and transformative coastal marine research: insights from Costa Rica

Astrid Sánchez-Jiménez[1,2]; https://orcid.org/0000-0003-1648-0232
Maraja Riechers[3]; https://orcid.org/0000-0003-3916-8102
Álvaro Morales-Ramírez[2]; https://orcid.org/0000-0002-0883-5366

1. Leibniz Institute for Baltic Sea Research Warnemünde, Seestrasse 15 D-18119 Rostock, Germany; asanjim@gmail.com (*Correspondence)
2. Research Center of Marine Science and Limnology (CIMAR), University of Costa Rica, 11501-2060, San José, Costa Rica; alvaro.morales@ucr.ac.cr
3. Thünen Institute of Baltic Sea Fisheries, Alter Hafen Süd 2, 18069 Rostock, Germany; maraja.riechers@thuenen.de

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ABSTRACT

Introduction: Transformative transdisciplinary research (TTDR) aims to address complex sustainability issues of our times by engaging researchers from different disciplines, practitioners, individuals, and policymakers.
Objective: This literature review is a first structured effort to understand how marine-coastal research published in English and Spanish can drive transformative change towards sustainability in Costa Rica (n = 30 articles) and is expected to foster critical reflection on the role of scientific systems in the design, production, and use of knowledge.
Results: The results show that in Costa Rica, knowledge production remains largely unidirectional, with stakeholder consultation prevailing over co-production. It highlights the need to foster collaborative research that includes historically underrepresented groups, such as women. Power and funding dynamics determine research priorities, with efforts concentrated in the North Pacific, while the Caribbean region remains underrepresented.
Conclusions: Furthermore, we highlight ways forward to transformative research: a focus on leverage points such as co-production of knowledge, creation of safe spaces for inclusive dialogue, and reform of funding models to support long-term interdisciplinary collaboration. As Costa Rica will co-host the upcoming Ocean Conference in France, this moment presents an opportunity to align national research efforts with global transformative trends, ensuring that marine research evolves towards more inclusive and action-oriented frameworks.

Key words: marine sciences; social-ecological systems; sustainability transformation; co-production; Costa Rica; Global South; transdisciplinary research.

RESUMEN

Hacia una investigación transdisciplinaria y transformadora en el ámbito costero marino: perspectivas desde Costa Rica

Introducción: La investigación transdisciplinaria transformadora (TTDR, por sus siglas en inglés) tiene como objetivo abordar cuestiones complejas de sostenibilidad de nuestros tiempos mediante la participación de investigadores de diferentes disciplinas, profesionales, individuos y formuladores de políticas.
Objetivo: Esta revisión de la literatura es un primer esfuerzo estructurado para comprender cómo la investigación marino-costera publicada en inglés y español puede impulsar un cambio transformador hacia la

sostenibilidad en Costa Rica (n = 30 artículos) y se espera que fomente la reflexión crítica sobre el papel de los sistemas científicos en el diseño, la producción y el uso del conocimiento.
Resultados: Los resultados muestran que en Costa Rica, la producción de conocimiento sigue siendo en gran medida unidireccional, y la consulta a las partes interesadas prevalece sobre la coproducción. Destaca la necesidad de fomentar la investigación colaborativa que incluya a grupos históricamente subrepresentados, como las mujeres. Las dinámicas de poder y financiamiento determinan las prioridades de investigación, con esfuerzos concentrados en el Pacífico Norte, mientras que la región del Caribe sigue estando subrepresentada.
Conclusiones: Además, destacamos las formas de avanzar hacia una investigación transformadora: un enfoque en puntos de influencia como la coproducción de conocimiento, la creación de espacios seguros para el diálogo inclusivo y la reforma de los modelos de financiamiento para apoyar la colaboración interdisciplinaria a largo plazo. Como Costa Rica será coanfitrión de la próxima Conferencia sobre los Océanos en Francia, este momento presenta una oportunidad para alinear los esfuerzos nacionales de investigación con las tendencias transformadoras globales, asegurando que la investigación marina evolucione hacia marcos más inclusivos y orientados a la acción.

Palabras clave: ciencias marinas; sistemas social-ecológicos; transformación de la sostenibilidad; coproducción; Costa Rica; sur global; investigación transdisciplinaria.

INTRODUCTION

In the Anthropocene our ocean is impacted by myriad challenges and pressures, hence advancing towards sustainability demands the coexistence of human activities, ecosystem conservation and restoration (Rockström et al., 2023). Scientists, institutional actors, and local stakeholders should work transdisciplinarily to rethink and transform the way we create, consume and interact within social-ecological systems to foster well-being (Partelow et al., 2023). The integration of different perspectives, and their interrelationships, is vital to overcome conflicting societal interests (Raymond et al., 2023). Collaborative knowledge production between academia and society is key to envisioning desirable futures and identifying the transformations necessary to achieve more sustainable states (Nash et al., 2022).

Strategies to understand and address the unprecedented environmental changes of our time require systems thinking in social-ecological systems (SES). SES consider marine and coastal areas in an integrated manner, addressing physical, chemical, and biological factors that affect and interact with society (Popova et al., 2023). Transdisciplinarity can bring socioeconomic and ecological systems together through research that integrates a diverse number of academic disciplines and societal stakeholders (Bennett et al., 2017). One of the main advantages of transdisciplinarity is the freedom to encompass different perspectives to approach complex problems, without allowing the premises of a particular discipline to overshadow the view of problems and solutions.

Integrating social, cultural, economic, and political dimensions into the ecological and physical factors of marine coastal management and governance demands a Transformative Transdisciplinary Research (TTDR), that is, solution-oriented research that understands the ocean as a complex SES, uses innovative participatory methods, collaborates with policymakers, local communities, and industry stakeholders, and aims for long-term impact. Democratic approaches that enable the integration of multiple knowledge systems, while strengthening the link between scientists and society (Loch & Riechers, 2021), for example, methods such as participatory action research and citizen science, can greatly enhance social inclusion. A clear intention is also required to drive fundamental change in the way marine ecosystems are understood, managed and governed to achieve a more sustainable and just futures (Bennett, 2022; Chambers et al., 2021; Pereira et al., 2020).

The United Nations has declared a Decade of Ocean Science for Sustainable Development

(2021–2030) to ensure that marine research contributes to improved conditions for ocean resilience, as well as prosperity and equity for current and future generations (Franke et al., 2023). Transformative transdisciplinary research (TTDR) aims to address complex real-world sustainability problems by involving researchers from different disciplines, professionals, peoples, and policymakers (Augenstein et al., 2024). Instead of merely making incremental improvements, its goal is to enable transformative change, which means fostering systemic shifts in the management, conservation, and policy-making of marine resources by co-producing more effective and equitable solutions that are grounded in real-world contexts, TTDR also empowers individuals and communities to drive and catalyze change (Grünhagen et al., 2022). and aims for long-term goals.

Achieving the Sustainable Development Goals (SDGs) implies that conservation initiatives are locally relevant and culturally appropriate (Zheng et al., 2021). The Third United Nations Ocean Conference (UNOC3), a major milestone in the scope of the United Nations Ocean Decade, will be held in Nice, France, from June 9 to 13, 2025, with Costa Rica as a co-host. UNOC3 responds to a demand for transdisciplinary research with diverse ocean stakeholders to accelerate action-oriented solutions and transformative change for both people and the ocean. However, despite global calls for transformative change in ocean governance and sustainability, there is still limited understanding of how transdisciplinary research concretely enables sustainability transformations in Global South regions like Costa Rica. This article addresses this gap by examining the role of transdisciplinary research in transforming social-ecological challenges through a systematic literature review of scientific articles in English and Spanish, focusing on coastal and marine areas in Costa Rica.

By examining Costa Rica as a case study, this research provides insights into a specific national context, while offering lessons for other regions in the Global South where marine sustainability go hand in hand with social inequalities. Emphasizing the dimensions of history, equity, and power relations is crucial to promoting just and effective transformations towards sustainability. This article explores how transdisciplinary research in marine sciences can facilitate sustainability transformations. Specifically, it asks: (1) What is marine TTDR like in Costa Rica, including which studies can be considered marine TTDR, when were they published, what are the authors' countries of affiliation, and what sustainability issues do they address; (2) what is the role of marine research in solving social-ecological challenges in Costa Rica, counting who is involved in knowledge production for sustainability, how do different actors (academics, policymakers, and local communities) collaborate?, where does TTDR is developed, and at what stage of transformation are the SES under study?

MATERIALS AND METHODS

Transformative transdisciplinary research (TTDR): The concept of transformative transdisciplinary research (TTDR) is understood for the purpose of this study as research that focuses on innovative solving of practical social-ecological challenges with close involvement of different disciplines and diverse societal actors, and that aims for long-term impact (Augenstein et al., 2024). Etymologically, transdisciplinarity means going beyond individual disciplines (Vilsmaier, 2021). Disciplinary research involves only one discipline and multidisciplinarity includes several disciplines working individually towards a common goal (Vilsmaier, 2021) (Fig. 1).

While interdisciplinary research is the two-way collaboration of disciplines to achieve set goals within a given project, transdisciplinary research involves groups of stakeholders from diverse backgrounds in co-design, co-evaluation and co-production of knowledge (Grünhagen et al., 2022; Lang et al., 2012), for example researchers from different disciplines collaborating with actors from tourism, agriculture or fisheries (Fig. 1).

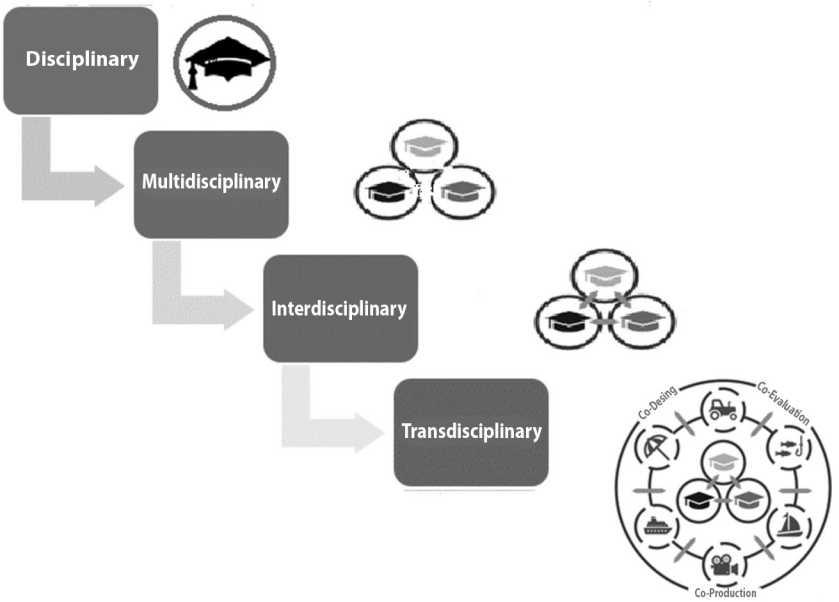

Fig. 1. Level of integration across scientific disciplines. Adapted from (Grünhagen et al., 2022).

In terms of levels of participation and societal engagement —information, consultation and co-production—(Krütli et al., 2010), information and consultation suggest a low level of participation among social groups. Information is mostly conveyed unidirectionally, either from social actors to the academic community or vice versa (Krütli et al., 2010). Sharing information typically keeps the public updated on the status of a process or project. In contrast, consultation is frequently used to ask the public about specific concerns or topics. In co-production, non-academic actors and researchers work together to design, analyze and produce knowledge, establishing bidirectional communication and a diverse integration of ways of knowing (Krütli et al., 2010).

In marine research with social-ecological impact, the transformation framework (Wiek & Lang, 2016) can be used as a reference as a methodological guide to understand the stage of transformative research, which comprises four steps. Typically, the TTDR process involves (i) analyzing the past and current state, (ii) creating and evaluating probable futures (scenarios), (iii) visualizing desirable futures, and (iv) designing and testing interventions to achieve those futures from the present moment (backcasting).

Sustainability transformations in social-ecological systems (SES) can be conceptualized in three phases (Fig. 2): (i) the phase of preparing for disruptive change, (ii) the phase of navigating that disruption, and (iii) the stabilization or institutionalization phase, which serve to build the resilience of the new state (Moore et al., 2014; Villasante et al., 2021). In the preparation phase, a disturbance or crisis in the SES often triggers alternative governance systems with disruptive potential, which can be transferred to the navigation phase and begin to become institutionalized (Herrfahrdt-Pähle et al., 2020). However, sustainability transformations are political processes that address asymmetric social power relations and conflicts, and these alternative modes can be contested by the status quo system or actively chosen (Blythe et al., 2018; Brodie Rudolph et al., 2020).

Systematic literature review:

Data collection: The systematic review includes scientific articles and book chapters

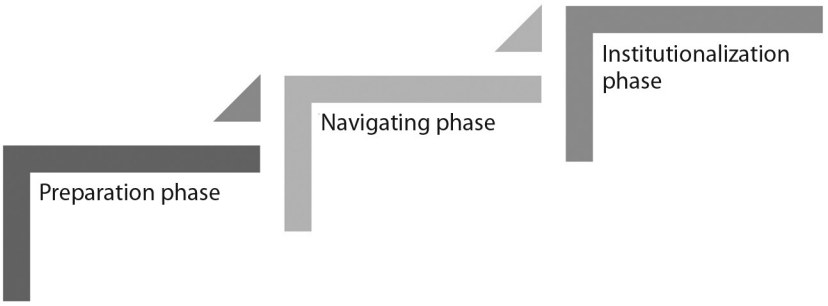

Fig. 2. Phases of sustainability transformations in social-ecological systems adapted from (Moore et al., 2014; Villasante et al., 2021).

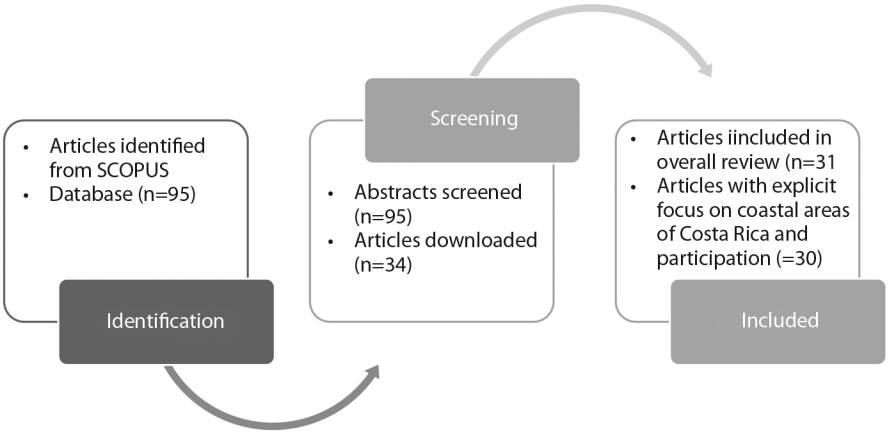

Fig. 3. Flow diagram for a systematic literature review selection process following PRISMA. Adapted from (Baumann et al., 2023; Page et al., 2021).

(1999–2024) in English and Spanish, focusing on transdisciplinary and transformational coastal marine research in Costa Rica. This nation is developing in the context of the Global South. The research process was structured using the Scopus database (www.scopus.com) and the Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) system (Page et al., 2021). The PRISMA system comprises three steps: identification, selection, and inclusion, as illustrated in Fig. 3.

The Scopus database was searched using a search string to identify relevant peer-reviewed that collected original data articles. The search string consisted of screened keywords, abstract and titles, containing: "(marine) OR (governance) OR (social AND ecological AND systems) (socio AND ecological AND systems) OR (sustainability) OR (ecosystem AND services) OR (small AND scale AND fisheries) OR (artisanal AND fisheries) OR (psychology) OR (perception) OR (participatory) OR (transformation) OR (communities) OR (management) OR (workshops) OR (interviews) OR (local) AND (costa AND rica) OR (collective) OR (transdisciplinary) OR (women) OR (behavior) OR (tourism) OR (engagement) OR (livelihoods) OR (fishing) OR (gulf AND of AND nicoya) OR (compliance) OR (transformation) OR (poverty) AND (pacific) OR (restoration) OR (conservation) AND (stakeholders)".

Data analysis: We conducted a deductive coding, based on following typology (Table 1):

Table 1
Typology of the transdisciplinary peer-reviewed literature in Costa Rica and its role in fostering societal participation and solving marine social-ecological problems (interpreted by the authors).

Category	Subcategory	Definition or example
(1) General characteristics	(i) N° of Published articles	Selected articles with titles, keywords and abstracts that meet the criteria of transdisciplinary and transformational coastal marine research in Costa Rica
	(ii) Sustainability themes	E.g., Conservation, fisheries management. ecosystem services
	(iii) Publication years	Selected from 1999–2024 as globally transdisciplinary research grew on this period
	(iv) Countries of affiliations of first authorship	Global North or Global South nations are used to describe socio-economic and political divide between wealthier and poorer nations, usually related with inequalities and the dominant research perspectives and funding sources
(2) Role played in solving marine social-ecological problems	(i) Who?	Stakeholders involved. E.g., fishing communities
	(ii) Where?	Study sites in Costa Rica. E.g., Isla Chira
	Region	Caribbean Sea, Pacific Ocean (North, central and South) and Gulf of Nicoya
	(iii) How?	Participatory methods and data analysis. E.g., interviews, workshops
	Level of participation of stakeholders	Information, consultation and co-production (Krütli et al. 2010): Sharing information allows the public to be kept informed about the status of a process. Consultation typically asks the public about specific topics. In co-production, non-academic actors and researchers work together to design the process and outcomes, establishing two-way communication.
	(iv) Transformational research (steps)	Based on Wiek and Lang (2016) and Baumann et al., 2023: (i) Descriptive research: (a) analyzing past and current state and (b) looking for probable futures (e.g., scenarios); (ii) Anticipatory research: forecasting paths to desirable futures (a) (intervention research)
	(v) Phases for transformative changes	Based on Moore et al., (2014) and Villasante et al., (2021) (i) Preparation for disruptive change, (ii) navigating that disruption and (iii) stabilization of alternative modes that are now institutionalized in the governance system and embedded at the seascape level E.g., Institutionalization of new values and the enforcement of new regulations and practices (e.g., shifting towards desirable sustainable fishing gears).

(1) general characteristics of marine TDTR in Costa Rica, we identified (i) the number of case studies in Costa Rica on marine transdisciplinary research, (ii) the years of publication of the studies, (iii) the countries of affiliation of the first authorship of the case studies, and (iv) the sustainability issues addressed. To elucidate (2) the role that marine research plays in solving social-ecological problems in Costa Rica, we investigate (i) the type of actors that participate in the research, (ii) in which geographic areas of the country the studies are developed, and (iii) how participatory research is produced, that is, (iv) the type of participatory methods and level of participation (contribution, collaboration or co-production), (iv) steps of transformative change (descriptive past-current state or scenario construction and anticipatory intervention research) and the (v) phase of transformation of the social-ecological system (preparation, navigation or institutionalization)

RESULTS

General characteristics of TTDR marine research in Costa Rica: Our analysis covered 30 articles on transdisciplinary transformational research conducted in marine and coastal systems in Costa Rica (Appendix 1). The articles ranged from 2013 (n = 1) to 2024 (n = 7). The first authorship derived from seven different nations: Costa Rica (n = 18; 45 % of

the 30 articles), Germany (n = 9; 23 %), United States (n = 9; 23 %), United Kingdom (n = 1; 3 %), Colombia (n = 1; 3 %), Ecuador (n = 1; 3 %), and Australia (n = 1; 3 %). Overall, 50 % of the first authorship came from countries in the Global South, and the other 50 % came from the Global North (Appendix 1).

The sustainability topics addressed in these articles (Fig. 4) were mainly related to (1) social-ecological approaches on coastal management (n = 66; %) (García Lozano & Heinen, 2016a; Naranjo-Madrigal et al., 2015; Palou Zúniga et al., 2023; Partelow et al., 2019), (2) fisheries (n = 70) and small-scale fisheries (n = 30) (Albers et al., 2021; Bystrom et al., 2017; Carrillo et al., 2019; Fernández Carvajal, 2013; García Lozano & Heinen, 2016a; García Lozano & Heinen, 2016b; Naranjo-Madrigal & van Putten, 2019; Partelow et al., 2019; Partelow et al., 2020b; Rivera et al., 2017a; Sánchez-Jiménez et al., 2019; Sánchez-Jiménez et al., 2021), (3) marine protected areas (n = 53) and marine conservation (n = 30) (Albers et al., 2021; Arias et al., 2015; López-Angarita et al., 2021; Naranjo-Madrigal et al., 2015; O'Bryhim et al., 2016; Partelow et al., 2019; Pereira et al., 2024; Sardeshpande & MacMillan, 2019; Valerio-Vargas & Espinoza, 2019) and (4) local communities (n = 59) (Allen et al., 2021; Fernández Carvajal, 2013; Little & Little, 2017; Mejías-Balsalobre et al., 2021; O'Bryhim et al., 2016; Rivera et al., 2017b).

On a second level of frequent topics, there are issues of (5) collective action (Carrillo et al., 2019; García Lozano & Heinen, 2016a; Rivera et al., 2017a), (6) environmental perception (Mejías-Balsalobre et al., 2021; Partelow et al., 2021; Sánchez-Jiménez et al., 2014; Villalobos-Cubero et al., 2023), (7) support to conservation (O'Bryhim et al., 2016; Sardeshpande & MacMillan, 2019) and (8) alternatives to development such as tourism (Carvache-Franco et al., 2022; Little & Little, 2017; Palacios-Martínez & Núñez-Zamora, 2021).

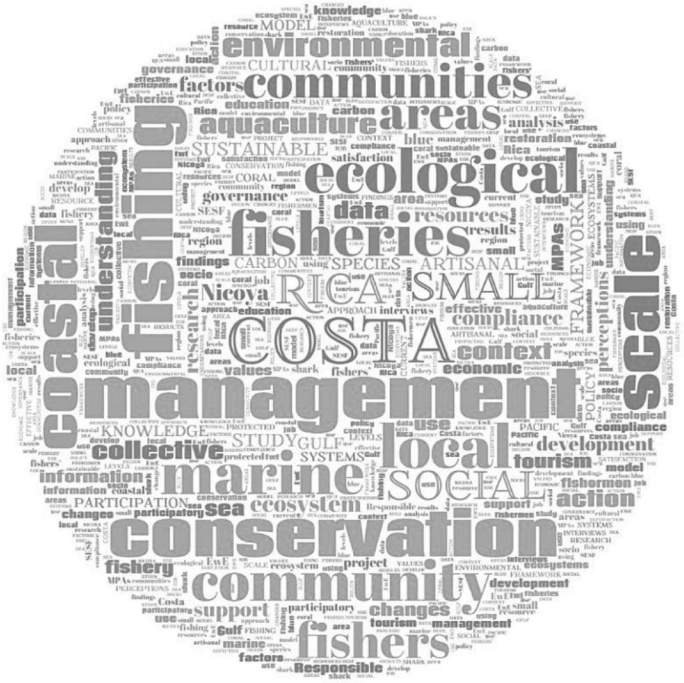

Fig 4. Most frequent sustainability themes mentioned in keywords, abstract and titles of the research under scrutiny: fisheries (n = 70), management (n = 66), community (n = 59), marine (n = 53), local (n = 43), small-scale (n = 30), conservation (n = 30).

Role of marine research in solving social-ecological problems in Costa Rica:

Stakeholders involved: We found that various groups (Fig. 5), including fishers, coastal communities, the tourism industry, NGOs, and researchers, are engaged in marine and coastal management. Conversely, we observed limited participation from women and government institutions such as SINAC, INCOPESCA, and the Coast Guard in the research analyzed.

Geographical focus of the research scrutinized: Most articles described studies in 26 study sites (Fig. 6) located in the North Pacific (n = 14; 45.16 % of the 31 articles), followed by the Gulf of Nicoya (29.03 %), South Pacific (16.13 %), and Caribbean (9.68 %) (Fig. 7).

Approaches to address transdisciplinarity and levels of participation: The articles reviewed draw on different approaches, conceptual frameworks and methods to address and analyze transdisciplinarity. The most used ones were semi-structured interviews and the identification of stakeholder perceptions. Methods often used in conjunction with deliberation or dialogue, participant observation, mapping, key informants, and a social-ecological framework (Fig. 8). To a lesser extent, we find articles on behavior change interventions, societal attitudes, and anecdotal records. Information is mainly shared unidirectionally from the social stakeholders to the academic community, mainly as a means of consultation, while co-production represents the smallest number of articles analyzed for the case of Costa Rica (see Appendix 1).

Steps of transformative change in the articles reviewed: The review examined the steps of transformative change in the articles under scrutiny, based on the transformation framework (Wiek & Lang, 2016). Fig. 9 displays the frequency of articles that have implemented steps of the transformation framework. Of the 30 articles reviewed, all of them focused on descriptive research (n = 30, 100 % of all articles), specifically 100 % (n = 30) performed a past and current state analysis (step i), and scenario construction (step ii), was conducted in 17 % (n = 5) of the articles. The least utilized aspect was anticipation research at 13 % (n = 4), in which visioning desirable futures (step iii)

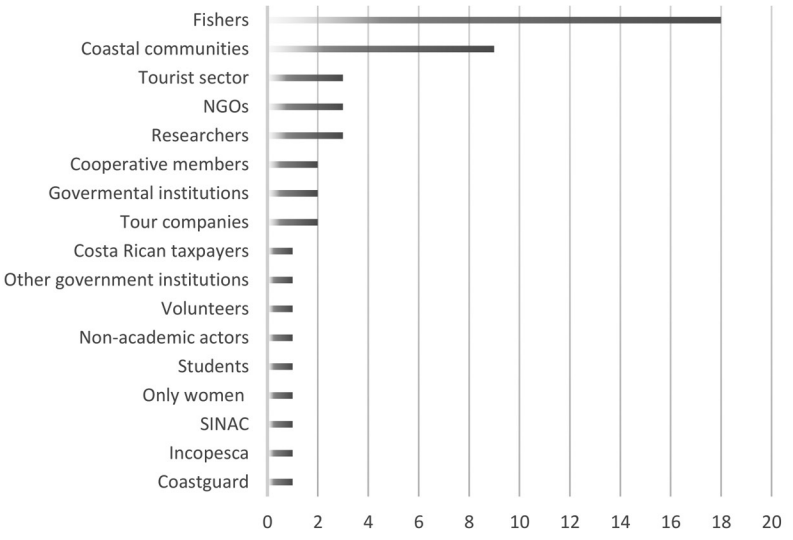

Fig. 5. Main societal stakeholders participating as informants or knowledge producers in Costa Rican marine transdisciplinary research in examination.

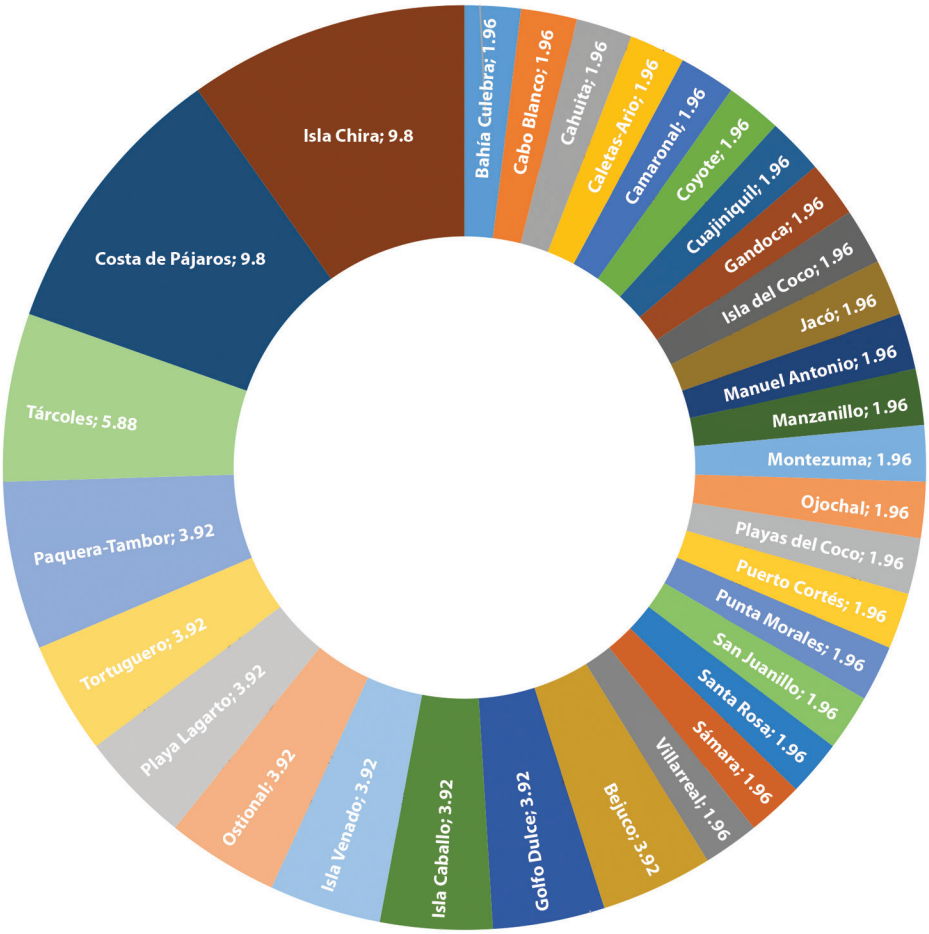

Fig. 6. Study sites of the reviewed articles on transdisciplinary marine research in Costa Rica.

was present in 0 % of the research and intervention research (step iv) was present in 13 % (n = 4) of the research (Fig. 3).

Phase of transformative change in the social-ecological system: As interpreted by the authors, the analysis of the articles revealed that in 56 % of cases, a shock or crisis in the social-ecological systems triggered the creation of alternative governance systems (Preparation for Change phase). In 32 % of the cases, the management process corresponded to the Navigation of Change phase (Appendix 1). In 12 % of the articles, phases 1 and 2 played a role in establishing the new regime and its stabilization (Institutionalization phase).

DISCUSSION

Main findings: The transdisciplinary research analyzed in this article included both academic and non-academic perspectives that allowed for a more inclusive view of the current and past state of Costa Rica's coastal marine systems. Knowledge co-production remains the least frequent research modality, while stakeholder consultation is the most common. The one-way exchange of information in several

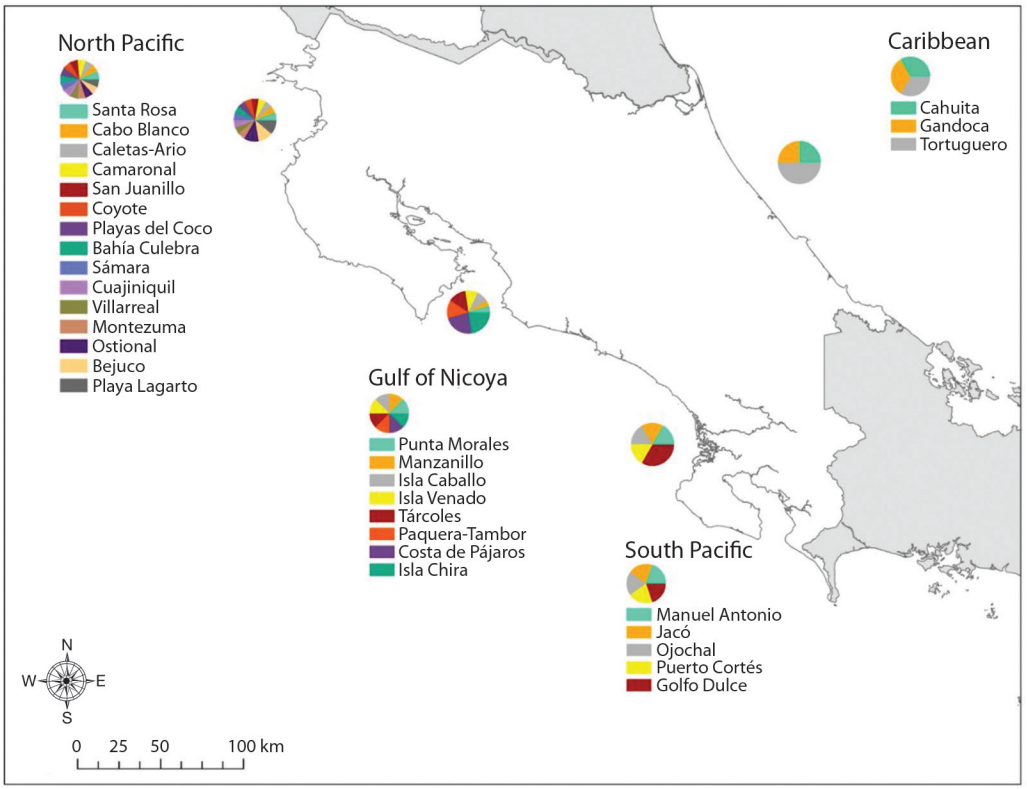

Fig. 7. Core regions of Costa Rican marine transdisciplinary research under scrutiny. Developed by Catalina Benavides Varela, SIGMAR-CIMAR.

of the reviewed articles responds to dominant scientific approaches in which inhabitants of the tropics are still largely seen as objects of research rather than subjects and agents of change (Partelow et al., 2020a). There is an evident need for deeper engagement beyond consultation that fosters collaboration between researchers and stakeholders. Knowledge co-production could lead to leverage points or significant constructive changes in SES moving to meaningful commitment.

In the reviewed articles, the participation of women and government institutions such as SINAC, INCOPESCA and the Coast Guard is limited. One of the challenges of transdisciplinary marine research in Costa Rica will be to transcend conventional divisions of science as merely a producer of knowledge and advisor, towards a system actor that intentionally facilitates the co-design, co-evaluation, and co-production of research projects with other sectors. Explicitly recognizing where it will be carried out, what points of view will count in the research, who will define the sustainability objectives and to whose benefit or detriment. Methods such as participatory action research, community led initiatives and long-term partnerships can be further explored as a means to institutionalize the co-production of knowledge. But not without simultaneously addressing the power dynamics that hinder equal participation, particularly from marginalized groups.

People's vulnerability to environmental changes, access, use and management of natural areas is influenced by national and international geopolitical power relations (Saunders et al., 2024). Historically, rural and coastal communities in the periphery of Costa Rica

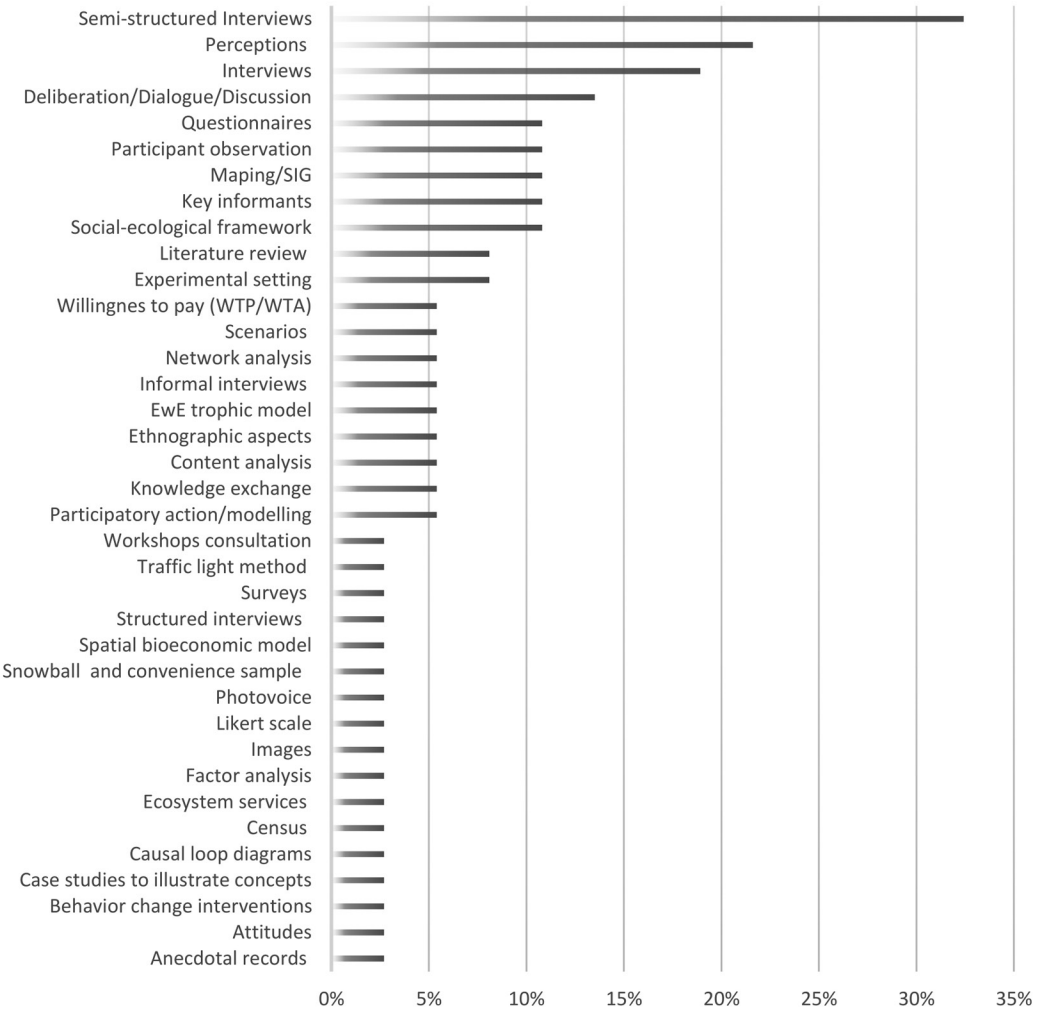

Fig. 8. Methods, approaches and conceptual frameworks to address transdisciplinarity in the Costa Rican marine research under inquiry.

have low or very low social progress indices (IPS) compared to the central cantons of the country with a particular deterioration in security, health, inclusion, water and sanitation (Instituto Centroamericano de Administración de Empresas, 2024; Programa de las Naciones Unidas para el Desarrollo, 2023). Addressing regional disparities will be a key aspect towards transformative research, the articles reviewed focused primarily on the North Pacific and the Gulf of Nicoya, showing the need to expand efforts towards underrepresented regions such as the Caribbean and the South Pacific. In general, in Costa Rica most of the marine research has been carried out in the Pacific (North Pacific and the Gulf of Nicoya) due to the logistical accessibility in terms of research stations, greater institutional presence and funding for long-term studies (Vargas, 1995).

Currently, various calls from the Global North for funding transdisciplinary marine research increasingly include initiatives that facilitate co-design, co-assessment and co-production of knowledge between societal actors.

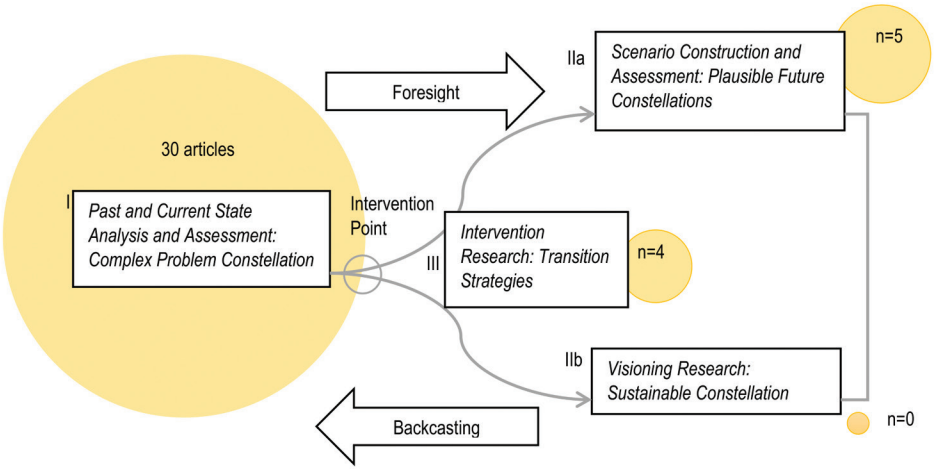

Fig. 9. Steps of transformative change in Costa Rican marine transdisciplinary research under study. Adapted from (Baumann et al., 2023; Wiek & Lang, 2016).

For instance, some projects funded by Horizon Europe's call, such as the current SEADITO (Social-ecological analysis and models for the digital twin ocean) project, are an example of initiatives that involve case studies from diverse geographies and contexts, including the Baltic Sea, the North Sea and the Mediterranean, and that engage diverse actors from academia and civil society in the co-design of decision support tools (European Union. HORIZON-MISS-2023-OCEAN-01, 2024). Monitoring the development, outcomes and funding of such projects provides valuable information for potential similar efforts in Costa Rica and other contexts in the Global South. Provided the funds are allocated to culturally appropriate projects and bolster existing local initiatives rather than imposing external agendas (Aguilar González, 2024).

As in other coastal areas of the Global South (Baumann et al., 2023), most of the literature reviewed still places marine research in Costa Rica in the phase of preparation for change, meaning that the system is going through crises, shocks and pressures that are driving innovation and new governance models. Thirty-two percent of the papers address these changes and a minority of the studies (twelve percent), suggest an early stabilization phase, where alternative governance structures, like marine areas for responsible fishing (AMPRs) are solidifying. AMPRs are legally constituted since 1999 and seek to use fishery resources responsibly, managed from the communities with a synergy between INCOPESCA as the governing body, academia and community organizations. Although there is still room for improvement to overcome the limitations towards collective action (Carrillo et al., 2019), by 2022 twelve AMPRs were distributed in the Gulf of Nicoya, Golfo Dulce and northern Caribbean, totaling more than 1 500 km^2 of co-managed areas (Ulate-Garita, 2022).

In the current literature review, research focusing on the past and present state of coastal and marine systems prevails. The results highlight the necessity to move beyond descriptive research towards future-oriented studies that allow for envisioning desirable and more sustainable futures, and a diversity of approaches focused on issues of equity and justice. For example, scenario planning, adaptive governance frameworks, and participatory visioning exercises with communities and policymakers are suggested for future methods. In Costa Rica, a budget-constrained Global South country, the prioritization of research topics is likely to reflect these limitations. Hence, transformative

changes in marine research will also require reforming funding models for transdisciplinarity and transformation.

The most common sustainability topics covered in the publications evaluated include social and ecological elements of coastal management, small-scale fisheries, marine conservation, and local communities. They contain powerful subjects with the potential to prompt transformations, such as ecosystem-based management, biodiversity-preserving interventions, and co-management approaches. The transformative potential will mainly reside in the collaborative development of acceptable and realistic solutions that are relevant to local needs and cultural preferences (Herrón et al., 2020). Sustainable tourism is among the development alternatives presented in the review. To investigate this and other possibilities, fishers, national authorities, academia and other stakeholders would need to combine their efforts and financial resources to conduct innovative research and test desirable outcomes.

The reviewed articles reflect some social transformations that have been taking place, for example, favorable conditions for restoration of coral ecosystems in the Golfo Dulce (Villalobos-Cubero et al., 2023) and the voluntary creation of Responsible Marine Fishing Areas (Carrillo et al., 2019). This raises the importance of investigating the role of groups typically marginalized from decision-making, as agents to actively transform the economy from the margins (Ravera et al., 2016). To generate marine research with social impact, it is necessary to advance in the development of diverse methods and safe enough spaces (Pereira et al., 2020) that openly address power dynamics and equity dimensions, as well as facilitate debate on differences in preferences between actors (Chuenpagdee & Jentoft, 2018).

Addressing complex marine challenges requires innovative research approaches that transcend traditional disciplinary boundaries. Transdisciplinary and transformative marine research offers a way forward in Costa Rica by integrating diverse perspectives and fostering collaboration. We see the co-production of knowledge as a leverage point or a key area for systemic change. Creating safe spaces for transformation can also ensure that historically marginalized voices are included in decision-making processes. Strengthening equity and justice in research practices, along with improving funding mechanisms, is essential to sustaining meaningful long-term impact. The following section explores these elements: leverage points, knowledge co-production, safe spaces, and funding, as essential strategies to promote transformative transdisciplinary marine research.

Ways forward for transformative transdisciplinary marine research in Costa Rica: Following the current analysis of transformative marine research, we highlight the next key themes as ways forward: (1) adopting a leverage points perspective, i.e. prioritizing interventions that can lead to significant positive changes in social-ecological systems, (2) focusing on knowledge co-production or collaborative integration of expertise from scientists, policymakers, industry and local stakeholders, (3) creating safe spaces and methods for transformation, equity, and justice, i.e. intentionally designing environments that allow diverse actors to meaningfully participate in shaping the future, especially groups conventionally marginalized in decision-making, and (4) enhancing funding for transdisciplinary research, with long-term, adaptable budgets that enable adaptive learning, are locally appropriate and support cross-disciplinary expertise. We elaborate on these four themes below.

Leverage points for transformative research: In the context of transdisciplinary marine research, leverage points (LP) can be defined as strategic interventions in a complex social-ecological system where relatively small changes may lead to significant transformations in the entire system (Meadows, 2015). LP can be classified into four categories based on the system features they address: (1) intent, (2) design, (3) parameters and (4) feedbacks (Abson et al., 2017) (Table 2). Adjustments in research approaches, governance structures, funding

Table 2

Twelve leverage points (Meadows, 2015) classified into four system characteristics according to the leverage for systemic change (Abson et al., 2017; Riechers et al., 2021a).

Leverage points	System Characteristics
12. Constants, parameters, numbers 11. The size of buffers and other stabilizing stocks, relative to their flows 10. Structure of material stocks and flows	4. Parameters: measurable system features
9. Length of delays, relative to the rate of system changes 8. Strength of negative feedback loops, relative to the effect they are trying to correct against 7. Gain around driving positive feedback loops	3. Feedbacks: interaction within the system
6. Structure of information flow, access to information; type and diversity of information (e.g., cultural or biological); biodiversity to improve genetic information diversity 5. Rules of the system 4. Power to add, change, evolve, or self-organize system structure	2. Design: systemic structures; institutional arrangements; sanctions, controls, incentives; co-management schemes
3. Goals of the system 2. Mindset out of which the system arises (goals, structure, rules) 1. Power to transcend paradigms	1. Intent: long-term trajectory of system behavior. Values, worldviews, beliefs

mechanisms, and stakeholder engagement can activate these systemic changes.

Parameters are the measurable characteristics of the system (e.g., numbers, sizes) (Table 2), and an example of modifying parameters within the existing coastal marine system in Costa Rica will be to expand research efforts and increase funding to underrepresented regions such as the Caribbean or South Pacific.

System feedback refers to positive and negative interactions within the system (Table 2), and an example of adjusting feedback in research will be to develop models to help predict natural systems responses and from society. Future scenarios, for example, can help visualize potential changes in ecosystems and trigger societal responses necessary for adaptation and resilience (Riechers et al., 2021b).

For some authors such as Westley et al., 2011, to move towards more sustainable states, research must fundamentally alter the way society sees and thinks about nature (system intent), as well as rethink the system's goals and rules (system design). Research capable of altering system design will focus on changing the relationships between actors, institutions, and knowledge systems, and an example for Costa Rica will be to move from one-way consultations to true co-production of knowledge. Adjusting system design can also trigger changes in social structures that impact rules, norms, and collective human behaviors.

Changes in system intent require interventions that reshape mindsets and affect the way the system behaves, generating emergent goals that result in a paradigm shift (Meadows, 2015). For instance, moving from extractive research models that impose external agendas and extract information, to cooperative research approaches between different stakeholders.

Marine research that intervenes SES intent and design may have greater potential to generate transformative changes (Abson et al., 2017), although it may also be more difficult to alter and are generally less investigated themes (Fischer & Riechers, 2019). For example, although less frequent in the reviewed articles, at the intent level, stakeholder perceptions are key processes as people make decisions based on their own perspectives and expectations of what is possible (e.g., Mejías-Balsalobre et al., 2021; Partelow et al., 2021; Sánchez-Jiménez et al., 2014; Villalobos-Cubero et al., 2023). The same is true for other less frequent topics

included in the review, such as processes of collective action, compliance, and understanding/information exchange, at the design level.

In summary, for marine research in Costa Rica to be more oriented in the near future towards social-ecological action, some deep leverage points will need to be addressed, including: (1) rethinking how participatory research approaches can help guide management to solve social problems (Pereira et al., 2020); (2) co-production of knowledge and social learning to reconnect and reorient human behavior with nature, resilience, and the capacity of ecosystems to sustain life (Martín-López & Montes, 2015); and (3) restructure institutions by improving the way in which diverse actors can be incorporated into research and management (Abson et al., 2017; Lindkvist et al., 2020).

Co-production of knowledge: the goal of transdisciplinary research: While in co-production non-academic actors and researchers work together to design the process and the results of a given project, establishing two-way communication and diverse integration of knowledge (Krütli et al., 2010), co-production represents the least frequent form of participation in the articles analyzed for the Costa Rica case study. This unidirectional flow of information falls into the category of information and consultation, which has the lowest level of stakeholder participation and does not leave many possibilities for knowledge co-creation (Krütli et al., 2010). In the context of these articles, information is mainly transferred in one direction from the public to academia through consultation. A weak level of participation can diminish the positive effects of transdisciplinary research (Krütli et al., 2010).

Higher levels of participation are desirable, as the greater the interaction there is between actors, the greater the potential for social impact (Jahn et al., 2022). Since people are more open to the opinions of others in their immediate social circles, the transfer of information and other resources through shared networks can lead to transformative changes (Toomey, 2023). Therefore, social learning environments are needed where people can listen carefully and think together to make sound decisions (Toomey, 2023). These spaces should be rich in opinions, experiences, and regular encounters (Pereira et al., 2020) For example, deliberative research techniques can allow participants to reflect on, discuss their views and help integrate diverse knowledge systems (Kenter et al., 2016; Partelow et al., 2019).

Research approaches in the Gulf of Nicoya that combine deliberation and scientific evidence as a method of social learning have proven to influence fishers' perceptions of the ease of supporting sustainability measures (Sánchez-Jiménez et al., 2021). A growing body of research suggests that social norms influence how often communities engage in environmental behaviors; on this point, one large-scale experiment (Fujitani et al., 2017) found that providing members of fishing associations with hands-on learning spaces, rather than simply lecturing them with scientific information, improved people's knowledge retention, even eight months after the research ended; participants' core beliefs, personal norms and behavioral intentions also changed. In research off the coast of Scotland, those who perceived their social connections as a favoring contribution to marine conservation also expressed support for marine protection in a group deliberation (Kenter, 2016).

Although important, conventional methods of scientific communication (Kadykalo et al., 2021), such as speaking directly to policy makers, using social media for broader audiences and writing policy briefs, often have limited impact in bringing about transformative changes in policy and behavior (Oliver & Cairney, 2019). The reason is that when reporting research findings, it is common to overlook what drives people to act and how they process information. Drawing from cognitive science (Toomey, 2023) it is now known that focusing on a dual exchange of local and scientific knowledge (co-production), is more likely to lead to lasting behavioral change. Empowerment is the highest level of participation, granting actors of

sovereignty in decision-making and agency to act (Krütli et al., 2010).

Safe spaces and methods for transformation, equity and justice: Marine and coastal actors harbor a diversity of heterogeneous values, perceptions, and preferences (Pascual et al., 2023). Even within the same coastal community, there are cultural and needs differences that are not well represented in decision-making. Some knowledge systems, such as those of women, youth, and older people in coastal communities, have long been ignored despite their importance for marine management (Bennett et al., 2022). In deliberative and collaborative knowledge research approaches, considering the current knowledge gap can help promote more equitable decisions based on the best available evidence (Bennett, 2022).

Is not uncommon that dominant discourses often benefit political elites to the detriment of smaller stakeholders. Furthermore, gender, race, and ethnicity, among other identity characteristics, shape diverse outcomes in processes of adapting to change (Wabnitz et al., 2021). Given the long bequest of colonization in the Global South (Pereira et al., 2020), deliberately incorporating the multiple values, needs, and interests of historically excluded people into decision-making and research is required (Vatn et al., 2024). Addressing marginalization and structural injustices in marine research can lead to transformative spaces. Traditional, indigenous and local knowledge systems can inform alternative solutions (to the status quo) to understand how people interact with each other and with nature in complex contexts (Pereira et al., 2020).

Marine research can influence social innovation, through democratic methods of dialogue in decision-making. But for this to be a true force for institutional change and to enhance the awareness, agency and action of actors to address environmental change, the design of the research must answer questions such as, who benefits? Who pays for solutions to climate change? What stories (and from whom) would we like to hear about the future? Are vulnerable groups, non-human life and ocean ecosystems considered? Where are the conversations taking place?

The limited participation of women in the analyzed research suggests on the one hand that some voices may remain underrepresented in decision-making. On the other hand, there is a need to institutionalize democratic research approaches that foster a stronger local governance structure and help integrate local ecological and scientific knowledge. This is particularly relevant in data-limited contexts, where direct users of resources are also custodians of rich ecological knowledge and could provide essential information for management (Sánchez-Jiménez et al., 2019). More transdisciplinary research is necessary to democratize the approach to finding solutions. As alternative empowering narratives spread, new norms diffuse across scales and can be mobilized into political agendas and centers of power (Chapin et al., 2022) (e.g., politicians and business leaders).

Improve the funding model of marine science to be more transdisciplinary: As found in other studies of the Global South (Baumann et al., 2023), a lack of adequate funding could explain the relatively low number of published articles on transformative transdisciplinary research in Costa Rican coastal marine ecosystems. While publication and funding modalities remain focused on specific sciences, transdisciplinary research, unlike disciplinary research, requires medium-term (5–10 years) and long-term (10–30 years) processes (Franke et al., 2023), as they are iterative progressions that require adjustments as conditions change. Building trust between scientists and other stakeholders also takes time and cannot be achieved in a single visit or session. Similarly, it is critical to mind the gap in the funding capacities between countries in the Global South and the North (Mahajan et al., 2023).

To integrate inclusive research methods into decision-making, investments in data collection and analysis, community monitoring for management, and participatory research approaches are needed; particularly

in data-scarce contexts. Concrete steps have already been taken in the reviewed articles, including the integration of multiple methodologies to interpret and analyze interdisciplinary, quantitative and qualitative data, as well as the promotion of collaboration between scientists from different disciplines and countries in the natural and social sciences and non-academic sectors. The aspiration is for science to be more than a knowledge producer of which society is its recipient (Riechers et al., 2021b), but an active agent within social-ecological systems (Skubel et al., 2019), participating in and fostering cross-sectoral collaboration.

A strategic action that supports the objectives of the Ocean Decade is to ensure that there is evidence-based management (Franke et al., 2023), sensitive to the local, regional and global context (Lindkvist et al., 2020), without imposing agendas and strengthening local initiatives. From the Ocean Decade perspective 2020–2030, long-term research and funding are critical to shaping how knowledge is currently produced and used to address increasingly frequent environmental and societal challenges (Franke et al., 2023).

Future directions and final thought: A look at the current state of marine and coastal ecosystems, along with future projections, can help reduce some of the uncertainties associated with decision-making in a complex social-ecological system. Descriptive studies on past and present state were the most common type of research in our sample, indicating that more transformative research is required. To actively facilitate innovation, prospective or anticipatory research can help establish a shared vision of the future (at the level of system design and intent) and the development of interventions that, as a result, contribute to the intended purpose (Fischer & Riechers, 2019; Riechers et al., 2021b).

The analysis of postgraduate theses on integrated coastal management and sustainability, as well as grey literature, is likely to produce different results and enriched data, indicating the need for more research on transdisciplinary and transformative approaches, as well as the training of more transdisciplinary personnel in Costa Rica. Theses' knowledge supplements the data and understanding of peer-reviewed literature for scientific-political processes and applied research, and grey literature frequently offers future visions with transformational potential (Yoshida et al., 2024). Notable efforts of projects with community involvement and education come from non-governmental organizations (NGOs) that were not reflected in this literature review. It is recommended to include this type of documentation in a future analysis.

Although there are challenges ahead in terms of conventional methods of publishing single disciplines, an absence of adequate funding, and even a still relatively small number of human resources trained in transdisciplinarity, TTDR is slowly advancing in Costa Rica, as in other coastal regions in the Global South (Baumann et al., 2023), and these challenges together represent a significant opportunity for Costa Rica. Transdisciplinary research allows experts from other disciplines, government agencies, and communities to collaborate nationally and internationally on common visions for the future. Such structured collaboration across disciplines, cultures and contexts and its obstacles are expected to be addressed and debated during the upcoming global conference in Nice, France, which Costa Rica will co-host.

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See supplementary material
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