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RESEARCH AND THEORY

Radical interdisciplinarity in scientific practice: placing social networks in marine and fisheries sciences

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Abstract
New modes of science involving more integrated collaboration between disciplines, as well as better links between knowledge, decision-making, and action, are increasingly argued as critical for environmental sciences. Yet interdisciplinarity itself is often unspecified and ambiguous, ranging from collaboration of similar disciplines to more radical interdisciplinarity spanning natural and social sciences. We use social network analysis to chart changes in interdisciplinarity and compare two fisheries science organizations in the Northeast and Pacific U.S., with similar mandates for sustainability but different cultures, contexts, and knowledge networks. We also surveyed scientific staff to better understand reasons for and impediments to collaboration. While scientific practice involves increasing participation of different disciplines and social sciences remain on the periphery, the emergence of a hybrid scholar indicates different pathways for knowledge production as well as the importance of the co-production of knowledge and community, offering insight into how to facilitate more integrated and participatory approaches.

Keywords Interdisciplinary science · Sustainability science · Fisheries management · Communities of practice · Knowledge production · Scientometrics

Introduction

Collaborative research practices, such as interdisciplinary and transdisciplinary approaches, have emerged as key components in rethinking how environmental and sustainability sciences might better meet a broader suite of ecological, social, and economic challenges. Key to such transformation is the recognition that a more fundamental engagement with and embrace of the social sciences is necessary (Hicks et al. 2016; Kagan and Burton 2018; Shrivastava et al. 2020; Longo et al. 2021; Fisher et al. 2022). Such participatory and cross-cutting approaches manifest the purported changes in knowledge production across the sciences, from disinterested, discipline-specific enterprises to team-based approaches with societal involvement: less about grand theories than about nimble problem-solving (Gibbons et al. 1994). Within the domain of fisheries science, for example, though long an applied science, it has for most of its history focused on biological questions to the exclusion of other perspectives. Yet with fisheries management stubbornly beset by "wicked problems," the need for integrated perspectives has been increasingly voiced, from such suggestions as

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better facilitating interdisciplinary research, education, and mentorship; involving stakeholders more substantively; to improving the interface between science and policy (Drakou et al. 2017; Andrews et al. 2020; Hare 2020).

Yet despite these frequent appeals for greater interdisciplinarity,[1] the notion itself is often poorly specified in terms of its actual practice, i.e., who actually does or should collaborate, particularly with respect to the social sciences. Interdisciplinarity is, in that sense, a black-boxed concept (Latour 1999): fundamental but itself unexamined. It can range from a collaboration between similar disciplines to more radical efforts that confront epistemic and ontological challenges, but when such internal heterogeneity is black-boxed, it becomes unproblematically explanatory instead of situated in time and place. While who collaborates with whom is precisely a key focus in bibliometrics and scientometrics, the standardized categories and databases typically employed in that literature tend to be insufficiently developed to fully capture participation from social science disciplines (Wagner et al. 2011). But without such specification, it is difficult to even begin exploring questions about the impact of interdisciplinarity on knowledge production or whether the complexities of effective collaboration are being addressed.

We build on previous research that explored changing forms of interdisciplinary collaboration, and how to account for the social sciences, among a "community of practice" of fisheries scientists, which documented increasing involvement of the social sciences but also its unevenness across topical domains and disciplines (Olson and Pinto da Silva 2021). Our aim here is to compare the interdisciplinary practices of two scientific organizations—one in the Northeast and the other in the Pacific Islands of the United States—in order to better bring contextual factors influencing knowledge production to the fore. These organizations provide a unique comparative opportunity, for both engage in scientific research pertaining to the management of fisheries and both share the same overarching policy and regulatory framework, namely national legislation such as the National Environmental Policy Act (NEPA) and fisheries-specific legislation such as the Magnuson–Stevens Act (MSA), which have together institutionalized a requirement since the 1970s for social science expertise in all regions. Yet the two regions also have distinctive historical trajectories that bring the interplay of science and context (Jasanoff 2005) and the importance of attending to the situated nature of knowledge production (Livingstone 2003) into better focus.

We draw on several different strands of literature, including the broad field of science and technology studies (STS), which has detailed the interdependency of social and material realms in the production of knowledge, as well as literature from scientometrics and other work on the "science of science," which has sought to reflect on the production of science through more macro and quantitative means (Clauset et al. 2017; Fortunato et al. 2018). These two fields of inquiry have maintained a wide berth but there is much to be gained from more productive dialog (Leydesdorff et al. 2020). Using social network analysis, a method for analyzing the organization of relationships (Yang et al. 2016) and visualizing collaborative networks (DeStefano et al. 2011), we examine shifts in co-authorship embodied in over 30 years of scientific work in the two regions. We also consider the reasons for and barriers to interdisciplinary collaboration using a survey of scientific personnel at both organizations about their research practices, as well as conversations with key personnel to flesh out a deeper appreciation of organizational context and culture. While both regions show increasingly collaborative scientific practices and greater integration of social sciences, there are continuing barriers and emerging differences, the reasons for which, and their implications for more collaborative practices in fisheries science and management, we explore.

Conceptual background: theorizing environment and interdisciplinarity

The relationship between people and their environments has been the focus of many different and overlapping social sciences, including ecological and environmental anthropology, ecological economics, environmental history, environmental humanities, environmental sociology, human ecology, and human geography. Some, like anthropology and geography, have long histories in the subject dating to their disciplinary beginnings, while others are more recent (a full review is beyond the scope of this paper, but see Castree et al. 2009; Robbins 2004; Descola and Pálsson 1996; Jasanoff 2005; Chakrabarty 2009; Lockie 2015; Kopnina and Shoreman-Ouimet 2017; Bruckmeier 2020; Hubbell and Ryan 2021). What many of these approaches now share is a

[1] Definitional distinctions between multidisciplinary, interdisciplinary, and transdisciplinary research highlight differing degrees of integration (Wagner et al. 2011). Given our concern with processes of knowledge production, we use interdisciplinary in a looser way to refer to any collaboration between disciplines, irrespective of the synthesis achieved. Collaboration also includes more applied kinds of knowledge, as scholarship on local/traditional knowledge and community-based management has long argued for their inclusion to meet sustainability objectives while balancing legitimacy and credibility (Hind 2015; Chuenpagdee and Jentoft 2019). But despite points of overlap with the social sciences, more fully addressing the factors impacting applied collaboration is beyond the scope of this paper, as they face different barriers to inclusion. We should also note that the encouragement of interdisciplinary collaboration does not imply disciplinary-specific research is unimportant. It is vital for a host of reasons; rather our interest here is in charting changes in an accommodation of the social into environmental research.

more nuanced understanding of environment, problematizing simplistic dualisms of nature and culture; rather than being the domain of the natural sciences, the very concept of environment is argued to represent "an extension of the social into nature" (Sörlin 2013).

But despite such boundary-crossing, social scientists have often found themselves marginalized in environmental policy, management, and science: tacked on belatedly or tokenized in research (Campbell 2005); consigned to only "an auxiliary, advisory, and essentially non-scientific status" (Holm et al. 2013:26); and being disrespected and misunderstood (Roy et al. 2013:751) or integrated asymmetrically and belittled (Viseu 2015). The development of human ecology is particularly instructive, for while its early proponents saw it as an interdisciplinary or adisciplinary approach to understanding human-environmental relations, it originated entirely within the social sciences (Borden 2017) and, until quite recently, met resistance within ecology, with people seen not as part of nature but as "disturbers" of it and thus de-legimitized from study (Dyball 2017). Within fisheries, while the argument that fisheries management is about managing people not fish is widely accepted (e.g., Hilborn 2007), fisheries science as a whole has been decidedly focused on biological and ecological questions. A consensus around the impact of fishing on fish populations emerged early twentieth century (Smith 1994), which by mid-century was modelled mathematically with the concept of Maximum Sustainable Yield (MSY), the largest theoretically sustainable harvest of fish. This focus, enshrined in U.S. law in the 1970s with the Magnuson-Stevens Act, was tightly coupled to geopolitical aspirations for both Americanizing marine resources and ensuring territorial control of navigable waters (Finley and Oreskes 2013). But it also led to a more constrained focus on stock assessment and population dynamics; social scientists, particularly qualitative or interpretive ones, were easily dismissed for relying on "anecdotal" data viewed as too compromised by the very people seen as causing environmental problems (Olson and Pinto da Silva 2019:375; van Ginkel 2006). Even in incipient work on ecosystem-based management, humans were missing from the environment except insofar as they impacted fishing mortality (McCay 2012).

But with the accelerated pace of global environmental changes giving rise to the Anthropocene, both social and natural scientists have voiced an increasing urgency to achieving integrated interdisciplinary work that thoroughly involves social and natural sciences and humanities (Holm et al. 2013, Pálsson et al. 2013). New directions include coupled human-natural systems, integrated environmental assessments, social-ecological systems modelling, complex adaptive systems, integrated ecosystem-based management, and sustainability science (e.g., Kates et al. 2001; Liu et al. 2007; DePiper et al. 2017; Partelow 2018), which not only seek a more dynamic sense of interconnections, but also embody a "relational turn" better at "capturing the complexity of human-nature connectedness" (West et al. 2020:305). Emerging approaches that "integrate incompatible perspectives" (especially quantitative with interpretive approaches) confront epistemological challenges in trying to reconcile different problem definitions and representational practices (Hvidtfeldt 2017), and even ontological challenges in how the environment is constituted, particularly when environmental problems are no longer seen as objectively defined or value-free (Weszkalnys and Barry 2013). Thus in the context of environmental sciences, like fisheries, in which social sciences have often been devalued, Holm et al. suggest "Interdisciplinary research *within* popular divides such as the "hard" or the "soft" sciences is called moderate interdisciplinarity, whereas interdisciplinarity *across* the traditional divides is called radical interdisciplinarity" (2013:28–29, italics added). Moreover, it is not only the processes and products of collaboration that are impacted but also the very identity of those involved, entailing "explicit efforts to create a new type of researcher" that embodies interdisciplinarity (Weszkalnys and Barry 2013:183). In what follows, and given the still-fledgling involvement of social sciences in integrated fisheries sciences, we refer to "radical interdisciplinarity" as approaches that attempt to integrate natural and social sciences. Likewise, we consider a "hybrid scholar" one who not only synthesizes natural and social science theories and methods in their own work but (in contradistinction to simply an interdisciplinary scholar) actively self-identifies their professional identity with these newer, integrated paradigms. There are of course degrees of radicalness and hybridity, a point to which we return.

Work in the social studies of science "starts from an assumption that science and technology are thoroughly social activities. They are social in that scientists and engineers are always members of communities, trained into those communities and necessarily working within them" (Sismondo 2004:10). Moreover as geographers and historians of science have argued, scientific practices are situated and sited: place matters in how and what science is produced (Kohler 2002; Livingston 2003, Henke and Gieryn 2008). For example, while the six regional science centers comprising the scientific arm of National Oceanic and Atmospheric Administration (NOAA) Fisheries share the same overarching mission and mandate, have the same general responsibilities, and are guided by the same national legislation, they are not simply duplicates of each other. On the contrary, they have their own organizational structures and cultures, unique social and environmental contexts in which they operate, and overlapping but also place-based knowledge networks involved in the production of scientific knowledge. These factors all influence what science is produced and by whom. Such communities of practice embody the "situated learning" that develops in collaborative interactions marked by commonality (Lave and Wenger 1991; Brown et al. 2016) and direct attention to the relational practices and processes of knowledge production in different contexts. Based on extensive oral histories with NOAA fisheries scientists and our own experiences, we argue that the juxtaposition of the Northeast Fisheries Science Center (NEFSC) and the Pacific Islands Fisheries Science Center (PIFSC) is particularly instructive for understanding the evolution of social sciences within fisheries research: the Northeast was the first to hire social scientists such as anthropologists[2] but also faced early controversial access, distributional, and allocation issues (invoking particular uses of social science) while the Pacific Islands were still involved in fisheries development and exploration (Olson and Pinto da Silva 2019:376–377). At the same time, both regions have been at the forefront of research on integrated ecosystem-based perspectives, accommodating a more reflexive and fluid science-policy interface and potentially more radically interdisciplinary efforts involving both social and natural sciences (Olson and Pinto da Silva 2020).

Methods

With our interest in understanding the interdisciplinary practices and processes underpinning knowledge production, we use co-authorship networks (Schummer 2004:437, Porter et al. 2007:121) to compare the "communities of practice" found in these two different research organizations. As Jasanoff (2005) argues, a comparative approach enables a finer consideration of the mutual interplay between knowledge production and its sociocultural context, helping in this case to understand the contingent but structured ways in which the social sciences have found their place in fisheries research. A methodological focus on communities of practice also allows one to better capture the scholarly output of all scientists, including topic and discipline-specific journals for both the natural and social sciences, in contrast to the more common reliance in scientometrics on large-scale bibliographic databases where coverage and pre-determined categories are poorly refined for social sciences (Wagner et al. 2011; Mingers and Leydesdorff 2015) or on fisheries-specific journals in which social sciences have historically been underrepresented (Syed et al. 2018, 2019). Co-authorship on publications is widely used in scientometrics as a proxy for understanding interdisciplinary research because publications are visible, accessible, and important to scientific reputation and impact, even though they may not capture all influences on and from scientific work (Melin and Persson 1996; Glänzel and Schubert 2004). Norms of publication and incentive structures may also differ widely between disciplines, which can hamper understandings of interdisciplinary research, especially if accounting for both natural and social sciences. One of the unique opportunities afforded by this comparison of two research centers that broadly share the same topic of concern (the conservation and management of marine resources) and are both part of the same overarching organization (NOAA), is that they both also share key performance metrics such as publication rates and tend to publish in similar journals (Table S1, Supplement).

But to remedy the underrepresentation of social sciences and better characterize the types of scholars engaged in fisheries, we adopted a methodology different to most scientometrics studies, instead categorizing the discipline of each article's contributing authors by a method more akin to grounded theory-building: continually reformulating understandings while moving back and forth between data and theory-building (Corbin and Strauss 1990). While grounded theory has seen recent methodological debate concerning the extent to which it relies on inductive or abductive reasoning (Reichertz 2009; Timmermans and Tavory 2012; Bruscaglioni 2016), and whether its methodology is actually followed by those who claim to use it (Deterding and Waters 2021), our concern here is more to contrast our approach with the more common usage in scientometrics of standardized disciplinary categories, pre-determined through the use of large-scale commercial databases. Instead, we began with a NOAA database containing all scholarly publications for scientists affiliated with the NEFSC during 1990–2018 (adding 2019 in this second phase), researching each publication's co-authors using resources such as Researchgate, Linkedin, and other biographies. (Although the bibliographic database was limited to publications in which NEFSC employees were authors, the analysis included any co-author, whatever their affiliation; see Table S2, Supplement). The discipline of the author's highest degree was one of the most important factors, though self-categorized disciplinary identities, topics

[2] NOAA Fisheries (also known as the National Marine Fisheries Service) is responsible for management and conservation of marine resources in the 200-mile U.S. Exclusive Economic Zone. NEFSC was the first laboratory established in the U.S., founded in Woods Hole, Massachusetts in the late 1800s. PIFSC was established in 2003 as an independent center, but formerly identified as a separate Honolulu Laboratory of the Southwest Fisheries Science Center (in La Jolla, California). Though an interest in industrial economics had been present in precursors to NOAA Fisheries since the nineteenth century, the inclusion of other social sciences is more recent. The first anthropologist was hired at a national level in 1974, and despite a succession of anthropologists and sociologists there was generally only one present at any moment. The first regional anthropologist was hired by the Northeast in 1992, while the Pacific hired their first sociocultural scientist in 2002 (Abbott-Jamieson and Clay 2010).

identified in researcher biographies, and similar sources of information were also used to corroborate discipline.[3]

Disciplinary categories were initially assigned but continuously revised as analysis proceeded. For example, the category of fisheries biology expanded to include marine ecology given overlap in many scientists; likewise, while biology as a whole rests on principles of genetics and evolutionary processes, evolutionary biology was later separated from other categories given a large enough cohort for whom it was a *focus* of training and research. In this second phase of research, the same approach was applied to the PIFSC. While publications are dominated by fisheries biology/marine ecology and oceanography, the appearance of scientists with different disciplinary backgrounds in the new region and year expanded and modified previous disciplinary categories, resulting in 37 disciplinary groupings total (Tables S3-S4, Supplement). We fully recognize throughout this process that disciplinary boundaries are fluid, messy, and historical constructs. But in order to meaningfully compare different forms of collaboration, we use disciplines as a starting point, relying on our "expert knowledge" of the field (Barthel and Seidl 2017:22), as a way to hold onto differences given the premise that the tools, methods, and knowledge of a corpus of literature come through deep study in a particular subject. While we recognize there are not rigid boundaries marking out the terrain of any particular discipline—which have in reality evolved over time and continue to evolve and overlap with other putatively separate but related disciplines—for the purposes of social network analysis, disciplines must be treated as discrete "nodes" and therefore as binary variables.

The final publication databases comprised 2275 publications and 4047 authors in the NEFSC and 963 publications and 1994 authors in the PIFSC. Adding disciplinary information resulted in 2275×37 and 963×37, 2-mode incidence matrixes for the NEFSC and PIFSC respectively, with the digit in each cell representing the number of authors of any given discipline for each article (Wagner and Leydesdorff 2005:190). These matrixes were converted into symmetrical, 1-mode 37×37 co-occurrence matrixes for each region and decade using the sum of cross-products, with disciplines along rows and columns and their intersecting cell marking co-occurrences. The original databases were also converted to co-occurrence matrixes for each region and decade using individual authors along rows and columns. The resulting social networks were analyzed with UCINET (Borgatti et al. 2002) and visualized with Gephi (Bastian et al. 2009) using the open-ord force-directed layout (Martin et al. 2011), which represents similarity by proximity. We also used the Louvain community cluster method (Blondel et al. 2008) to detect communities and hierarchies of sub-communities among co-authors, which iteratively measures the density of ties (their modularity score) within clusters and aggregated cluster-communities, relative to the density of ties between clusters. Such analysis aids understanding the extent to which researchers work in more or less intensely collaborative clusters, enabling fine-scaled analysis of changes in relationships over time.

Social network analysis can present compelling insight into the collaborative practices emanating from these different communities of practice, as well as the uneven distribution of "power" in the network (Bodin and Crona 2009). But as Brown et al. (2016:236) note, social network analysis alone cannot explain what motivates or prevents collaboration, why networks change, or whether changes reflect any substantive shifts. To this end, we also undertook a survey of scientific personnel at both NEFSC and PIFSC, to better understand whether scientists viewed themselves as interdisciplinary scholars, and what motivated or prevented them from engaging in such research (see Table S6-S7, supplement, for survey questions). The survey was pre-tested with social and natural scientists and implemented online over several weeks, beginning in April 2021 with emailed introductions and later reminders to staff in both regions. The response rate was 40% (68 responses out of 168) and 39% (33 out of 84) for the Northeast and Pacific respectively. R statistical software tools (R Core Team 2021) such as Mann-Whitney and Kruskal-Wallis tests were used to assess statistically significant differences in Likert-scale responses by region, science-type, gender, education, and years working, while factor analysis (Fox 2019) was used to explore underlying characteristics of interdisciplinary practices. Open-ended questions were analyzed qualitatively by classifying and organizing responses thematically, again using traditional qualitative grounded analysis (Corbin and Strauss 1990) to iteratively code themes as they emerged from the data. Finally, we also had informal, semi-structured conversations with colleagues and key personnel, utilized materials from oral histories conducted with scientists at NOAA Fisheries Science Centers (Olson and Pinto da Silva 2019, 2020), and relied on our own "participant-observation" in

[3] Some scholars have rejected co-authorship analyses, as assessing disciplinary backgrounds can be difficult and relies on expert judgement, but other bibliometric measures are also prone to uncertainties (Melin and Persson 1996; Wagner et al. 2011:19). For example, the predetermined categories in bibliometric databases tend to be non-specific and less developed for social sciences (Wagner et al. 2011:24), while studies using departmental affiliation (e.g., Schummer 2004) would be inappropriate in this study. But as participant-observers, core groups of authors were known to us directly or indirectly, enabling us to groundtruth our methods by asking a subset of colleagues to review their and their co-authors' suggested disciplines. Only one relatively minor change was suggested (from Ecology and Evolutionary Biology to Fisheries Biology). For further details, see Olson and Pinto da Silva 2021.

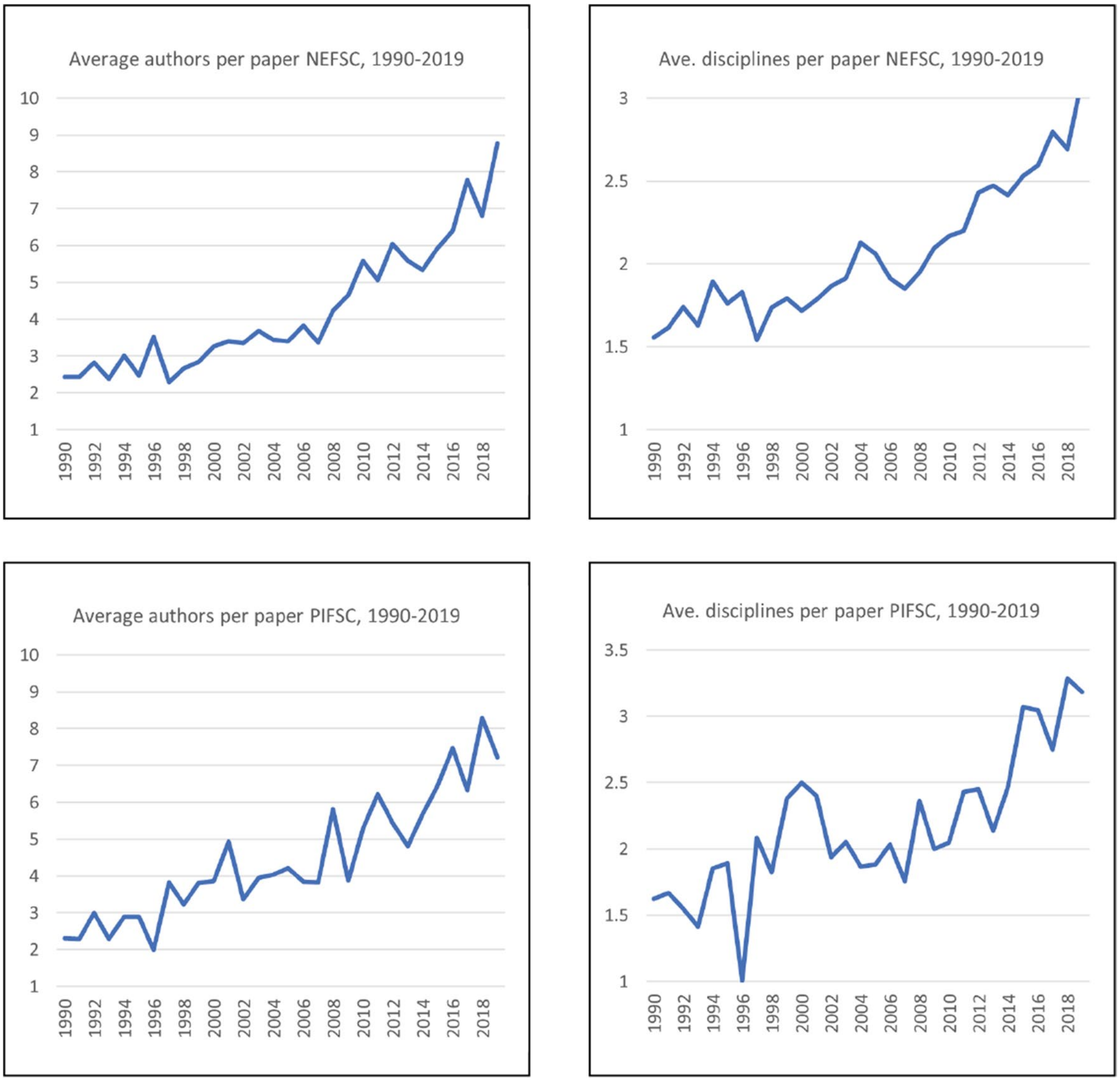


Fig. 1 Average number of co-authors and disciplines per paper, 1990–2019

this environment, as social scientists working in or with the NEFSC.

Results

Comparison of social networks and collaborative practices

Over the past three decades, scientific production across the globe has seen an "explosion" in co-authorship (Adams 2012) and fisheries science is no exception (Aksnes and Browman 2016). In the Northeast, articles with three or fewer co-authors accounted for over 75% of the total in 1990 but less than 20% in 2019; in the Pacific, almost all articles were authored by three or fewer in 1990 but under 25% in 2019 (Fig. 1). Likewise, in both regions around half of articles published in 1990 involved a single discipline, but by 2019 single-discipline articles accounted for less than 20% of publications, with papers involving four or more disciplines accounting for 30% in the Northeast and 50% in the Pacific. Commonly used metrics in social network analysis (Table 1) show scientific practice in both regions becoming more active, connected, and interdisciplinary.[4] Disciplines

[4] Comparing measures like density from differently-sized networks can be problematic, as theoretically in a bigger network it is harder for actors/nodes to become acquainted or maintain strong ties (Hislop 2005). In an early effort to address comparability, Snijders and Borgatti (1999) wrote "there are no established, widely applicable, ways of calculating standard errors for network statistics" (1999:161), while van Wijk et al. (2010:2) noted "an approved, unbiased method for empirical data does not exist" for which "networks of different size and connectivity density [can] be accurately compared." None-

Table 1 Social Network Measures

Social Network Measures for discipline co-occurrences						
	1990–1999	2000–2009	2010–2019	1990–1999	2000–2009	2010–2019
	NEFSC			PIFSC		
Count of nodes (i.e., disciplines)	30	34	37	19	25	32
Degree (or number of ties)	234	414	830	110	204	568
Average degree	7.80	12.18	22.43	5.79	8.16	17.75
Density (number of ties relative to the total possible)	0.27	0.37	0.62	0.32	0.34	0.57
Average distance (average of the shortest paths between nodes)	1.88	1.67	1.38	1.68	1.63	1.43
Degree centralization	0.1405	0.0959	0.1191	0.2208	0.1898	0.1424
Betweenness centralization index	30.18%	23.03%	3.92%	52.23%	31.90%	4.21%
Average clustering coefficient	0.618	0.695	0.781	0.600	0.649	0.739
Social Network Measures for co-author co-occurrences						
	NEFSC			PIFSC		
	1990–1999	2000–2009	2010–2019	1990–1999	2000–2009	2010–2019
Count of nodes (i.e., authors)	592	1477	2664	271	536	1478
Degree	3064	13,674	65,776	1342	5378	23,112
Average degree	5.2	9.3	24.7	5.0	10.0	15.6
Density	0.009	0.006	0.009	0.018	0.019	0.011
Average distance	5.6	4.6	3.7	4.2	3.5	3.6
Connectedness	0.434	0.951	0.987	0.831	0.913	0.977
Degree centralization	0.0065	0.0047	0.0039	0.0177	0.0081	0.0037
Betweenness centralization index	9.20%	22.07%	15.92%	48.22%	32.22%	18.64%
Average clustering coefficient	0.811	0.820	0.874	0.756	0.826	0.870

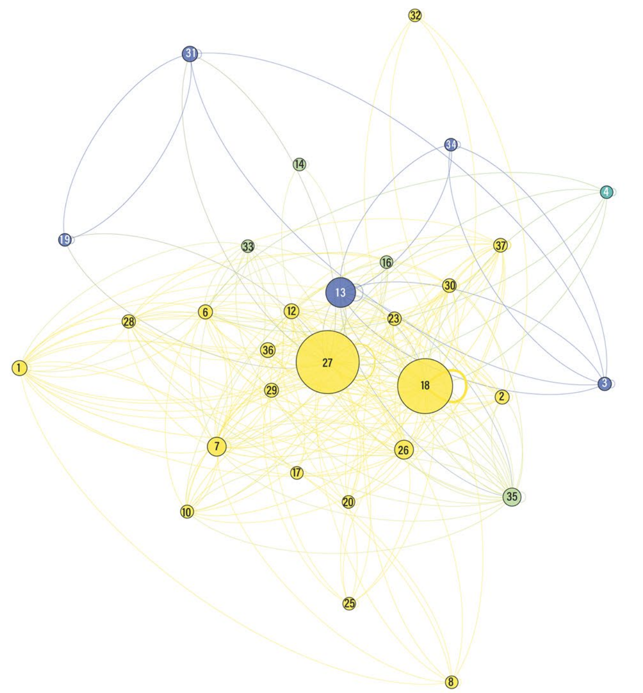
increased while ties between them tripled, indicating higher levels of activity; network density doubled, indicating greater cohesiveness; and average distance decreased, suggesting knowledge flowed more easily between disciplines. Likewise at the level of individual scientists, the number of nodes, ties, and average degree in both regions increased significantly. Author "connectedness" also increased while average distance decreased, together implying more closely connected scientists and fewer isolated ones. However, density decreased among scientists and remained relatively low, suggesting little change in low structural cohesion of either network, dominated in absolute numbers by one-time collaborators outside the primary core of center-based researchers.

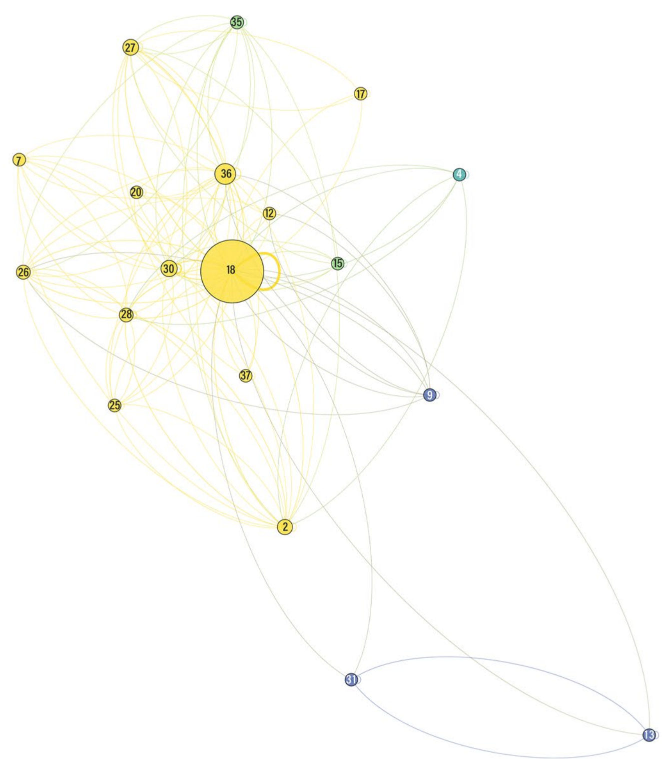
Centralization measures that assess the extent of domination in a network decreased for the disciplinary network in both degree (i.e., "popular" nodes) and betweenness (indicating how often a node is on the shortest path between others, and thus its bridging role in the network). However, the increase in average clustering coefficient (indicating the extent to which the "friends" of a node are also friends) suggests that while there are fewer overly central nodes, and most disciplines have at least nominal ties, there are increasing clusters of more intense collaboration among select disciplines. At the author level, the increase in clustering coefficients in both regions, coupled with decreasing degree centralization, may simply suggest recurring collaborations amongst scientists and horizontal expansion of personnel consistent with organizational-based communities of practice. But increases in betweenness centralization in the Northeast, and decreases in the Pacific from a relatively high level to more closely approximate the Northeast, signals a degree of concentration in who holds important bridging roles.

Looking more closely at which disciplines collaborate shows similar patterns of interdisciplinarity in both regions in the 1990s, with fisheries biology (and oceanography in the Northeast) central and dominant in scientific output (Fig. 2). Social sciences are peripheral in both regions but with a more pronounced disconnect in the Pacific. In part this reflects the earlier establishment of social sciences at NEFSC, and the smaller size of the PIFSC; in later decades

Footnote 4 (continued)

theless as Tantardini et al. (2019:3) observe, comparisons of "simple metrics" are "useful for a first analysis." In our case particularly, we are not sampling from a wider universe but are comparing two unique cases whosedifferences we would not want to control for as such, but rather explore for the impacts on collaborative processes.





however, a more varied and integrated picture of interdisciplinary collaboration emerges (Fig. 3): fisheries biology and oceanography are no longer the only core disciplines, and tighter and more extensive connections between all fields are evident. While the social sciences remain relatively peripheral to both networks, and despite rising numbers still represent a small fraction of scientific staff (Table S5, Supplement), the final decade hints at more radically interdisciplinary efforts and a different pattern of integration in the Pacific. Likewise within the author networks, numerous clusters of denser interaction are visibly evident as is the predominance of social scientists in more peripheral

◂**Fig. 2** NEFSC (top) and PIFSC (bottom), 1990–1999 co-authorship networks. Network nodes are colored by science type (yellow, natural sciences; blue, social sciences; dark green, hybrid social/natural approaches; light green, maths/engineering/GIS; aqua, applied specialities) and proportional to their betweenness centrality degree on a scale of 5 to 25. Disciplinary key: 1, Agricultural, Plant, and Soil Sciences; 2, Animal Sciences (including Aquaculture and Veterinary Sciences); 3, Anthropology; 4, Applied; 5, Archaeology; 6, Biogeochemistry; 7, Chemistry and Biochemistry; 8, Climate and Atmospheric Sciences; 9, Communications, Information Science, and Decision-making; 10, Community and Systems Ecology; 11, Data Visualization; 12, Ecology and Evolutionary Biology; 13, Economics; 14, Engineering: Applied; 15, Engineering: Electrical and Acoustical; 16, Engineering: Mechanical, Ocean, Civil; 17, Environmental Restoration and Coastal Management; 18, Fisheries and Marine Biology/Ecology; 19, Geography; 20, Geology and Earth Sciences; 21, History; 22, Human Dimensions Conservation and Management; 23, Hydrology, Water Quality, and Environmental Engineering; 24, Interdisciplinary Socio-Ecological Modelling; 25, Medicine and Public Health; 26, Microbiology, Molecular Biology, and Genetics; 27, Oceanography; 28, Pathobiologies; 29, Physics, Optics, and Acoustics; 30, Physiology, Neurobiology, Endocrinology, and Chronobiology; 31, Public Policy, Law, and Political Science; 32, Quantitative Ecological Modeling; 33, Remote Sensing and GIS; 34, Sociology; 35, Statistics, Mathematics, and Computer Science; 36, Wildlife Biology and Ecology; 37, Zoology, Taxonomy, and Morphology/Anatomy

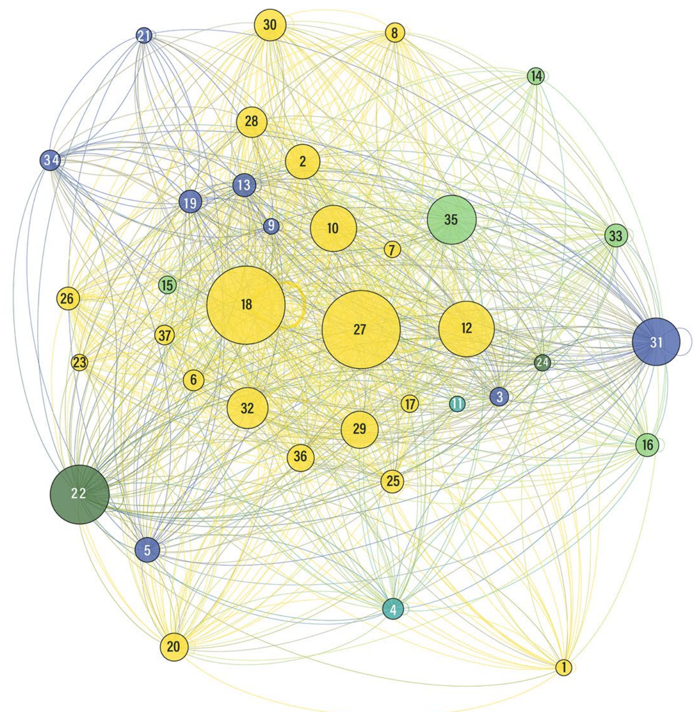
clusters (Fig. 4). In the Northeast, most social scientists in the 1990–1999 period are completely disconnected from the main network, and those more central are only loosely connected; in the 2010–2019 period, social scientists still primarily interact with each other on the network periphery, but there are signs of more central integration of some individuals. In the Pacific, minimal interaction between different research clusters was even more pronounced for the social sciences in the 1990–1999 period than in the Northeast. But during 2010–2019, while more densely connected clusters of social scientists are still found on the periphery, there are increasing numbers of social scientists centrally located in the network with increasingly varied connections to other researchers. Understanding these relational changes and their impact on knowledge production requires closer consideration of the presence, strength, and nature of subgroups and bridging ties, which we examine in greater detail in the next section.

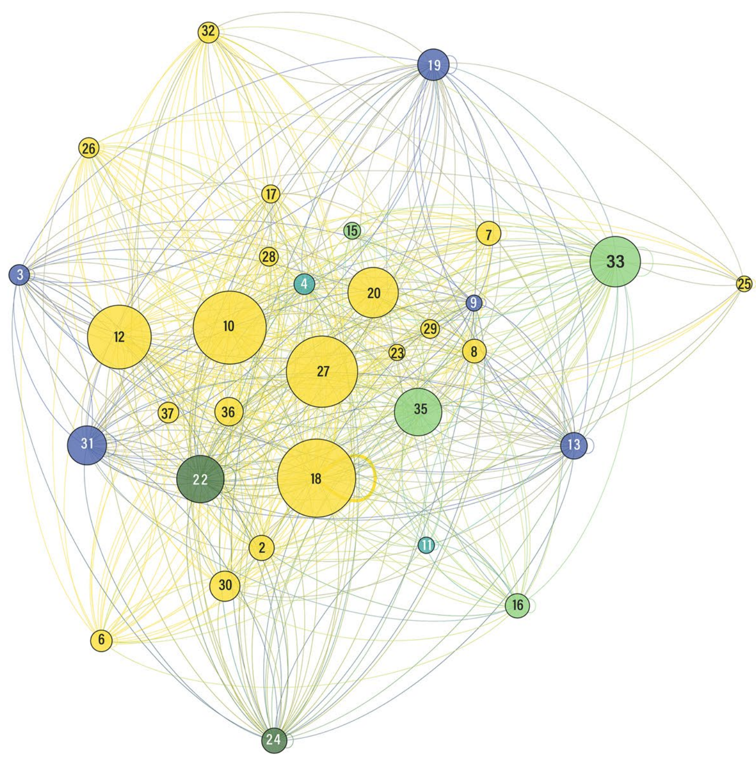
Research clusters and the hybrid scholar

The Louvain method of detecting communities in large networks indicates that while both regions are characterized by densely clustered research groups, over time the strength of community organization has weakened, with increasingly overlapping ties between researchers (Table 2). In the Northeast the number of distinct research clusters decreased while sub-groups within them increased; the decreasing modularity score indicates a weakening in partitioning between groups. In the Pacific Islands, while the extent and modularity of research clusters were relatively stable, internal sub-groups also increased. In both regions, the average number of authors in each cluster increased with the expanding network, with a smaller concentration of authors in the top quarter of research clusters. In the Pacific Islands, this change in concentration is more pronounced, with the earlier decade centered around a core of researchers working on more focussed areas of study. Over time, social scientists have become increasingly integrated into more central and connected research communities in both regions, though still in smaller numbers than other scientists and often on only limited publications. Nonetheless, while the early absence of social scientists is more pronounced in the Pacific, social scientists have over time become more prevalent in central clusters, largely through integrated and participatory studies of management and modelling and involving a mix of disciplines from both the social and natural sciences.

Other indicators also suggest an increasing intensity of bridging efforts across research communities (Table 3). The tripling of papers in both regions whose co-authors bridge different research clusters is highly suggestive of a need to address crosscutting issues and implies increased collaboration with novel (i.e., non-repeat) researchers, if not necessarily different disciplines. Similarly, the increasing percentage of papers bridging natural and social sciences (with at least one natural and one social/hybrid scientist) indicates more radical forms of interdisciplinarity, as defined earlier. In the Northeast, radical interdisciplinarity has nearly tripled, with topics centered primarily on ecosystem-based management, fisheries management, marine mammals and protected species, and climate change (Figure S1, Supplement). While earlier decades focused on general overviews or assessments, the latter decade has seen more attention paid to engagement and social-ecological systems (SES) modelling. Radical interdisciplinarity has followed an even more pronounced trajectory at PIFSC (Figure S2, Supplement). Topics also revolve primarily around ecosystem-based management, fisheries management, and climate change, but touch more strongly on participation, conservation, engagement, and SES modelling. While the percentage of papers crossing the natural and social sciences was initially even lower, radical interdisciplinary collaboration now accounts for a higher percentage of papers in the Pacific.

In general, both networks have become more loosely structured, where diverse research clusters define distinct areas of focus but overlapping ties and shorter distances mean communication between clusters is increasingly bridged. However, these critical bridging roles are played by fewer scientists, making such bridges more precarious and less representative. Authors with normalized betweenness greater than one have decreased markedly, implying that a handful of scientists, most of whom are either biologists or oceanographers, have more powerful bridging roles.





In the Northeast, there are fewer social scientists playing such integrative roles, and despite widespread involvement in a variety of research clusters, involvement is still relatively minor. For example, in over half (53.2%) of papers involving radically interdisciplinary collaboration, social sciences accounted for only a minority (less than 25%) of authorship. While bridging roles in the Pacific are likewise dominated by biological scientists and oceanographers, there are slightly more social scientists playing these roles (8.9% compared to 6.8% in the Northeast). And while nearly 40% of radically interdisciplinary papers in the Pacific also have a low social science component (with less than 25% of the

◂**Fig. 3** NEFSC (top) and PIFSC (bottom), 2010–2019 co-authorship networks. Network nodes are colored by science type (yellow, natural sciences; blue, social sciences; dark green, hybrid social/natural approaches; light green, maths/engineering/GIS; aqua, applied specialities) and proportional to their betweenness centrality degree on a scale of 5 to 25. Disciplinary key: 1, Agricultural, Plant, and Soil Sciences; 2, Animal Sciences (including Aquaculture and Veterinary Sciences); 3, Anthropology; 4, Applied; 5, Archaeology; 6, Biogeochemistry; 7, Chemistry and Biochemistry; 8, Climate and Atmospheric Sciences; 9, Communications, Information Science, and Decision-making; 10, Community and Systems Ecology; 11, Data Visualization; 12, Ecology and Evolutionary Biology; 13, Economics; 14, Engineering: Applied; 15, Engineering: Electrical and Acoustical; 16, Engineering: Mechanical, Ocean, Civil; 17, Environmental Restoration and Coastal Management; 18, Fisheries and Marine Biology/Ecology; 19, Geography; 20, Geology and Earth Sciences; 21, History; 22, Human Dimensions Conservation and Management; 23, Hydrology, Water Quality, and Environmental Engineering; 24, Interdisciplinary Socio-Ecological Modelling; 25, Medicine and Public Health; 26, Microbiology, Molecular Biology, and Genetics; 27, Oceanography; 28, Pathobiologies; 29, Physics, Optics, and Acoustics; 30, Physiology, Neurobiology, Endocrinology, and Chronobiology; 31, Public Policy, Law, and Political Science; 32, Quantitative Ecological Modeling; 33, Remote Sensing and GIS; 34, Sociology; 35, Statistics, Mathematics, and Computer Science; 36, Wildlife Biology and Ecology; 37, Zoology, Taxonomy, and Morphology/Anatomy

authorship), a particular kind of hybrid interdisciplinary scholar (bridging social and natural sciences in their own training and research) has become more prominent in such collaborations. In 2010–2019, radical interdisciplinarity in the Pacific involved 39 papers with traditionally-trained social scientists and 37 papers with hybrid scholars, while in the Northeast 50 papers involved traditional social scientists and only 24 papers involved hybrid researchers. And while numbers of hybrid scholars have increased in both regions in the last decade, the number is significantly higher in the Pacific than in the Northeast in absolute terms, despite being a smaller organization (Figure S3, Supplement). The trajectory of social sciences in the Pacific thus involves a different form of interdisciplinarity stressing hybridity, participation, and engagement to a greater extent than in the Northeast, a point to which we return.

The multiplicity of interdisciplinarity

Scientific personnel were also surveyed about their research practices, with a focus on their experiences with interdisciplinary collaborations (see Table S6-S7, Supplement, for the full list of questions). Most respondents were mid-career (56.5%), trained in the natural sciences (81%), and PhD-level (61.4%). Social scientists appear to be overrepresented in the survey in both regions relative to staffing levels.[5] There was pronounced agreement with questions indicating an interdisciplinary orientation; indeed, only one respondent disagreed with all five questions designed to gauge interdisciplinarity. (This high level of agreement may indicate self-selection bias, in which case responses may be less informative about barriers to interdisciplinarity). Most respondents worked with researchers in other disciplines (93.1%), used work of other disciplines in their own research (88.1%), sought opportunities to work with interdisciplinary groups (82.2%), and/or considered their own training to be in an interdisciplinary field (60.4%). Nonetheless, the propensity to consider one's own field interdisciplinary varied within the same discipline, suggesting not only differences in training and outlook but also the inherent ambiguity of the term.

Asked about a number of potential reasons influencing with whom one collaborated, the single most important factor chosen was being colleagues in the same office/division (80.2%), while the second stemmed from being contacted for one's expertise (79.2%), thus expanding collaborative networks. Common reasons for engaging in interdisciplinary work were to access expertise (91.1%), exchange ideas (84.2%), and work with diverse perspectives (72.3%), while more instrumental reasons like specialized instrumentation were less important (33.7%). Though few experienced barriers to engaging in interdisciplinary research (which again, may indicate low survey participation by non-interdisciplinary researchers), most respondents agreed or strongly agreed that interdisciplinary work was within their work remit (85.1%), encouraged by colleagues (76.2%), and positively affected by involvement in external working groups (79.2%), informal interactions at work (67.3%), and personnel (64.4%). Moreover, a clear majority (81.2%) wanted to increase their involvement in interdisciplinary research and more opportunities for stakeholder involvement (72.3%).

While the overall impression indicates highly positive experiences with interdisciplinarity, there are nuances by region, disciplinary background, degree level, and gender (Tables 4 and 5). The tendency to regard oneself as interdisciplinary, actively communicate research, and draw on academic networking is associated more strongly with having a PhD. Social scientists are more likely to consider their field inherently interdisciplinary, while natural scientists more likely to seek access to specialized instrumentation. Gender was also statistically significant, with women more likely to enjoy working with diverse perspectives, but also less likely aware of research being done by other groups at their organization. While respondents in both regions felt opportunities for interdisciplinary work were enhanced

[5] Social scientists comprise 17.9% of survey respondents in the Northeast (12 of 67 disciplines), compared to 8.6% (14 of 163) of staff in 2020, and 18.8% of survey respondents in the Pacific (6 of 32 disciplines), compared to 8.6% (6 of 70) of 2020 staff (Tables S5, S7, Supplement). However, staffing categories only roughly correspond to the more refined categories used in this study, making a fuller comparison imperfect.

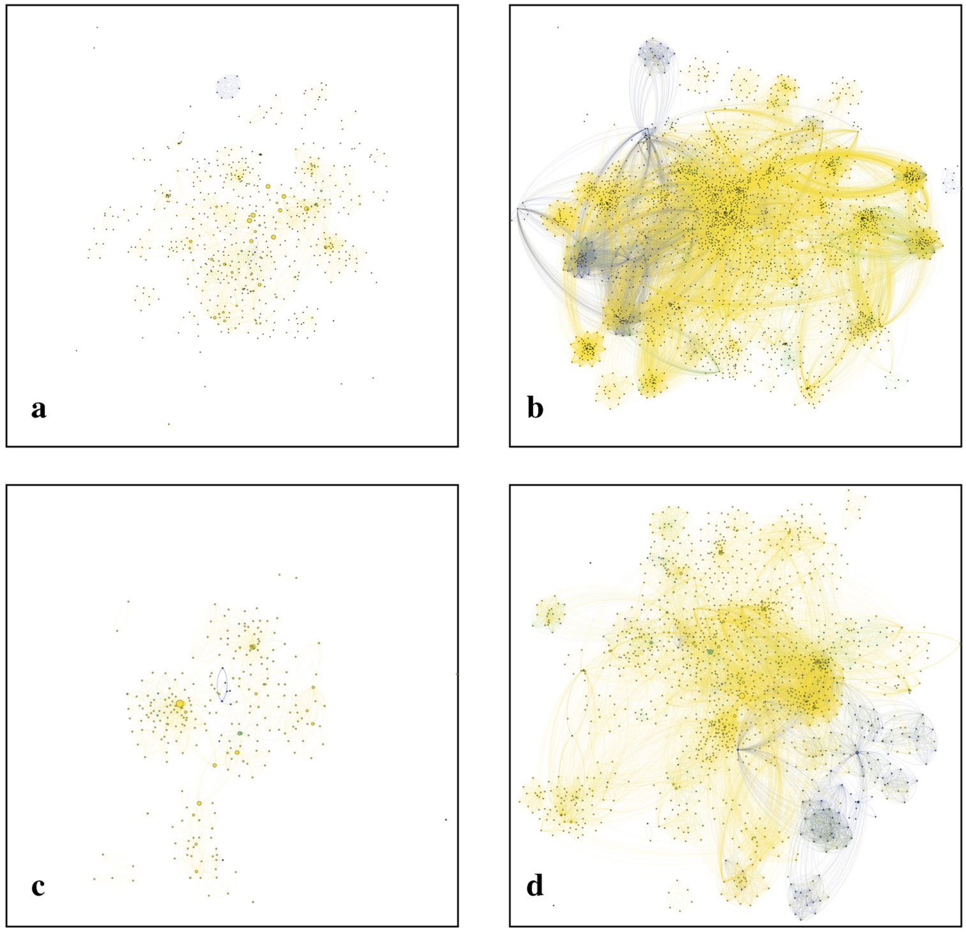


Fig. 4 Co-authorship networks of individual scientists: **a** NEFSC 1990–1999, **b** NEFSC 2010–2019, **c** PIFSC 1990–1999, **d**. PIFSC 2010–2019

by informal interactions at work and external working group involvement, Northeast scientists were more likely to agree. Both natural and social scientists were involved in external groups, but with a stronger tendency among natural scientists. Relatively few natural scientists found differing research norms a barrier to interdisciplinary work, but significantly half of social scientists did. And while a minority of natural scientists felt their expertise was sought after important decisions were made, over half of social scientists experienced this.

Factor analysis suggests a variety of "types," reasons, and experiences with interdisciplinarity (Table S8, Supplement). The two highest-loading factors condense a number of positive reasons and experiences with collaboration, from an all-around interdisciplinary scholar scoring high on different measures of and reasons for collaborating, to an advanced degree holder with a positive and external orientation to research collaborations. But the next factors point to obstacles to integrating into fisheries sciences, from having a social scientific or interdisciplinary orientation, where different research norms present barriers to interdisciplinarity, to lacking traditional markers of scientific authority. Other factors express the positive impacts from collaborating internally but also point to challenges in integrating staff with less scientific seniority, particularly in the Northeast. The remaining factors condense elements of research sharing, contact, and satisfaction with interdisciplinarity, indicating networked experts with stable research portfolios; instrumental rationales for collaboration; seeking of novel perspectives; and learning new skills and knowledge. These different factors reinforce the multiplicity of ways to engage with interdisciplinary research, but also suggest that certain positions and experiences are marked by difficulties in fully integrating into fisheries science.

Facilitating interdisciplinarity

The survey also asked several open-ended questions, which help shed light on these differences in experience with interdisciplinarity. Out of the total 101 respondents from both the Northeast and the Pacific, 91 respondents provided thoughts about successful interdisciplinary work, with responses falling into four broad and overlapping categories: open-mindedness (38.5% of responses), clarity of communication (29.7%), trust and respect (17.6%), and various concrete suggestions

Table 2 Louvain analyses of research cluster-communities

	No. of clusters (no. of sub-communities)	Modularity score	Social scientists in top quartile of clusters	First social science majority cluster	Research focus of 5 largest clusters
Northeast					
1990–1999	56 (147)	0.923	6 social scientists out of 537 authors	27th largest (bottom 13% of network)	oceanography-biogeochemistry, marine mammals, marine mammals, life history, habitat, pollution
2000–2009	43 (238)	0.896	10 social scientists out of 908 authors	24th largest (bottom 7% of network)	marine mammals, oceanography-biogeochemistry, 2 clusters of oceanographic/ecosystem modelling/ stock assessment, physiology
2010–2019	34 (275)	0.833	73 social scientists out of 1541 authors	14th largest (bottom 19% of network)	two clusters of ecosystem modelling and dynamics (including climate change), oceanographic/climatic studies, marine mammals, aquaculture/animal health
Pacific Islands					
1990–1999	21 (68)	0.852	1 social scientist out of 196 authors	10th largest (bottom 12% of network)	sea turtles, physiology, monk seals, fish ecology/life history, fish biology/stock assessment
2000–2009	23 (77)	0.822	1 social scientist out of 355 authors	15th largest (bottom 4% of network)	sea turtles, physiology/gear, coral reefs, biological oceanography/fisheries, monk seals
2010–2019	21 (182)	0.814	97 social scientists out of 746 authors	5th largest (bottom 49% of network)	socio-ecological modelling; oceanography-ecosystem modelling; sea turtles, gear, bycatch; integrated participatory ecosystem-based management

(14.3%). Scientists in the Northeast were more concerned about open-mindedness (42.6% compared to 30%), while in the Pacific there was greater concern with communication (36.7% compared to 26.2%). A scientist in the Northeast wrote that interdisciplinary work required a "willingness to work together and to be open-minded to new ideas and approaches" and another stated "Open mind and no egos." The necessity for clear and open communication was noted for all stages of research, with a Pacific scientist advising "Frequent meetings and discussions among the authors. Often, one discipline may take for granted some ideas/methods/results that are novel/ challenging for the another discipline. Good communication is key to avoiding misunderstandings that lead to rabbit holes and hinder progress." Closely related to open-mindedness was "mutual respect and trust." As one Northeast respondent explained, "Being generous, with your own research, program capacity, ideas and time. Mentoring students to get exposure to new ways of doing things. Build trust by supporting "open science" and not the close-hold type of proprietary research that dominates academia historically." Additionally, respondents gave concrete suggestions for how to successfully collaborate, from adhering to deadlines, to having adequate time, resources, and support.

Respondents also suggested ways to better facilitate interdisciplinary research in their workplace, with 69 (out of 101 in both the Northeast and Pacific) providing suggestions, including organizational and physical space changes (33.3%), building awareness of research (29%), increasing funding and support (21.7%), fostering diversity (11.6%), and improving communication and credit (4.3%). A concern to increase diversity was seen as more pressing in the Northeast (15.9% of responses compared to 4%). Organizational and space issues involved several overlapping issues, such as encouraging more physical interaction, a concern expressed primarily by respondents in the Northeast, from suggestions to "Co-locate staff from different divisions in office spaces" to "break down the artificial barriers and silos formed by line offices." Organizational changes ranged from creating "standing cross-disciplinary teams" in the Northeast to making "the EBFM [ecosystem-based fisheries management] framework […] a common currency to work with" in the Pacific. Closely related was a desire for increased awareness of ongoing research, with Northeast scientists voicing concerns from "Establishing better channels of communication with groups outside my branch" to creating "Opportunity for more informal engagement."

Better support was also sought, from funding to time to improve understanding of the particularities of interdisciplinary work, such as a need voiced in the Pacific to "Relax strict results-based outlook to promote opportunities for innovation. Ensure that it is okay to carve out time to push boundaries, explore new ideas." A need to increase diversity was also noted; as one respondent in the Northeast

Table 3 Indicators of community bridging

	Percent of papers bridging different Louvain clusters	Percent of radically interdisciplinary papers	Percent of authors with a normalized betweenness centrality > 0	Percent of authors with a normalized betweenness centrality > 1
Northeast				
1990–1999	9.8	2.5	27.2	9.5
2000–2009	14.4	2.1	27.1	5.0
2010–2019	29.5	7.2	27.0	2.2
Pacific Islands				
1990–1999	10.4	1.9	23.2	10.7
2000–2009	22.1	0.7	29.9	8.2
2010–2019	32.8	11.4	26.0	3.8

suggested, "Bring in more expertise in a variety of fields. There are many disciplines where we only have 1 expert at the Center and it is overwhelming for a single person to be the only expert." Finally, another Northeast scientist advised, "Don't hire loners. The cliche of the lone scientist at a microscope shouting "Eureka!" in the middle of the night no longer has any relevance to discovery. Meaningful findings today require multidisciplinary collaboration." Taken together, these sentiments point to a shift in scientific practice from a more hierarchical enterprise to an emerging ethos of interdisciplinarity as more transparent and shared, but troubled by place-based and discipline-specific differences.

Discussion

Communities of practice of fisheries scientists in the Northeast and Pacific—sharing similar mandates for sustainability but different cultures, contexts, and knowledge networks—embody different forms of collaboration and different accommodation of the social sciences. Social network analysis (see the "Comparison of social networks and collaborative practices" section) indicates the extent to which collaboration in both regions has increased: no single discipline like fisheries biology dominates today as it did in the past, but more intense collaboration between traditionally central disciplines continues despite increasing and more connected disciplines involved in fisheries science. The social sciences in particular remain on the periphery, though to a lesser extent than before. Scientists are also more closely connected and less likely to work in relative isolation, but low levels of network cohesion with its associated clustering merits attention. Such clustering can signal divisive "us-them" cliquishness (Borgatti and Foster 2003) and isolation from novel ideas (Syed et al. 2019:847) or, alternatively, the specialization necessary for strengthening diverse knowledge bases (Bodin and Crona 2009:368 – 69). Though clustering is common in human networks (Newman and Park 2003), a critical factor in how clustering manifests itself is not only the extent but also the character of bridging ties between groups (see the "Research clusters and the hybrid scholar" section), for highly centralized networks—in which a handful of actors dominate key bridging roles—are not only less apt at solving complex problems but their asymmetric influence also raises issues of legitimacy, power, and representation (ibid.:370 – 71).

The increasing intensity in both regions of bridging across distinct research clusters, and the rise in radical interdisciplinarity involving both natural and social sciences, however marginal the participation of social sciences may still be, suggests robust collaborative networks and an increasing need to address crosscutting issues across disciplines (see the "Research clusters and the hybrid scholar" section). But the asymmetrical distribution of influential roles, such as bridging ties between groups, suggests gaps in the representation of more diverse perspectives. For example, fewer social scientists acting as influential bridging nodes in the network is partly an artifact of differing norms of authorship and participation in large, team-based approaches. But it also stems from limited numbers of social scientists, traditionally under-resourced and heavily tasked with management-support responsibilities, making them much less likely to have time or resources to participate in multiple, bridging projects (e.g., Anderson et al. 2003; Hanna et al. 2009; Wiley et al. 2013). An internal lack of social scientists could conceivably be met by greater collaboration outside the network, and wider-ranging engagement with new collaborators may become increasingly important in the face of such challenges as climate change, wind energy, and ecosystem-based management. But knowledge networks depend on personal knowledge, as can be seen by the dearth of social scientists in the network before social scientists were hired in any numbers. To make social science more central to an interdisciplinary fisheries science, an obvious conclusion is that more diverse hires that provide strength in numbers are necessary but also insufficient without increasing awareness

Table 4 Yes-no responses with statistical significance of $p < 0.1$

	p-value		No	Yes
Question 2: In thinking about your own work, please check any of the following that apply.				
My own research draws on other disciplines	0.0146	Phd	4.8	95.2
		MA/MSc	28.6	71.4
I seek research opportunities to work with interdisciplinary groups	0.0580	Phd	11.3	88.7
		MA/MSc	32.1	67.9
I share my work on scientific networking sites (such as Researchgate)	0.0008	Phd	25.8	74.2
		MA/MSc	60.7	39.3
I use social media to publicize my research	0.0329	Phd	59.7	40.3
		MA/MSc	78.6	21.4
I am trained in an interdisciplinary field	0.0537	Natural Science	44.4	55.6
		Social Science	16.7	83.3
Questions 3: In thinking about researchers you have collaborated with (including interdisciplinary and non-interdisciplinary collaboration), what are the primary reasons for working together? Check all that apply.				
Because of my involvement in external working groups	0.0102	Phd	24.2	75.8
		MA/MSc	53.6	46.4
They were former academic classmates or mentors	0.0026	Phd	56.5	43.5
		MA/MSc	82.1	17.9
Question 4: If you have participated in interdisciplinary research, what are your primary reasons for engaging in it? Check all that apply.				
For access to specialized instrumentation	0.0502	Natural Science	61.7	38.3
		Social Science	88.9	11.1
Because I enjoy working with groups that bring together a diversity of perspectives	0.0324	Female	13.6	86.4
		Male	37.7	62.3

of the value of such diverse perspectives and ensuring organizational changes that support interaction at all levels of scientific endeavor (see the "The multiplicity of interdisciplinarity" section).

Attention to the processes of knowledge production in these organizational contexts helps point to continuing impediments to engaging in interdisciplinary research, and their uneven experience by different scientists. That social scientists, for example, are more likely to find different disciplinary norms hindering collaboration in fisheries science, or find themselves asked to participate as an afterthought (see the "The multiplicity of interdisciplinarity" section)—and many have a tale to tell of being dismissed as unscientific, anecdotal, or political—is particularly suggestive of how interdisciplinarity does not just happen. Rather, it needs intentional investments, decisions, and organizational structures (see the "Facilitating interdisciplinarity" section). Groups that have traditionally been excluded from fisheries science or from science more generally, including but not limited to social sciences, still face barriers to integration, and acknowledging their importance is only the first step to integrating their perspectives. Fortunately, as survey respondents made clear, there are many steps that can be taken to further this process. Better facilitating interdisciplinarity ranges from the personal to the structural and involves making broad-ranging interaction possible, from breaking down physical and divisional barriers to improving diversity.

But as the geographer David Livingstone argues, "It is only when the practices and procedures that are mobilized to generate knowledge are located—sited—that scientific inquiry can be made intelligible as a human undertaking. In important ways, scientific knowledge is always the product of specific spaces. To claim otherwise is to displace science from the culture of which it is so profoundly a part" (2003:86). In the Pacific, the social sciences have gone from being far less common than the Northeast to being more prevalent in central research clusters, more likely to result in radical interdisciplinarity and have a social/hybrid scientist in a key bridging role, and more likely to stress hybridity and participatory engagement (see the "Research clusters and the hybrid scholar" section).The differing emergence of a hybrid and participatory scholar in particular speaks to the contrasting ways that the social sciences have integrated into collaborative networks in the two regions, and speaks to the place-based differences that permeate the practices of fisheries science. Place "enables copresence" of "people, instruments, specimens, and inscriptions" (Henke and Gieryn 2008:356), which in the case of fisheries science intrinsically involves not just stocks of fish but also the potentially-participatory ground of encounters with fishing

Table 5 Likert questions with statistical significance of $p < 0.1$

	p-value		Strongly agree	Agree	Neutral	Disagree	Strongly disagree
I have opportunities for informal interaction at work that positively impact my engagement in interdisciplinary research	0.067	Northeast	20.6	52.9	13.2	11.8	1.5
		Pacific	9.1	45.5	33.3	9.1	3.0
My involvement in groups or other formal activities external to NOAA is an important factor in my engagement in interdisciplinary research	0.097	Northeast	39.7	45.6	10.3	4.4	0
		Pacific	30.3	36.4	24.2	9.1	0
	0.038	Natural Science	39.5	44.4	12.3	3.7	0
		Social Science	22.2	38.9	22.2	16.7	0
I find that differences in research norms between disciplines is a barrier to engaging in interdisciplinary research	0.010	Natural Science	0	18.5	24.7	49.4	7.4
		Social Science	11.1	38.9	16.7	33.3	0
It is difficult to determine the quality of work in an unfamiliar field	0.088	Northeast	4.4	27.9	38.2	27.9	1.5
		Pacific	9.1	45.5	0	24.2	21.2
In my experience with interdisciplinary work, my expertise is often sought after important research decisions have been made	0.036	Natural Science	4.9	22.2	42.0	27.2	3.7
		Social Science	5.6	50.0	27.8	16.7	0
	0.089	BA/BSc	0	50.0	33.3	16.7	0
		Prof. degree	0	100.0	0	0	0
		MA/MSc	6.7	30.0	43.3	20.0	0
		Phd	4.8	19.4	40.3	30.6	4.8
I am aware of the research being done by other groups at my Science Center	0.013	Female	2.3	29.5	34.1	22.7	11.4
		Male	11.3	41.5	28.3	13.2	5.7

communities and the broader public inherently imbricated in management, policy, and science.

The two regions inherit a different legacy of such co-presence. While the Northeast was the first to expand social science expertise beyond economics, with anthropologists employed as early as the 1970's (Abbott-Jamieson and Clay 2010), the region was also forced much earlier than other regions to reckon with declining fish stocks and reducing fishing effort in the wake of several centuries of "expansion, industrialization, capitalization, and overexploitation" in the region (McKenzie 2012:293). Highly contentious allocation debates—and an accompanying need for economic and social impact assessments—associated the social sciences with the regulatory apparatus. The emphasis on impacts also invoked a particular use of the social sciences that framed communities as passive sites being impacted rather than proactive participants in fisheries (Olson 2005). A history of both talking past each other (M. Estellie Smith's classic 1990 work was based on the New England Fisheries Management Council) and entrenched mistrust between fishermen and federal fishing authorities has also colored faltering attempts at collaborative work with stakeholders in the region (Johnson and McCay 2012).

Oral histories with scientists in the Pacific, however, have touched on a different legacy: a beginning which involved working closely and cooperatively with local fishermen in research, development, and exploration in what one scientist called "a synergy, a symbiosis" between the two—in sharp contrast to contentious fishing effort reductions in the Northeast (Olson and Pinto da Silva 2019:376)—and which continues in contemporary experiences in Hawaii involving participatory citizen-based science with "diverse, very passionate" and highly involved communities (Olson and Pinto da Silva 2020:53). As Verwoerd et al. (2022) write, such an organizational context is not a "passive backdrop" but rather is an active ingredient in any movement towards co-production of knowledge. As a former Pacific social scientist explained, key players in the region equated fishing with culture, tying its future to cultural survival. In this context, social scientists were "well received" by fishing communities, viewed as "allies helping to tell their story." Organizational boundaries that kept social scientists separate from the regulatory apparatus and impact assessment, and focused on research, also contributed to their reception as "impartial scientists" not aligned with a particular agenda. The PIFSC has also had social scientists in early leadership roles, who increased exposure to the social sciences at a wider organizational level, insisting research programs actively seek out and integrate social sciences. As one former leader described, natural scientists in the large PIFSC coral reef program, for example, had "much broader exposure to social scientists" and the "sustainability paradigm," and their lack of direct involvement in fisheries management "gave them latitude to work on the human side." While there is an element of serendipity to having the right person at the right time, such hybridity is also the result of actively seeking such perspectives through interdisciplinary hires and changing group dynamics to make, as another informant explained, "seeking out different perspectives second nature," what (Barry et al. 2008:25–26) term an interdisciplinary "logic of ontology" that enables creative hybrids more open to inventive recombination.

Conclusion

Interdisciplinarity is increasingly identified as critical to realizing sustainable futures, but it is not an unambiguous notion, ranging from collaboration between closely aligned disciplines to more radically interdisciplinary efforts involving both the social and natural sciences. Fostering collaboration, particularly more radical forms of interdisciplinarity, involves building awareness, enabling interaction, and providing a firmer and better supported institutional scaffolding for integrated approaches in not only scientific practices but also the regulatory structures they inform. As surveyed scientists make clear, interaction and integration involve physical dimensions, such as shared meeting spaces; institutional ones, like hybrid offices and divisions; conceptual interactions, such as shared integrative frameworks like ecosystem-based management; and intellectual interaction, such as enhanced awareness.

Such practices reinforce the importance of attending to the interplay of knowledge production and the context in which it is produced. An intense pressure to provide management-driven analyses in the Northeast has arguably precluded the messy reflexivity demanded of a more participatory and fluid science-policy interface (Olson and Pinto da Silva 2020:50; see also Arnott and Lemos 2021), and found itself reflected in differing degrees of radical interdisciplinarity. We should be clear that there has long been engagement in such work in the Northeast (e.g., Clay and McGoodwin 1995; Pinto da Silva and Kitts 2006); the issue is whether such wholesale rethinking happens in conjunction with traditionally dominant approaches, and the contextual factors that play a role in enabling such radical interdisciplinarity. Work in bioeconomics, for example, was revolutionary in its combination of population dynamics and economic modelling, but nonetheless the two approaches share a theoretical concern with productivity and a mathematical representation of such processes. More current examples of social-ecological systems modelling, such as participatory modelling (Sterling et al. 2019) or biocultural indicators (Dacks et al. 2019), not only embody radical interdisciplinarity in their synthesis of natural and social sciences but arguably reflect a more profound rethinking of the environment and of environmental problems more generally (cf. Weszkalnys and Barry 2013).

There is no one-size-fits-all experience of interdisciplinarity, making it critical to recognize and account for how the co-evolution of science and context involve path-dependencies that impact the import of different perspectives. Without such awareness, one risks reproducing, for example, prior legacies that reductively frame the role and value of different disciplines, such as the social sciences. It is only by reflecting on these experiences that we can better prepare, plan, and engage in support of more participatory and engaged scholarship that meet ongoing challenges for more sustainable futures. If fisheries science requires integrated and diverse perspectives to truly engage with its multifaceted remit, fostering such diversity requires cognizance of the diverse contexts in which science is produced and practiced, and the social relations of which it is intimately a part.

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Data availability The bibliometric data underlying this article are available from the Northeast (https://www.fisheries.noaa.gov/new-england-mid-atlantic/science-data/northeast-fisheries-science-center-publications) and Pacific Islands (https://www.fisheries.noaa.gov/resource/publication-database/pacific-islands-fisheries-science-center-publications-database) Fisheries Science Center publications offices. Survey responses and any personally identifiable information cannot be shared publicly to ensure privacy of participants. Such data may be shared on reasonable request to the corresponding author.

Declarations

Competing interests The authors declare no competing interests.

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