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Food for Thought

Science, social networks, and collaboration: an analysis of publications in fisheries science from 1990 to 2018

Julia Olson [1] and Patricia Pinto da Silva[2]*

[1]Independent researcher, c/o Environmental Assessment Services, 350 Hills St., Richland, WA 99354, USA
[2]Social Sciences Branch, Northeast Fisheries Science Center, 166 Water Street, Woods Hole, MA 02543, USA

*Corresponding author: tel: +1 508 495 2000; fax: +1 508 548 2649; e-mail: patricia.pinto.da.silva@noaa.gov.

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Understanding the nature of collaboration underpinning scientific work in fisheries is critical to building the social foundations for effective scientific progress in addressing complex socio-ecological systems. We examine the nature of interdisciplinary work in fisheries through an analysis of nearly three decades of peer-reviewed papers authored by researchers affiliated with NOAA Fisheries' Northeast Fisheries Science Center in the United States. Using social network analysis, and approaches novel to scientometrics such as grounded theory building, we map and analyse the relationships between authors of different disciplinary backgrounds, visualize these changing networks over time, and evaluate the nature of collaboration with a particular emphasis given to the integration of the social sciences. Our analysis suggests that areas of research such as ecosystem-based management and climate change have helped create synergies between the natural and social sciences, pointing to the importance of organizational changes promoting multiple perspectives, the institutionalization of integrated approaches, and openness to diverse understandings.

Keywords: interdisciplinary, multidisciplinary, transdisciplinary, scientometrics, social network analysis, sustainability science

Introduction

Fostering interdisciplinarity is increasingly seen as key to more sustainable futures in fisheries. Interdisciplinarity, as the "emblematic recombinant process", fundamentally involves the novel combinations of previously unconnected ideas and is precisely where breakthroughs in science more often occur (Fortunato *et al.*, 2018, p. 2). To this end, a variety of efforts have directed attention to how to better encourage and support fisheries scientists engaging in collaborative work, with recommendations ranging from better training, enhanced mentorships, to more emphasis on teamwork (e.g. Drakou *et al.*, 2017; Andrews *et al.*, 2020). But interdisciplinarity is not a singular notion and itself requires some unpacking, in terms of both who does or does not collaborate and how this has changed over time. We see this as particularly important for understanding the role of the social sciences within fisheries work, for while a tight co-occurrence of topics and persistent underrepresentation of the human dimensions persists within fisheries journals overall (Syed *et al.*, 2018), the need to address fisheries as complex socio-ecological systems is increasingly recognized (Berkes, 2012; Degnbol *et al.*, 2006; Drakou *et al.*, 2017; Hare, 2020).

Such recognition also manifests itself in such policy directives as the explicit recognition by the United Nations of livelihoods and societal benefits in its marine sustainability goals (U.N., 2020), to its related guidelines for small-scale fisheries that promote social development and human rights goals (F.A.O., 2015).

Likewise, changes to fisheries management in Canada have explicitly articulated the needs of indigenous and inshore communities (D.F.O., 2019), just as the European Union Common Fisheries Policy has increasingly directed funds and attention to the support of community development (E.C., 2018). All these initiatives critically hinge on interdisciplinary knowledge and understanding that bridge the social and natural sciences. Of course such changes are not isolated to fisheries nor are they entirely new. The United Nations, for example, significantly incorporated human dimensions into its work on sustainable development over thirty years ago in its well-known Brundtland Report (Brundtland, 1987). Likewise, practitioners in international development have for some time recognized the need for participatory methodologies that centre on local values and understandings (Chambers, 1997). There are many other examples, but in all these various efforts, more complex ideas about what knowledge counts in making a difference have emerged.

Understanding how and why such scientific practices in general have changed over time has seen increasing interest from a variety of scholars. Science, many argue, is now undertaken through increasingly interdisciplinary, private–public, and international collaborations, along with greater concern for societal relevance and participation (e.g. Jasanoff, 1990; Funtowicz and Ravetz, 1993; Gibbons *et al.*, 1994; Etzkowitz and Leydesdorff, 2000). For sustainability sciences in particular, addressing problems rather than academic disciplines per se has become a clarion call for moving “knowledge to action” (Kates, 2011) and achieving effective “solution sciences” (Doubleday and Connell, 2020). Though scholars of scientific practice have long noted its social underpinnings (e.g. Pickering, 1993), a specific interest in the networks of and relations between scientists has found expression in the fields of bibliometrics and scientometrics (Wagner *et al.*, 2011). Through primarily statistical and social network analyses, this burgeoning interest in a “science of science” has not only charted changing dynamics in collaborative practices but also generated interest in how to use such knowledge to enhance scientific work and creativity (Fortunato *et al.*, 2018).

But while calls for increasing interdisciplinary analysis often touch on the need to involve both the natural and social sciences, a clearer sense of who tends to collaborate or not is often lacking. Moreover, the standardized categories often used in bibliometric databases can be non-specific and ambiguous, the predetermined categories typically used often lack applicability to the questions at hand, and inclusion of social sciences is generally less developed than natural sciences (Wagner *et al.*, 2011, p. 24). To address these limitations, we sought to examine the changing nature of interdisciplinary work in fisheries science over time through a detailed and more tailored inspection of connections among and between researchers from different disciplines, using papers published from 1990 to 2018 by scientists at a governmental research organization in the United States focused on marine science. As we describe in greater detail in the next section, our focus on scientific publications from one of the science centre arms of NOAA (National Oceanic and Atmospheric Administration) Fisheries provides a unique lens from which to understand how the collaborative practices and research priorities of a community of scientists evolved in response to changes, such as the 1996 Sustainable Fisheries Act, that necessitated greater attention to social and economic issues.

Such reflexive examination helps not only to situate the past challenges and concerns motivating scientific work but also to inform future paths for collaborative focus, especially for governmental scientists entrusted with sustaining complex socio-ecological systems. To describe the characteristics of interdisciplinary collaboration and more fully account for the social sciences, we approached the limitations in bibliometric analysis from standardized databases by coupling the qualitative techniques of grounded theory building with the quantitative methods more common in bibliometrics. Our expectation was to observe the trend of increasing interdisciplinary output in fisheries science seen in scientific work generally, but we also sought to explore whether there was more wide-ranging involvement of different disciplines, and especially of social sciences, in newer fields like climate change and ecosystem-based fisheries management (EBFM), where the policy needs for a multifaceted approach, and the institutional scaffolding to support it, have been strongly articulated from their inception. Indeed with climate change intensifying impacts to fisheries and the communities dependent on them, and at the same time sharpening the trade-offs inherent to EBFM, critical self-reflection on collaborative potentials in fisheries science has a renewed urgency.

Background: motivations, setting, and limitations

This paper draws its inspiration from previous work analysing a collection of oral histories of fisheries scientists that explored the changing nature of scientific practice (Olson and Pinto da Silva, 2019, 2020). The scientists interviewed were all employed or formerly employed at NOAA Fisheries, at centres of marine science across the United States. NOAA Fisheries (also known as the National Marine Fisheries Service) is the US federal agency responsible for managing the nation’s oceanic resources and habitat in the 200-mile Exclusive Economic Zone. As the majority of these oral history interviewees were at or nearing retirement, their reflections underscored significant changes in organization and legislative mandate at NOAA Fisheries, and their impact on research priorities and fisheries science. Increasing demands for greater policy relevance, for example, encouraged emphasis on assessment and modelling, often at the expense of more basic science. At the same time, legislative changes moved increasingly towards an ecosystem-based approach and introduced standards that, among other things, mandated greater consideration of social, cultural, and economic impacts.

In the midst of these changes, oral history interviewees frequently noted increasing collaboration among disciplines and proffered reasons for this change, from the push of budgetary constraints to the pull of newly emerging “wicked problems”—or greater understanding of existing ones—that demanded a newly collaborative approach to their investigation. Other interviewees noted increasingly diverse kinds of scientists with whom they worked, in part catalyzed by new legislative mandates but also mirroring an increasing consensus in fisheries science on the need for better integration of social, economic, and ecological perspectives. Indeed research directed more squarely at answering why researchers collaborate has similarly indicated such factors as increasing specialization (Barnett *et al.*, 1988), intrapersonal factors valuing openness and diversity (Stokols *et al.*, 2008), proximity and support (Birnholtz, 2007), and institutional facilitation (Ponomariov and Boardman, 2010).

Yet despite frequent reference to interdisciplinarity in the oral histories, its exact meaning was often unclear. In the literature on collaboration, of course, such words have precise meaning: multidisciplinary is the juxtaposition of different disciplines, interdisciplinary the integration of them, and transdisciplinary transcendence beyond separate disciplines (Wagner *et al.*, 2011, pp. 15–16). Our interest was piqued, however, by seeing work that involved closely aligned disciplines labelled interdisciplinary by the oral history interviewees just as readily as work seeking to integrate radically different theories, methodologies, and orientations. As social scientists working in what is still a primarily natural science organization, we were thus keen to tease apart a fuller accounting of collaborative work in practice. We were particularly interested in work in which both social and natural sciences contributed because collaboration across often quite distinct perspectives is especially difficult, but also due to its pressing need in the social–ecological context of fisheries science and management.

We focused our study on the scientific output of the Northeast Fisheries Science Center (NEFSC), one of the six regional Science Centers in NOAA Fisheries. This was in part to keep a highly labour intensive project to a manageable size while also allowing a large enough temporal dimension to capture changes in practices. While this immediately raises the question of representativeness, a number of factors point to greater applicability. Governments are often major producers of fisheries science, in part because of managerial responsibilities but also from the filtering down of priorities to others dependent on funding, such as academic institutions. NEFSC's precursor was established in 1871, making it the oldest governmental institution in the United States dedicated to marine science. Current fisheries include some of the most valuable and highest volume in the nation, involving stocks deemed both overfished and sustainable. NEFSC staff have been involved in national and international scientific endeavours for decades, ensuring participation in issues affecting fisheries worldwide. While NEFSC conducts scientific research in an area delimited by New England and the Mid-Atlantic, it comprises different laboratories engaged in diverse topics, capturing different aspects of fisheries science. The main laboratory is in Woods Hole, Massachusetts (home of stock assessment and social science staff), with other laboratories in Orono, Maine (salmon studies); Narragansett, Rhode Island (oceanographic research); Milford, Connecticut (aquaculture science); and Sandy Hook, New Jersey (ecological research). At the same time, however, NEFSC was the first in NOAA Fisheries to hire sociocultural staff, beginning in the 1970s and with permanent staff by the early 1990s (Colburn *et al.*, 2006; Abbott-Jamieson and Clay, 2010), making it particularly well placed to examine the impact of hiring staff in new disciplines. Thus, our starting point in 1990, together with nearly three decades of publications, allows capture of changes in research output occurring generally in fisheries science but also in conjunction with significant organizational changes, namely the sweeping changes to fisheries management with the reauthorization of the Magnuson-Stevens Fishery Conservation and Management Act in 1996 (which formalized the inclusion of human dimensions into management) and growth in the number of social scientists (Supplementary Tables S1 and S2).

A number of recent studies have also directed bibliometric tools to understanding changes in fisheries science content (e.g. Aksnes and Browman, 2016; Syed *et al.*, 2018) and collaboration (Syed *et al.*, 2019), using databases such as the Science Citation Index to delimit fisheries-specific journals. While such databases provide immediate access to many key journals, a significant disadvantage is that the pre-selection of fisheries journals weighs heavily towards the natural sciences and effectively precludes asking the very questions in which we were interested. Another difficulty in accounting for both natural and social sciences stems from different norms around authorship, for example, with single-authored monographs common in many social sciences especially in academic settings (with collaborative input more likely accounted for in acknowledgements). Indeed any of the various methods and sources used in bibliometrics have their own limitations, such that which to use is less about avoiding those weaknesses per se than about suitability for the topic at hand (e.g. Aksnes and Browman, 2016, pp. 1004–1005; Syed *et al.*, 2018, pp. 644–666). As our research question focused specifically on interdisciplinary collaboration and the practices and processes involved in knowledge production, we examined co-authorship specifically (Schummer, 2004, p. 437; Porter *et al.*, 2007, p. 121) through a focus on a "community of practice", rather than a more "top-down" approach limited by predefined categories and journals (cf. critique in Syed *et al.*, 2018). Drawing on anthropological notions of "situated learning" that emphasize learning-by-doing in social interaction, the notion of communities of practice stresses how groups defined by commonality deepen knowledge through their very interaction (Lave and Wenger, 1991; Brown *et al.*, 2016). Indeed, given suggestions from scientometrics that natural scientists engage in more collaboration than social scientists due to institutional co-locations in research teams (De Stefano *et al.*, 2011, p. 1092), our focus on a multidisciplinary community of practice allows specific consideration of such claims and better ensures consideration of the full variety of scientific output produced by both natural and social scientists during the course of meeting obligations to sustain complex socio-ecological systems.

We should be clear that we are not suggesting that only interdisciplinary research is important. On the contrary, writing for and publishing in a single discipline is critical for many reasons, such as testing out new ideas resting on specialized knowledge, seeking validation by one's scholarly peers, and more fundamentally, the need for basic knowledge and understanding that ultimately undergirds interdisciplinary collaboration in the first place. Disciplinary research is also especially important at particular moments in a career trajectory, for example, for a new scholar publishing individual work done in the course of degree attainment. But the recognition that natural resource management is not removed from the human experience but rather involves interconnected and dynamic socio-ecological systems—that an endeavour such as fisheries science is inherently natural *and* social—means its scientific underpinning should encourage a variety of scientific approaches that can contribute to interdisciplinary, multidisciplinary, and transdisciplinary efforts.

Methodology

Assembling the database

We began with a dataset that collated publications by all NEFSC scientists by year for 1990–2018. Publication lists recording all scholarly publications by NEFSC employees are produced annually by the NEFSC publications office. The lists include basic reference material such as author, title, journal, and so on. We excluded grey literature, such as NOAA Technical Memoranda, for though it often contains assessment results and scientific work, it also includes database descriptions, workshop proceedings, methodologies, and works in progress, some of which is later published in scholarly journals. The dataset was further cleaned to remove work that was not peer-reviewed research, such as book and software reviews, obituaries, and so on. The finalized dataset contained 2188 unique documents, which includes book chapters in addition to journal articles. The exclusion of grey literature may raise the question of bias, for it is difficult to assess whether there is any differential representation of particular kinds of work in the excluded literature, such as interdisciplinary work, or the extent to which such work is later published. Nonetheless, the rationale for using peer-reviewed publications to assess interdisciplinary collaboration is widely accepted in bibliometric studies, despite acknowledged limitations in capturing all of the varied forms of influence on scientific work (Melin and Persson, 1996, p. 364; Wagner and Leydesdorff, 2005, p. 189). Publications are used so commonly in bibliometrics in part because of their very importance to scientists, with impact and reputation hinging directly on them. Coupled with the sustained and active involvement that co-authorship entails, and the need especially acute in a resource management context to not just bridge but to articulate those connections, research articles are arguably an ideal proxy for charting changes in interdisciplinary collaboration.

The next step involved creating a list of unique authors. Since the database provided author names with initials instead of full names, each article was examined and full name, where possible, confirmed and institution recorded. This allowed us to, for example, separate as unique individuals those authors who might share the same initials and combine a given author whose name appeared in inconsistent ways, for example, with or without non-English characters. Since NEFSC publications include co-authors in many different institutional locations, the full list of authors and their disciplines contains all co-authors, wherever their institutional location. NEFSC-based authors accounted for over one-third of co-authorship in the database, and they commonly co-authored with scholars based at academic institutions (primarily in the United States but with a significant international component) and also other governmental agencies (Supplementary Table S3). We made no distinction in author order, the norms for which vary between different disciplinary conventions. Likewise, although limitations associated with assessing the true extent of authorial input have been noted in the bibliometric literature (Ponomariov and Boardman, 2016), NEFSC publication standards provide clear guidelines that active and substantial involvement defines authorship (Gibson *et al.*, 2003).

Using the unique author-institution list of 3699 individuals, we began an extensive online search on each author for information about disciplinary affiliation. While some studies have determined discipline primarily by departmental affiliation (e.g. Schummer, 2004), such an approach would have been insufficient for this study as governmental scientists typically lack the disciplinary-based departments found in universities. Sources included: ResearchGate (https://www.researchgate.net/), university and other profile pages, LinkedIn (https://www.linkedin.com/), Google Scholar (https://scholar.google.com/), ORCID (https://orcid.org/), Gulfbase (https://www.gulfbase.org/), obituaries, past directories of marine scientists, and occasional publications in which personal history was described. In early stages of this process, we used self-identified disciplinary topics found on ResearchGate profiles from a subset of authors to create a provisional discipline list based on common clustering of topics. For example, ecology, marine biology, and zoology, or ecology and marine biology, were commonly chosen by authors labelling themselves fisheries or marine biologists. Later this discipline group was expanded to include marine ecology, due to such frequent overlap that distinction was difficult. As additional information on each author was gathered, the overall discipline list was gradually revised, expanding or contracting iteratively as an overall picture emerged. Every attempt was made to corroborate a disciplinary affiliation across multiple sources of information.

The difficulty in reliably ascertaining author disciplinary background, and the intensive time and labour involved in assembling such information, has reduced the appeal of co-authorship analyses, though other bibliometric measures are no less prone to ambiguity (Melin and Persson, 1996; Wagner *et al.*, 2011, p. 19). But we view the inductive process we used as analogous to the process in social science research known as grounded theory building, in which ideas are formulated and reformulated as the researcher moves back and forth between data and theorizations (Corbin and Strauss, 1990). We fully recognize the degree of uncertainty and potential arbitrariness in the data categories used. As social scientists are often keen to point out, boundaries are fluid and disciplinary boundaries are no exception. The clustering of disciplines that made sense for this community of practice—centred as it is on fisheries and marine sciences broadly conceived—implies that a different community might yield different groupings. Also, fundamental to our approach lay our view that while a given scientist is not so much strictly bounded by a discipline, the particular tools, methods, and knowledge of a corpus of literature only come from a long and deep study in a particular subject. Thus while scientists working in such a multidisciplinary context as fisheries science and management often come to learn from other people and seek their input, understanding the value of different perspectives and knowledge is quite different from actually possessing that knowledge and knowhow itself. Although a time-intensive process, we were helped in part by being participants ourselves in the very milieu we were documenting, as both authors are or have been employed in the Social Sciences Branch of the NEFSC for a majority of the time under analysis. Thus, a core group of authors was known to us directly or indirectly. Because of these connections, we were also able to ground truth our methods by asking a subset of colleagues to review the discipline to which they and their co-authors had been assigned. Only one relatively minor change was suggested (from Ecology and Evolutionary Biology to Fisheries Biology). In the end, thirty-three disciplines were defined, with 313 (out of the 3699) author disciplines based on institutional affiliations due to a lack of additional information and 15 remaining unknown (Table 1). It was necessary to restrict authors to a single discipline at any particular moment in time, in order to facilitate the relational analyses that we describe below. However, the disciplinary groupings broadly capture many commonly overlapping specialities, and any author fundamentally changing their discipline in the database time-frame would be accounted for.

Social network, factor, and content analysis

We combined the publication and author datasets into a rectangular 2188 × 33, 2-mode incidence matrix, with a unique article on each row and disciplines arrayed across columns. The digit in each cell represented the total number of co-authors of that article associated with a given discipline, using the integer counting method instead of binary (presence–absence) data more common to social network analyses (Wagner and Leydesdorff, 2005, p.

Table 1. Discipline grouping with author counts.

Discipline groupings	Abb.	Type	Author* pubs	%	Unique authors	%
Fisheries and marine biology/ecology	FISH	Natural	4 490	47.7	1 560	42.2
Oceanography	OCEAN	Natural	1 468	15.6	494	13.4
Zoology, taxonomy, morphology/anatomy	ZOO	Natural	469	5.0	123	3.3
Microbiology, molecular biology, genetics	MICRO	Natural	364	3.9	218	5.9
Economics	ECON	Social	265	2.8	110	3.0
Ecology and evolutionary biology	ECOEVO	Natural	252	2.7	146	4.0
Physiology, neurobiology, endocrinology, chronobiology	BODYREG	Natural	249	2.7	87	2.4
Statistics, mathematics, computer science	MATHCOMP	Engineering and maths	200	2.1	95	2.6
Aquaculture, veterinary sciences, animal health	ANIMAL	Natural	192	2.0	104	2.8
Chemistry, biochemistry	CHEM	Natural	192	2.0	71	1.9
Community and systems ecology	SYSECO	Natural	185	2.0	97	2.6
Wildlife biology and ecology	WILD	Natural	125	1.3	72	2.0
Pathobiology, toxicology, immunology, virology, parasitology, epidemiology	PATHOS	Natural	112	1.2	67	1.8
Quantitative ecological modeling	QUANECO	Natural	97	1.0	25	0.7
Climate and atmospheric sciences	ATMOS	Natural	82	0.9	53	1.4
Geography, remote sensing, GIS	GEOGIS	Mixed	72	0.8	35	1.0
Anthropology	ANTHRO	Social	67	0.7	15	0.4
Hydrology, water quality, environmental engineering	H20ENV	Natural	61	0.7	38	1.0
Agricultural, plant, and soil sciences	AGSOIL	Natural	59	0.6	34	0.9
Physics, optics, acoustics	PHYSIC	Natural	51	0.5	28	0.8
Engineering: mechanical, ocean, civil	ENGMECH	Engineering and maths	49	0.5	28	0.8
Geology, earth sciences	GEOEARTH	Natural	47	0.5	36	1.0
Public policy, law, political science	POLICY	Social	44	0.5	21	0.6
Biogeochemistry	BIGEOCH	Natural	42	0.5	21	0.6
Social sciences	SOCIO	Social	43	0.5	27	0.7
Engineering: electrical, acoustical	ENGELAC	Engineering and maths	38	0.4	18	0.5
Engineering: applied	ENGAPP	Engineering and maths	17	0.2	9	0.2
Unknown discipline	n/a	n/a	17	0.2	15	0.4
Applied: fishermen, boat captains, industry analysts	APPLIED	Applied	14	0.2	12	0.3
Environmental restoration, coastal management	ENVCOAST	Natural	14	0.2	11	0.3
Medicine, public health	MEDPUB	Natural	12	0.1	12	0.3
Archaeology	ARCH	Social	9	0.1	9	0.2
Data visualization, cinematography, photography	VISUAL	Applied	5	0.1	5	0.1
History	HIST	Social	3	0.0	3	0.1

Note: Climate and atmospheric sciences include environmental engineering when related to atmospheric research; biogeochemistry refers to a focus on nitrogen cycling, especially terrestrial systems; fisheries and marine biology/ecology include phycology; geology and earth sciences include geochemistry when related to the past; medicine and public health include biomedical engineering; oceanography includes biogeochemistry when related to oceanography; community and systems ecology refers to a primary focus on system relations and includes aquatic, estuarine, coastal, landscape, and benthic ecology; economics includes industrial engineering; and social science includes sociology and generalist subjects such as marine affairs.

190). We converted this matrix into a symmetrical, 1-mode 33 $\times$ 33 co-occurrence matrix (also called proximity or similarity matrix), with disciplines appearing as both rows and columns and their co-occurrence in the intersecting cell. We did this in two different ways: using the sums of cross-products for an absolute measure and Pearson correlation for a relative measure. As Luukkonen *et al.* (1993) argue, absolute and relative methods are both necessary for a full analysis of social networks for they answer different questions: absolute measures shed light on the centrality of nodes and core-periphery relationships, while relative measures shed light on the "intensity" of relationships. We also repeated this for 5-year increments, dividing the database into six time periods: 1990–1994, 1995–1999, 2000–2004, 2005–2009, 2010–2014, and 2015–2018 to more easily visualize change in collaborative networks over time.

We used the rectangular incidence matrix for factor analyses and the absolute and the relative co-occurrence matrixes for social network analyses, using UCINET (Borgatti *et al.*, 2002) and Gephi for visualization (Bastian *et al.*, 2009). Both factor and social network analysis have emerged as central to understanding interdisciplinary co-authorship. Factor analysis helps pinpoint clusters of strongly related communities, or in this case, of disciplines, where "the elements of the matrix that load upon multiple factors above some preset threshold are considered the most interdisciplinary ... defin[ing] an emergent structure from data based on a set of distances, rather than using a pre-imposed structure" (Wagner *et al.*, 2011, p. 20). Social network analysis, on the other hand, helps understand and visualize the structure and dynamics of relationships (Yang *et al.*, 2016). Measures commonly used to understand network structure include the number of ties between nodes (i.e. disciplines), which shows how active or connected the network is in absolute terms; the average degree, a centrality measure indicating the average of connections; network density, a proportional indication of the extent of interconnectedness, or "information" flow between disciplines; connectedness and fragmentation, which suggest the "reachability" of nodes; and average distance, which indicates their proximity (Borgatti, 2002). Using Gephi to visualize these networks, nodes are coloured by science type and proportional to their centrality degree, with a ForceAtlas 2 layout and its force-directed algorithm spatially representing similarity by closeness in the graph.

Finally, we performed a word frequency count on article titles (the publication database does not include keywords or abstracts), as an elementary indication of change in research content and to compare with trends observed in fisheries science as a whole.

Results

Changes over time in scientific practice and output are clearly notable both in terms of authorial and interdisciplinary collaboration. To begin, the number of co-authors per paper (Figure 1a) has increased significantly over the past three decades. In 1990–1994, many publications had a single author, the vast majority three or fewer, and no publications had more than ten co-authors. By 2014–2018, however, publications with three or fewer authors were the minority, with three papers having >50 co-authors, including one with 72. Likewise, the number of different disciplines involved in co-authored papers has also increased (Figure 1b). In 1990–1994, around half of all publications involved a single author discipline, but by 2015–2019, nearly half of the publications had at least three different author disciplines contributing. Indeed the average number of co-authors has nearly doubled during the 1990–2018 time frame, with the average number of author disciplines nearly tripling (Supplementary Figure S1). Though fisheries biology and marine ecology, other biological sciences, and oceanography continue to dominate research output, a small but increasing presence of social sciences is also evident (Figure 1c). At the same time, the very topics to which research has been directed have shifted; word frequency analysis indicated a change in emphasis from the assessment of individual species to the emergence of new topics, such as climate, habitat, and modelling (Supplementary Figure S2).

To understand which disciplines tend to work together and in what ways they do so, we turn to social network analysis. Figure 2 visualizes network structure in the years 1990–1994 and 2015–2018 using the absolute matrix of co-occurrences. Changes to the density and connectivity of the network of interdisciplinary collaboration, and in particular the changing positionality of specific disciplines, are visibly evident. In 1990–1994, the network is less dense and well-connected, and distinct sub-clusters are more evident, particularly in the social sciences where the discipline of economics performs the role of "gatekeeper" (it should be noted that at this time, NEFSC social scientific staff consisted of one newly hired anthropologist and seven economists; see Supplementary Table S2). But in 2014–2018, more disciplines are central, as both the number and distribution of connections between disciplines have increased; fisheries biology/marine ecology and oceanography are less dominant though still central; and no discipline is connected to the network through a gatekeeper. However, many disciplines continue to skirt the periphery of the total network of collaborations, including a number of social science disciplines critical to the production of work such as fishery impact assessments. These social sciences, not coincidentally with more numerous and diverse staff, are far more integrated than before, with more connections to each other and other disciplines as well. Yet compared to other disciplines they are less connected to the overall network and they remain on the periphery of collaborative work. Indeed, a core-periphery analysis on the absolute co-occurrence matrixes found that Fisheries and Marine Biology/Ecology and Oceanography dominated as "core" disciplines throughout the entire time period. Nonetheless, between 1990–1994 and 2015–2018 the number of ties (i.e. connections) and network density more than tripled, average degree increased fourfold, and connectedness and proximity also nearly doubled, showing how overall research has become more connected and interdisciplinary at a network level (Supplementary Table S4).

Figure 3 visualizes network structure using a relational matrix of co-occurrences computed with Pearson correlation to better realize underlying "network architecture" (Wagner and Leydesdorff, 2005, p. 198). In 1990–1994, the almost complete separation of natural and social sciences is dramatically evident, with economics, anthropology, and other social sciences separate from the rest of the network. Oceanography serves as the key node connecting policy studies and geography, the only non-natural science disciplines in the network (through a number of publications about Large Marine Ecosystems, an early concept in ecosystem-based management). Moreover, there are distinct clusters such as disease and physiological studies, wildlife and coastal studies, and relatively isolated disciplines such as zoology. In the later time period, the higher level of integration of all disciplines is again evident, but the greater integrated presence of some social science disciplines becomes clearer, suggesting meaningful collaboration across natural and social sciences despite the smaller absolute number of socials scientists.

Factor analysis was also performed on the raw co-occurrence matrix for the six time periods. In all time periods, the first ten factors explained between half and two-thirds of variation (Supplementary Table S5), suggesting that disciplinary affiliations fairly accurately capture separate traditions. But distinct research clusters are also evident: namely the tight connections between social sciences found throughout the time period, the independence of fisheries biology/marine ecology, and particular research foci such as aquaculture disease, acoustics, physical oceanography, ecological studies, and quantitative modelling. Moreover, it is in the later time periods that clusters of collaboration involving both natural and social sciences become more evident.

We also looked directly at those publications that exhibited higher levels of interdisciplinary collaboration. A total of 81 publications over the entire time period involved at least one social and one natural scientist collaborating. Each was individually examined and eight research foci identified: fisheries management (both concerning specific regulatory regimes and more general examinations), with 24 papers; ecosystem-based fishery management, 19 papers; bio-economic modelling, 10 papers; climate change papers, also 10 papers; and several smaller topics: marine mammals (6), aquaculture (5), data tools (4), and environmental history (3). Collaboration among researchers with social science and natural science expertise was relatively muted until the final time period, when it increased significantly (Supplementary Figure S3). Management papers appear in all time periods, and EBFM and bioeconomics appear in most, which is unsurprising for a science arm of a management agency. Climate change papers increase in number in the final period especially, also unsurprising given the timeliness of the topic. Bioeconomics is, among social sciences, the exclusive focus of economics and,

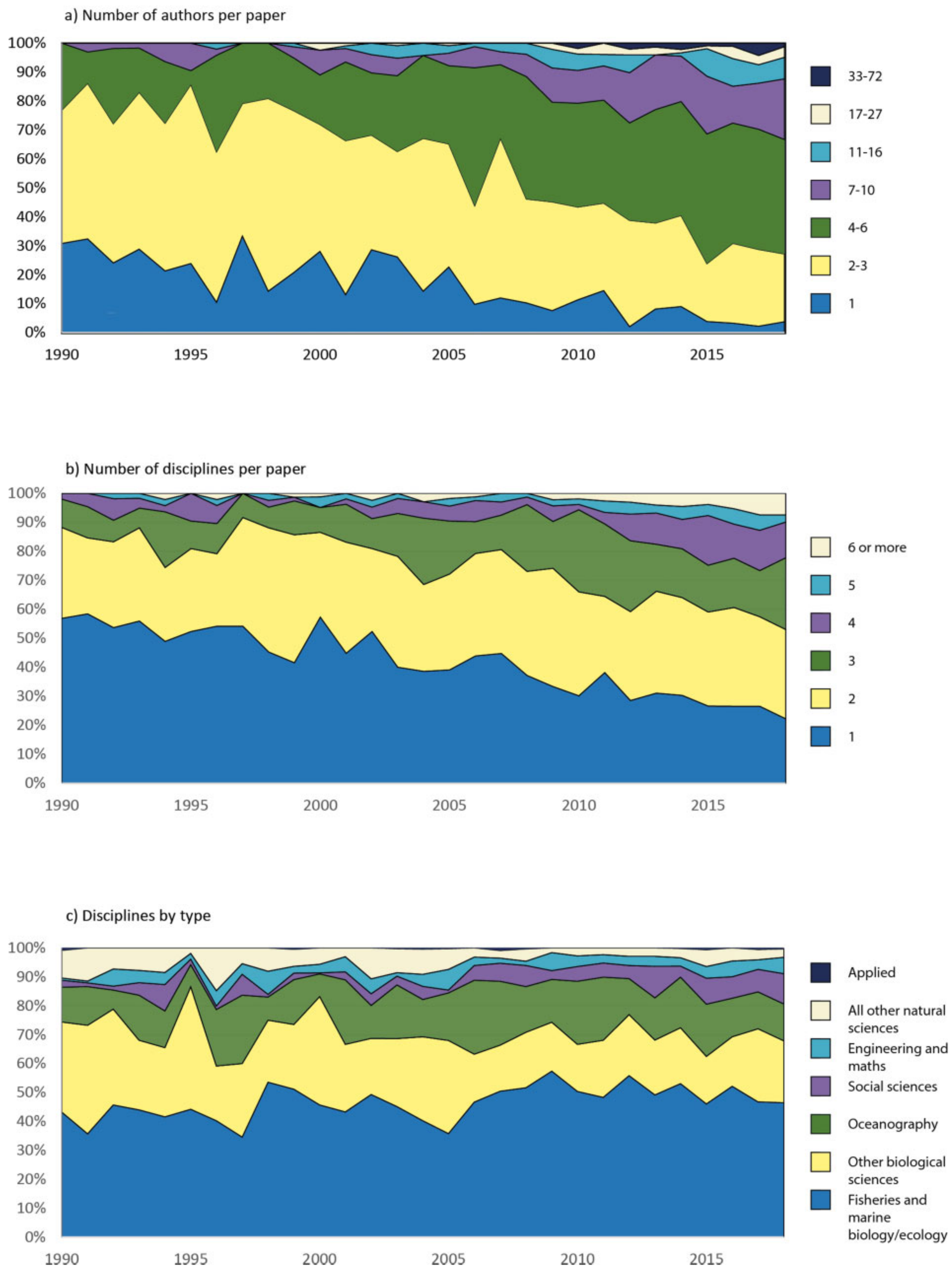

Figure 1. Publications by number of authors, number of disciplines, and disciplines by type, 1990–2018.

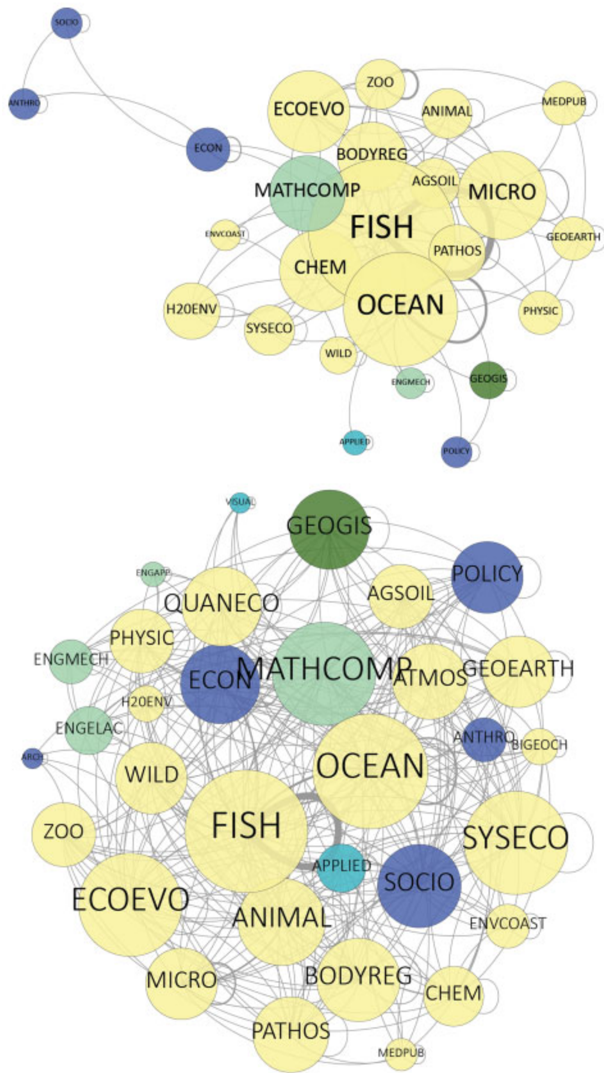

Figure 2. Network analysis of interdisciplinary collaboration on the absolute co-occurrence matrix, 1990–1994 (top) and 2015–2018 (bottom).

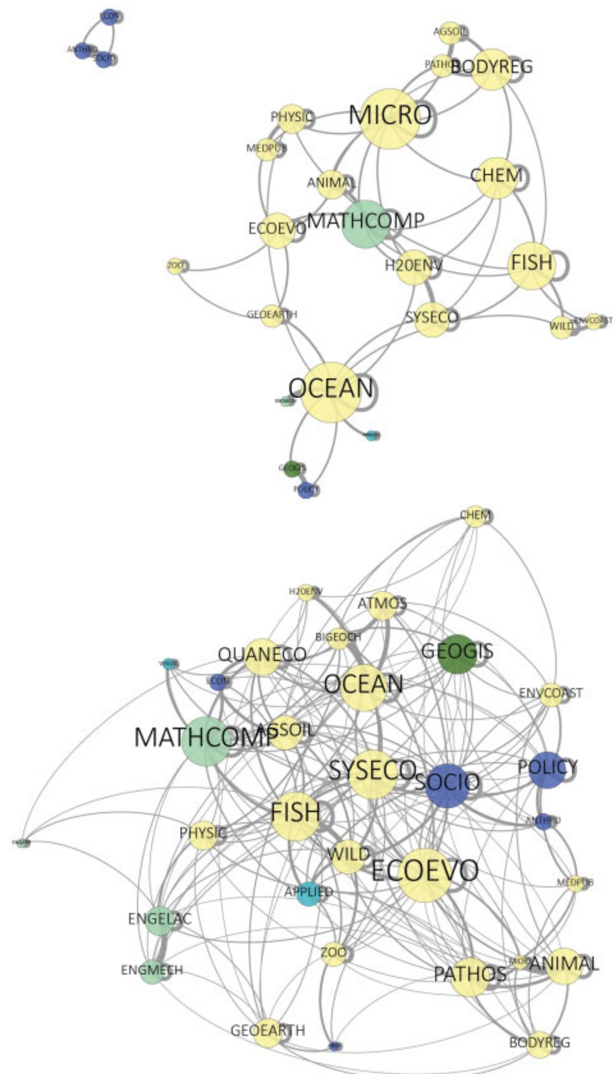

Figure 3. Network analysis of interdisciplinary collaboration on the relative co-occurrence matrix, 1990–1994 (top) and 2015–2018 (bottom).

among natural sciences, heavily dominated by fisheries and marine biology/ecology. A total of four social science disciplines appear in management, EBFM, and climate papers, but only the latter is not dominated by economics. Likewise, climate change papers show a total of 18 natural science disciplines contributing, with none dominating, whereas both management and EBFM papers are dominated by oceanography and fisheries and marine biology/ecology (with a total of 13 and 9 natural science disciplines appearing, respectively). In addition, ten papers had at least two social science and two natural science disciplines contributing. All were published in the last decade (and all but three in the final period), and the majority concern climate change and EBFM (climate change: 4 papers; EBFM: 3 papers; management: 2 papers; data tools: 1 paper).

To examine the collaborative networks characterizing climate change and EBFM specifically, we extracted subsets of papers concerned with these subjects using key climate-related keywords (variations on climate, warming, greenhouse, regime shift, and temperature) and EBFM keywords (ecosystem, ocean planning, and portfolio management). This resulted in 80 articles about climate change and 111 about EBFM, all of which were examined to confirm subject. For climate change, the early time period (using 1993–2003, given no earlier publications) shows the almost complete absence of all but the natural sciences, with only policy studies evident. Both fisheries biology/marine ecology and oceanography are central to the network in absolute terms, along with a number of other disciplines such as atmospheric sciences. But in relative terms, fisheries biology is isolated, and oceanography is the gatekeeper to the more central core of disciplines. In contrast, the later time period shows a far denser and connected network of disciplines participating. Though fisheries biology/marine ecology and oceanography remain dominant, a more diverse range of disciplines both participate and are central, including both social and natural sciences (Supplementary Figures S4 and S5). For EBFM, the contrast is particularly stark. The early time period saw only a handful of disciplines, while in the later time period, though the network is less dense and with fewer disciplines than climate change, the participation of disciplines appears more equivalent. Especially striking is that social science disciplines are almost as numerous and central as biological ones, especially in relative terms (Supplementary Figures S6 and S7).

Discussion

Our concern has been to explore interdisciplinary collaborative networks in fisheries science, looking directly at which disciplines collaborate, whether and how such collaborations have changed over time, and specifically consider the trajectories of emerging topics like climate change and EBFM. We have also sought to explicitly account for the social sciences, critical for addressing complex socio-ecological systems but often poorly specified in scientometrics investigations. Although we have focused our analysis on a particular community of practice, the changes seen at NEFSC mirror general trends in scientific work: scientists are working with greater numbers of more varied collaborators, in the context of widespread changes such as new communication tools and greater computing power (Fortunato *et al.*, 2018). Likewise, a movement from studies on individual species to more processual concerns like modelling has also been found in other fisheries scientometrics (Aksnes and Browman, 2016; Syed *et al.*, 2018). These trends are part and parcel of the very changes in scientific production we noted earlier: greater concerns for expanding perspectives and understandings, for relevance, and for action (Jasanoff, 1990; Funtowicz and Ravetz, 1993; Gibbons *et al.*, 1994; Etzkowitz and Leydesdorff, 2000; Kates, 2011; Fortunato *et al.*, 2018; Doubleday and Connell, 2020). At the NEFSC, such changes have manifested themselves in an institutional widening increasingly driven by the need for policy-relevant information. From an overriding focus on basic research concerned with fisheries biology, other traditions—such as the social sciences—now increasingly play a part (Olson and Pinto da Silva, 2019, 2020).

Network analysis helps specify how collaborative networks of scientists have changed as a result, and scientific output at NEFSC clearly indicates increasing ties between disciplines, greater connectivity, and less isolation and fragmentation. These results mirror Syed *et al.*'s recent study of co-authorship among fisheries scientists, with the exception of their finding that network density (at an individual level) had decreased. This, they suggest, indicates "collaborative silos" in which knowledge exchange is constrained (2019, pp. 846–847) through repeat collaboration with the same co-authors (2019, p. 849). But our focus on a community of practice, instead of a set of fisheries journals, gives a window into local dynamics that might otherwise be obscured. At the disciplinary level of our analysis, the tripling of density measures points instead to greater exchange of ideas among different disciplines, important as densification "at the boundaries" can "signal ... transdisciplinary exploration, fusion, and innovation" (Fortunato *et al.*, 2018, p. 2). For example, NEFSC networks in the 1990–1994 period showed sub-networks characterized by gatekeeping, a notion in network analysis for understanding the flow of knowledge and information between nodes. Gatekeepers can control access and shape the network. Though knowledge exchange is not limited to co-authorship relationships, it points to important dynamics. Overall, the picture reinforces how the dearth of sociocultural staff in particular manifested itself in a lack of connectivity of such perspectives to other research. Conversely, although fisheries biology and oceanography continue to dominate the network, the picture of denser and more varied collaboration arguably reflects in part organizational changes that created new potential pathways for interdisciplinary collaboration. These range from new regulatory requirements to utilize social sciences and the authorization of funding lines to hire such expertise, as well as visionary leadership that was even earlier willing to support and invest in such changes (Colburn *et al.*, 2006; Abbott-Jamieson and Clay, 2010).

But a specific focus on the social sciences reveals that while papers representing collaboration between natural and social scientists are relatively few, such collaboration has accelerated in recent times and manifested particularly in EBFM and climate change. Such results supported our initial expectations, based on our own involvement in such research. But it also raises its own questions. While social scientists struggled to ensure that humans were seen as part of the ecosystem in early EBFM work, this is little different from the early argument that fisheries management concerns managing people and not fish. And though important collaboration between disciplines occurs in the context of fisheries management, with bioeconomics being a clear example, both EBFM and climate change work indicate far deeper and more extensive collaboration. What accounts for the difference? As Brown *et al.* (2016, p. 236) argued in their examination of communities of practice in carbon cycle research, social network and content analysis by themselves cannot explain why collaborative networks change, or whether shifts in content reflect broader framings or actual substantive change. Qualitative research could aid understanding of the reasons why scientists do or do not collaborate, while a regional comparison of different groups within NOAA Fisheries might help sharpen understanding of the influence of different organizational structures—with different historical trajectories and different policy foci—as well as the role of geographic place in knowledge networks. But our focus on disciplines does point in intriguing directions.

The early period of EBFM work at NEFSC, especially in LME work, shows the impact of actors in key structural positions (cf. Bodin and Crona, 2009) who were curious about, receptive to, and proactive in seeking multiple perspectives. The social sciences have also been institutionalized into emerging research agendas that have specifically sought integrated ecosystem approaches: the development of groups in ICES such as the Working Group on Maritime Systems (WGMARS) and the Northwest Atlantic Regional Sea (WGNARS), for example, was heavily influenced by social scientists, or natural scientists with a keen interest and willingness to bring in other disciplines, showing the importance of an organizational scaffolding for interdisciplinary and international collaboration in EBFM, especially as more integrated approaches to management and governance develop (DePiper *et al.*, 2017). Other groups with a disciplinary focus, such as WGSOCIAL and WGECON (for social scientists and economists respectively), provide space to encourage the expansion of social sciences in fisheries more generally. In our own experience, a critical factor has been the effort and willingness to understand each other's contributions and, fundamentally, to consider the metaprocesses involved in such collaborations. As Kelly *et al.* (2019) write, such efforts are time-consuming and inherently challenging. Rather than seeking a strict accounting of causality, we see collaborative networks better conceptualized in terms of emerging practices and co-evolved understandings. The similarities with work on adaptive governance systems are striking: building resilient systems requires openness, vision, and trust to find commonality within diverse experiences and knowledge bases; institutions flexible enough to foster learning environments (Folke *et al.*, 2005; Armitage *et al.*, 2009); and robust linkages to resource users (Anderies *et al.*, 2004), implying the need for inclusion of knowledge systems broader than the natural and social sciences alone.

Fisheries science has changed significantly over the past three decades, both globally as well as at NEFSC. But despite greater interdisciplinary collaboration, fisheries science is still dominated by particular disciplines and topics, with the social sciences still underrepresented and under-connected. While disciplinary-specific research critically undergirds interdisciplinary endeavours, integrated approaches are requisite for better sustaining complex socio-ecological systems such as fisheries, and more likely to generate the novel breakthroughs in understanding to do so. Our focus on the social sciences has pointed to areas in which such collaboration has had particular expression, such as climate change and EBFM, and suggested the cooperative spirit and institutional undergirding that help enable such efforts. But a detailed delineation of the disciplines participating in fisheries science also shows us the gaps in our knowledge base. In our own work as social scientists, for example, we see a need to better understand the role of land-sea connections in fostering sustainable resource use and see keenly the lack of specializations in such topics as food systems or the geography of supply chains. There are also important practical implications for management and governance, with previous regulatory modes that considered environmental, economic, and social impacts as important (if not always equal) but separate increasingly challenged by the integrated thinking demanded by socio-ecological assessments and analyses. Continuing reflection about the practices of scientific work, and who remains less connected to collaborative networks, is intrinsic to furthering interdisciplinary understanding in the fisheries world, to which we hope that this article has provided food for thought. Interdisciplinarity is never an afterthought.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Data availability statement

The bibliometric data underlying this article are available from the Northeast Fisheries Science Center publications office (https://www.fisheries.noaa.gov/new-england-mid-atlantic/northeast-fisheries-science-center-publications). Yearly reports are produced as Center Reference Documents (e.g. https://doi.org/10.25923/dav7-kt67). Any personally identifiable information cannot be shared publicly to ensure privacy of participants. Such data will be shared on reasonable request to the corresponding author.

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