Speaking across boundaries to explore the potential for interdisciplinarity in ecosystem services knowledge production

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Abstract: Conservation is likely to be most successful if it draws on knowledge from across the natural and social sciences. The ecosystem services concept has been called a boundary object in that it facilitates development of such interdisciplinary knowledge because it offers a common platform for researchers, policy makers, and practitioners. However, a question that remains is to what extent the interdisciplinary knowledge needed is provided by disciplinary diversity within the field. We asked where is knowledge on ecosystem services produced, how interdisciplinary is this knowledge, and which disciplines facilitate the greatest disciplinary integration? We defined interdisciplinarity as the extent to which published research draws on knowledge that crosses disciplinary borders and used citations as a quantitative indicator of communication among disciplines, based on journal classification. We used disciplinary diversity, richness, and heterocitation as measures of interdisciplinarity and betweenness centrality as a measure of disciplinary integration. Our data set contained 22,153 publications on ecosystem services, published from 1983 to 2018. We found that ecosystem services research matured; average yearly output growth was 33.8%, more than the 8–9% growth in scientific output across all fields. Over time, the network clustering coefficient, measuring connectedness of individual disciplines, rose from 0.388 to 0.727, suggesting increased density in the network of citations. Researchers in the field published more articles (3566 in 2018 alone) across more disciplines (77 unique disciplines in 2018). However, this growth was not mirrored by an increase in the diversity (stable at 0.7–0.9) or richness (averaging 0.35 unique disciplines per citation) of citation patterns. Heterocitation scores, or out-of-group citations, for arts, humanities, social sciences, and law ranged from 56% to 64%, which was lower than we expected, although this may serve to protect the integrity of social science disciplines and attract broader engagement from within. Ultimately, a small number of productive disciplines are central to supporting disciplinary integration. However, opportunities exist for conservation practice to draw on a broader field of research, to realize the potential that the diverse body of knowledge of interdisciplinary work offers.

Keywords: bibliometrics, citation analysis, CytoScape, multidisciplinary, network analysis, publication

Resumen: Es probable que la conservación sea más exitosa si parte del conocimiento que proviene más allá de las ciencias naturales y sociales. El concepto de servicios ambientales ha sido considerado un objeto fronterizo pues facilita el desarrollo de dicho conocimiento interdisciplinario ya que ofrece una plataforma común para los investigadores, los formuladores de políticas y los profesionales. Sin embargo, todavía permanece la pregunta de cuánto del conocimiento interdisciplinario requerido es proporcionado por la diversidad de disciplinas dentro del campo. Preguntamos en dónde se produce el conocimiento sobre los servicios ambientales, cuáles disciplinas facilitan la mayor integración disciplinaria. Definimos a la...
interdisciplinarity as the degree to which the studies published use knowledge that crosses the borders of disciplines and we use as references knowledge indicators quantitatively of the communication between the disciplines with base in the classification of journals. We use the diversity, richness and heterogeneity of references of disciplines as measures of the interdisciplinarity and the centrality of the intermediation as a measure of the integration of disciplines. Our dataset included 22,153 publications on ecosystem services, published between 1983 and 2018. We find that the study of ecosystem services matured; the growth of production annually averaged 33.8%, whereas the growth of 8-9% in scientific production in all areas of study. With time, the coefficient of aggregation of references, a measure of the connectivity between the disciplines, increased from 0.388 to 0.727, which suggests an increase in the density within the network of references. The references with a greater than expected in the diversity (stable at 0.7-0.9) or in the richness (with an average of 0.35 unique disciplines per reference) of the sources of references. The sources of heterogeneity of references, or citations from outside the group, for the arts, humanities, social sciences, and law varied between 56% and 64%, which was lower than expected, even though this might work to protect the integrity of the disciplines from the sciences as a whole. Finally, a small number of disciplines for which productivity is more than doubles overall (IPBES 2019). These declines are caused by people, but also affect them negatively (Ishbel et al. 2017). Furthermore, the ecosystems most vulnerable to decline tend to be where people are most dependent on their environment (Barlow et al. 2018). Effective conservation of biodiversity is therefore a critical concern for both people and nature. However, efforts to stem the loss of biodiversity are failing (CBD 2020), in part due to the need for widespread support from a variety of actors from different backgrounds (Sandbrook et al. 2011, 2013). The ecosystem services concept emerged in the 1980s as an effort to raise support for biodiversity conservation and has since become key to conservation science and practice (Fisher & Brown 2015). In applications of the concept, interdependencies between human societies and ecosystems are captured through the myriad ways biodiversity contributes to human well-being (Mooney & Ehrlich 1997; Mooney & Ehrlich 1997; Haines-Young & Potschin 2010). By considering the linkages between ecosystem functioning and human well-being, ecosystem services research draws on a diversity of disciplines to balance social, environmental, and economic interests (Sachs & Reid 2006). Consequently, ecosystem services has been termed a “boundary object” (Star 1989; Steger et al. 2018), which recognizes its role in providing a common platform for researchers, policy makers, and practitioners from different disciplines and backgrounds to coalesce (e.g., the Intergovernmental Science-Policy Platform on Ecosystem Services and Biodiversity [IPBES] [Díaz et al. 2015] and Ecosystem Services for Poverty Alleviation [Daw et al. 2011]). However, work that crosses disciplinary boundaries is challenging, particularly because disciplines embody very different accepted ways of knowing, doing, and writing (Carter 2007). Furthermore, despite a considerable body of research on ecosystem services in which a diversity of methods has been used (Martín-López et al. 2019) to tackle interdisciplinary topics (Droste et al. 2018), drawing on a diversity of disciplines (Chaudhary et al. 2015), a lack of social science engagement has been identified, limiting interdisciplinary potential (Chaudhary et al. 2015; McDonough et al. 2017; Martín-López et al. 2019). Some further argue that ecosystem services has been co-opted by narrow disciplinary framings, leading to a focus on monetary valuation and payment schemes that commodify nature rather than fulfill aspirations to protect it (Gómez-Baggethun et al. 2010; Kosoy & Corbera 2010; Stoeckl et al. 2018). Consequently, a common understanding among disciplines of what ecosystem services captures is lacking, creating challenges for collaboration and adoption of recommendations in policy and practice (McDonough et al. 2017). Evidently, both supportive and critical evaluations exist of the interdisciplinary scope and achievements of ecosystem services research. However, evaluations have tended to focus on the content of a selection of published articles, leaving unclear the full extent to which disciplinary diversity is reflected across the field. We sought to address this gap by examining all articles on ecosystem services published over 35 years. We used citations to measure the flow of knowledge among disciplines based on the assumption that interdisciplinary...

**Introduction**

Biodiversity levels worldwide are declining at unprecedented rates (IPBES 2019); both terrestrial and marine ecosystems are exposed to the impacts of human-induced climate change, pollution, and overexploitation (Pereira et al. 2012). These declines are caused by people, but also affect them negatively (Ishbel et al. 2017). Furthermore, the ecosystems most vulnerable to decline tend to be where people are most dependent on their environment (Barlow et al. 2018). Effective conservation of biodiversity is therefore a critical concern for both people and nature. However, efforts to stem the loss of biodiversity are failing (CBD 2020), in part due to the need for widespread support from a variety of actors from different backgrounds (Sandbrook et al. 2011, 2013). The ecosystem services concept emerged in the 1980s as an effort to raise support for biodiversity conservation and has since become key to conservation science and practice (Fisher & Brown 2015). In applications of the concept, interdependencies between human societies and ecosystems are captured through the myriad ways biodiversity contributes to human well-being (Mooney & Ehrlich 1997; Mooney & Ehrlich 1997; Haines-Young & Potschin 2010). By considering the linkages between ecosystem functioning and human well-being, ecosystem services research draws on a diversity of disciplines to balance social, environmental, and economic interests (Sachs & Reid 2006). Consequently, ecosystem services has been termed a “boundary object” (Star 1989; Steger et al. 2018), which recognizes its role in providing a common platform for researchers, policy makers, and practitioners from different disciplines and backgrounds to coalesce (e.g., the Intergovernmental Science-Policy Platform on Ecosystem Services and Biodiversity [IPBES] [Díaz et al. 2015] and Ecosystem Services for Poverty Alleviation [Daw et al. 2011]). However, work that crosses disciplinary boundaries is challenging, particularly because disciplines embody very different accepted ways of knowing, doing, and writing (Carter 2007). Furthermore, despite a considerable body of research on ecosystem services in which a diversity of methods has been used (Martín-López et al. 2019) to tackle interdisciplinary topics (Droste et al. 2018), drawing on a diversity of disciplines (Chaudhary et al. 2015), a lack of social science engagement has been identified, limiting interdisciplinary potential (Chaudhary et al. 2015; McDonough et al. 2017; Martín-López et al. 2019). Some further argue that ecosystem services has been co-opted by narrow disciplinary framings, leading to a focus on monetary valuation and payment schemes that commodify nature rather than fulfill aspirations to protect it (Gómez-Baggethun et al. 2010; Kosoy & Corbera 2010; Stoeckl et al. 2018). Consequently, a common understanding among disciplines of what ecosystem services captures is lacking, creating challenges for collaboration and adoption of recommendations in policy and practice (McDonough et al. 2017). Evidently, both supportive and critical evaluations exist of the interdisciplinary scope and achievements of ecosystem services research. However, evaluations have tended to focus on the content of a selection of published articles, leaving unclear the full extent to which disciplinary diversity is reflected across the field. We sought to address this gap by examining all articles on ecosystem services published over 35 years. We used citations to measure the flow of knowledge among disciplines based on the assumption that interdisciplinary...
research draws on knowledge produced in a diversity of disciplines. Specifically, we asked: where is knowledge on ecosystem services produced, how interdisciplinary is this knowledge, and which disciplines facilitate the greatest interdisciplinary integration?

**Methods**

We defined *interdisciplinary research* as research that draws on knowledge from across disciplinary boundaries; we were therefore interested in the flow of information among disciplines (Hicks et al. 2010). Scholarly journals reflect disciplinary traditions in formal communication, working practices, and underlying bodies of knowledge (Becher 1987). Scientific communications, through citation patterns, reproduce cognitive structures that inform a discipline’s research vis-à-vis other disciplines (Vincenot 2018). Therefore, studying patterns of citations among disciplines provides information about the flow of knowledge among disciplines and the extent of interdisciplinary knowledge production (Leydesdorff 2007). We used citations as an indicator of this knowledge flow, assuming that an author cites an article when there is relevant information that informs or supports the new knowledge produced (Garfield 2004; Moed 2005).

We used the Web of Science journal classification scheme (Clarivate 2020) to assign disciplines.

**Where Knowledge on Ecosystem Services is Produced**

To establish where knowledge on ecosystem services is produced, we identified all disciplines, based on journal classification, that have published on ecosystem services over the past 35 years. We focused on 3 periods that reflect key developments in ecosystem services (Chaudhary et al. 2015; Droste et al. 2018): 1983–2000 represents the early years and aligns with the first implementation of Payments for Ecosystem Services schemes in Costa Rica; 2001–2010 represents a period of global uptake and rapid growth in disciplines’, during which the 2005 Millennium Ecosystem Assessment synthesis report was published; and 2011–2018 represents a period of institutionalization and rapid growth in publications and the formation of the IPBES (Chaudhary et al. 2015; Droste et al. 2018). We used the SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, and ESCI databases in the Web of Science (WoS) search engine and the search query “ecosystem services” to identify all articles published in English with this phrase in their keywords, abstract, or title. We identified 26,306 journal articles, published from 1983 through 2018. We exported data on authors, year of publication, journal, and references for all articles, yielding a total of 22,153 complete entries.

Next, we assigned each article and the references cited therein to a research discipline, based on the WoS journal classification scheme, in the R package bibliometrix (Aria & Cuccurullo 2016). The function metaTagExtraction in this package extracts the source (journal) of each cited reference. We used lookup tables and the WoS classification scheme of journal research disciplines (list obtained from Clarivate Analytics Technical Support) to replace journal names with their primary research disciplines. Clarivate allocates journals to 254 subject categories (hereon disciplines) based on journal citation patterns, journal titles, keywords, and user feedback (Katz & Hicks 1995; Clarivate 2020). The category scheme is continuously monitored and managed by editors to maintain relevance and logical content relationships and respond to feedback, particularly on new specialty areas (Boletta 2019). The processes of article submission and peer review and the resulting journal in which articles are published constitute a selection procedure that affects structures of disciplinary knowledge (Leydesdorff 2007). These disciplinary categorizations are thus also shaped by academics. The Clarivate classification scheme is only one approach to classifying journals into disciplines and is necessarily subjective, but provides the narrowest categorization with the highest level of detail available (Clarivate 2020). Notwithstanding shortcomings of such an approach, the existence of an accepted and established system for classifying journals into research disciplines offers a sufficiently robust foundation to evaluate the flow of information among discrete disciplinary groupings.

Finally, we quantified the number of unique disciplines cited in each year and the proportion of those that were STEM (science, technology, engineering, and mathematics) versus AHSSL (arts, humanities, social sciences, and law) disciplines.

**Interdisciplinarity of Ecosystem Services Knowledge**

To establish the interdisciplinarity of knowledge produced in the ecosystem services field, for each discipline we calculated the average richness (number of unique disciplines cited by each article) and diversity of disciplines cited in articles in that discipline. We organized our data by creating an adjacency matrix of citing to cited disciplines in R package igraph (Csardi & Nepusz 2006) and then created an edge list that connected each citing and cited discipline, weighted based on the number of times a discipline had been cited by each discipline. We used this structure for each discipline and year in the complete database to calculate the average number of disciplines cited per article and to calculate the average diversity of disciplines cited per article (Eq. 1) based on Simpson’s diversity index in R package vegan (Oksanen et al. 2017). Simpson index values range from 0 to 1, with 1 being the highest possible diversity. We chose Simpson’s diversity index, over, for example, Shannon’s index of diversity (Dejong 1975) because we were interested in how evenly citations were distributed across the cited
Disciplines Facilitating the Greatest Disciplinary Integration

To establish which disciplines facilitate the greatest disciplinary integration across the field, we used network analysis, based on citation patterns, to examine the flow of information across disciplinary boundaries. For each citing discipline (node) in the ecosystem services network, we calculated a measure of betweenness centrality. Betweenness centrality is a measure of how often a node (discipline) is on the shortest path between 2 other nodes (disciplines) in a network (Freeman 1977). A discipline with a higher betweenness centrality is likely to connect disciplines, through its citations, that are otherwise unconnected and thus potentially to play an important role in the flow of disciplinary knowledge and to have an influence over other disciplines (Freeman 1979). Betweenness centrality has been used for assessing interdisciplinarity in bibliometric analysis because it offers insight into how visible a discipline is in the broader citation network (Leydesdorff 2007; Barnett et al. 2011). This is especially relevant in our study, where we were interested in the flow of knowledge among different disciplines. We used the function NetworkAnalyzer in Cytoscape (Assenov et al. 2008) to calculate normalized betweenness centrality metrics for each citing discipline in each period, based on directed networks (that includes connections from citing to a cited discipline but not vice versa).

We used NetworkAnalyzer again to calculate a network clustering coefficient (average of all nodes) as a measure of density of the entire network. The clustering coefficient is a normalized score that represents the number of edges between a node and its neighbors as a proportion of the maximum number of edges that could possibly exist between a node and its neighbors (Max Planck Institute for Informatics 2014). A network with a higher coefficient tends to be more connected, reducing the influence any individual discipline may have.

We plotted the ecosystem services citation network in Cytoscape with a Prefuse Force Layout algorithm (Shannon et al. 2003; Assenov et al. 2008). To focus on the greatest roles in disciplinary integration, we plotted only those connections that together constituted the top 95% of the total weight of connections for each period. We identified the most important disciplines in facilitating disciplinary integration based on betweenness centrality.

Results

Where Knowledge on Ecosystem Services is Produced

The number of articles published per year that contained the phrase ecosystem services in their title, abstract, or keywords increased rapidly in the last 35 years. The first article appeared in 1983, and in 2018 alone there were 3566 articles (Fig. 1a). With an average yearly growth rate of 33.8% since 2005 (when numbers first exceeded 100 articles), publications on ecosystem services have grown considerably faster than the 8–9% growth identified for scientific output overall (Bornmann & Mutz 2015). Articles on ecosystem services were published by both STEM and AHSSL disciplines. Biology was the first STEM discipline to publish on ecosystem services in 1983 (Ehrlich and Mooney [1983] in BioScience), and in 1997, law was the first AHSSL to publish on ecosystem services (Saltzman [1997] in Ecology Law Quarterly). The number of different disciplines engaging in the field also increased year on year; there were 77 unique publishing disciplines in 2018 (Fig. 1b).
Over the years, environmental sciences and ecology prevailed as key publishing disciplines, along with forestry, environmental studies, multidisciplinary sciences, biodiversity conservation, geography, and biology (Table 1). In terms of relative production, environmental science publications on ecosystem services increased from approximately 14% in the first 2 periods to 22.5% in the most recent period, making it the most productive discipline relative to ecosystem services in the most recent years (Table 1). Ecology’s relative contribution started off high, producing more than 37% of all publications in early years. Its relative output has declined since to 30.3% in the middle period and 20.1% in more recent years. The only 2 AHSSL disciplines in the top 10
productive disciplines were environmental studies and geography. The number of STEM and AHSSL disciplines engaging in ecosystem services research increased; however, the proportion of AHSSL disciplines relative to STEM disciplines, after fluctuating in earlier years due to small numbers, remained relatively stable in more recent years (since 2010) at 10–14% (Fig. 1b).

**Interdisciplinarity of Ecosystem Services Knowledge**

Richness (i.e., the number of unique disciplines cited by each article) of STEM and AHSSL citation patterns remained relatively similar through time; variability between years decreased (Fig. 2a). Although the number of disciplines each article cited and the number of references per article increased through time, the average number of disciplines cited, relative to the number of references in an article, remained around 0.35 since about 2006. In 2018, on average, AHSSL disciplines cited 12.64 disciplines across 43.73 references per article and STEM disciplines cited 12.23 distinct disciplines across 48.93 references per article. Therefore, the number of references seemingly did not bias richness.

The diversity of STEM and AHSSL citation patterns also remained similar through time and variability through time decreased (Fig. 2b). The average diversity of citations in articles published in both AHSSL and STEM disciplines remained high (approximately 0.8) and steady since 2006; although there was greater variance in earlier years for both STEM and AHSSL, most years ranged from 0.7 to 0.9.

The HCS for STEM disciplines remained relatively stable through time, ranging from 7% to 12% (Fig. 3a), indicating 7% to 12% of citations from STEM disciplines were to AHSSL disciplines. For AHSSL disciplines, the heterocitation rate was much higher. Since 2005, it ranged from 56% to 64%, suggesting the majority (>56%) of citations from AHSSL disciplines were to STEM disciplines (Fig. 3a). Prior to 2005, there was more variability in the HCS due to the small number of AHSSL publications (<10).

There were far more STEM than AHSSL publications; therefore, there was a greater probability that a publication on ecosystem services would cite STEM journals. The heterocitation balance indicated the deviation of the HCS from what would be expected based on the size of each corpus (Fig. 3b). The STEM corpus deviated very little from the expected HCS (approximately 0); thus, it cited as many AHSSL disciplines as would be expected. Conversely, the heterocitation balance for AHSSL was mostly negative, indicating AHSSL articles cited fewer STEM disciplines than would be expected based on the size of the STEM corpus. With the exception of 1998, the AHSSL disciplines collectively cited 74% (in 2001) to 7% (in 2003) fewer STEM disciplines than the size of each corpus would predict (Fig. 3b).

**Disciplines Facilitating the Greatest Disciplinary Integration**

In all 3 periods, ecology and environmental sciences had the largest betweenness centrality measures (indicated by node size) in the ecosystem services research citation network (Figs. 4a–c). In the early years, a core network of STEM disciplines occupied a central position in the network; AHSSL disciplines were on the periphery. Engineering, biology, and multidisciplinary sciences had a moderate betweenness measure (Fig. 4a). In the period of global uptake and rapid growth in disciplines, the network remained divided into STEM and AHSSL disciplines, and engineering was replaced by biology in terms of moderate betweenness (Fig. 4b). Most recently, in the period of institutionalization and rapid growth in publications there was a far greater degree of citation mixing between STEM and AHSSL disciplines. The AHSSL disciplines geography, environmental studies, forestry, and biodiversity conservation demonstrated moderate levels of interdisciplinarity based on the betweenness measure (Fig. 4c). This is further evidenced by more AHSSL disciplines, including sociology, anthropology, urban studies, and law, occupying a more central network position among STEM disciplines (Fig. 4c). The largest AHSSL nodes in the most recent network were geography and environmental studies. These nodes had the highest betweenness centrality of all AHSSL nodes and were also larger than most STEM nodes (apart from ecology, environmental sciences, and multidisciplinary sciences). All other disciplines had smaller betweenness measures, in all periods, indicating they did not connect disciplines that would otherwise be unconnected.

Through time, the ecosystem services network grew to include a large number of both STEM and AHSSL disciplines and became more connected, and the density of connections in the network increased. Disciplines that were more recent additions to the group of publishing

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**Table 1. Percent output per discipline relative to total number of publications on ecosystem services per period.**

| Discipline            | 2011–2018 | 2001–2010 | 1983–2000 |
|----------------------|-----------|-----------|-----------|
| Environmental Sciences | 22.5      | 14.2      | 14.3      |
| Ecology              | 20.1      | 30.3      | 37.8      |
| Forestry             | 6.2       | 3.6       | 0.8       |
| Environmental Studies | 5.0       | 3.7       | 0.8       |
| Multidisciplinary Sciences | 4.8      | 4.0       | 1.7       |
| Biodiversity Conservation | 3.9      | 6.8       | 5.0       |
| Geography            | 3.6       | 3.3       | 2.5       |
| Biology              | 2.7       | 5.3       | 4.2       |
| Engineering          | 2.6       | 2.4       | 6.7       |
| Water Resources      | 2.5       | 1.6       | 0.0       |
Figure 2. Average (a) scores of richness of citation patterns as percentage of total number of references per publication for science, technology, engineering, and mathematics (STEM) and arts, humanities, social sciences, and law (AHSSL) disciplines per year (richness, number of unique disciplines cited by each article) and (b) disciplinary diversity (i.e., distributions of citations over unique disciplines) scores (1, each citation in an article pertains to a different discipline) for STEM and AHSSL disciplines per year (dotted vertical lines—demarcation of 3 periods: 1983–2000 [early years], 2001–2010 [global uptake and rapid growth in disciplines], and 2011–2018 [institutionalization and rapid growth in publications]).

disciplines were (inter alia) as follows: political science, anthropology, sociology, international relations, ethics, and area studies. The early-years network contained only 5 AHSSL disciplines and a network clustering coefficient of 0.388 (Fig. 3a). During the global-uptake period, both of these grew to include 13 AHSSL disciplines and a network clustering coefficient of 0.627 (Fig. 3c). The final institutionalization period involved 23 AHSSL disciplines and a network clustering coefficient of 0.727 (Fig. 3c).

Discussion

Previous research has demonstrated a diversity of topics, disciplines, and methods employed in ecosystem services research (Chaudhary et al. 2015; Droste et al. 2018; Martín-López et al. 2019). We contribute an understanding of the extent of interdisciplinary engagement, over 3 decades, across the field. We found ecosystem services research was dominated by ecology-orientated disciplines that facilitated disciplinary integration. Although ecosystem services has always been a multidisciplinary field, which has grown rapidly over the past 3 decades, it has until recently lacked representation from AHSSL (hereon social science) disciplines. Ecosystem services will likely continue to influence science and policy. However, there is a need for more disciplines that inform understanding of science and society to shape ecosystem services research (Díaz et al. 2018; Woodhead et al. 2019).

Ecosystem services as a concept has thrived over the past 3 decades, growing rapidly in terms of articles (Chaudhary et al. 2015; Droste et al. 2018) and disciplines producing research, as well as disciplines cited. Yet, we found a persistent dominance of ecology-orientated publishing disciplines, reflecting the origins of the concept from the ecological sciences (e.g., Westman 1977; Ehrlich & Mooney 1983). The influence of ecology was particularly apparent in the early years (Chaudhary et al. 2015; Droste et al. 2018), when over one-third of articles were published in ecology journals. Although the focus of production diversified beyond ecology in the periods of global uptake and institutionalization (Chaudhary et al. 2015; Droste et al. 2018), a core
of 10 mostly ecology-orientated disciplines, in all 3 periods, produced nearly three-quarters of all publications on ecosystem services. Similarly, in all periods, ecology and environmental sciences played the main interdisciplinary role, connecting otherwise unconnected disciplines.

The high diversity of disciplines cited 3 decades ago reflects ecosystem services’ conception as a multidisciplinary endeavor from the outset (Westman 1977). The original multidisciplinary ideals also meant that the social sciences were represented, albeit in the minority, from the outset. As the number of citing and cited disciplines increased, richness and diversity of article citation patterns remained largely the same, retaining the multidisciplinary character. However, the low proportion of research produced in social science disciplines also remained the same. Although through time, ecology-orientated disciplines succeeded in broadening the scope of ecosystem services research, incorporating social science perspectives remained challenging and increasingly so the more the ecology-orientated field grew.

Interdisciplinary research is necessary for the development of creative solutions to practical problems, specifically societal and environmental problems (Morillo et al. 2003). However, interdisciplinarity is challenging for practical and philosophical reasons (Campbell 2005). In all 3 periods, ecology and environmental sciences contributed to expanding the field of ecosystem services, and, through their role as brokers, affected a large number of other STEM (hereafter natural science) and social science disciplines. Conversely, only 2 of the 10 top-producing disciplines were social science disciplines, geography and environmental studies, and up until the latest period they played only a minor role in connecting otherwise unconnected disciplines, suggesting a lesser...
role for these disciplines. The central role of ecology and environmental sciences suggests that the structures of disciplinary knowledge in journals in these categories are highly influential on the field of ecosystem services.

The rapid growth in ecosystem services research, combined with a consistent core group of disciplines publishing on the topic, in an increasingly dense network, could suggest ecosystem services has become a discipline, or interdisciplinary, in itself. However, if ecosystem services were to be considered a discipline, although diverse, it would remain dominated by ecological and environmental sciences and would be little influenced by social science. If ecosystem services knowledge is to inform practical conservation challenges, researchers should draw on the wider variety of disciplines required to reconcile conflicts at the intersection of humans and nature and especially include more social sciences (Mascia et al. 2003). Ecosystem services appear to still have some way to go in terms of providing an avenue to such interdisciplinary solutions. Indeed, many social scientists argue the field reflects narrow disciplinary framings (Gómez-Baggethun et al. 2010; Kosoy & Corbera 2010; Spash & Aslaksen 2015) and is limited to monetary approaches (Nieto-Romero et al. 2014).

Although we found that ecosystem services research draws on and publishes in a diversity of disciplines and there has been a considerable growth in social sciences disciplines producing ecosystem services research, the relative contribution from the social sciences has remained under 15%. Accordingly, 15% of citations from natural science publications were to social sciences, compared with over 50% of citations from social science publications to the natural sciences. Thus, a wider variety of disciplines are engaging with
ecosystem services, but the sheer volume of knowledge produced on ecosystem services from the natural sciences overwhelms the considerable gains made in the social sciences.

Yet, in ecosystem services research the social sciences continue to publish and grow, despite being underrepresented in publishing and citations and existing at the periphery of the network. Social sciences cited a greater proportion of natural sciences than vice versa, but they still cited more social sciences than would be expected based on the size of its corpus, suggesting greater tendency to communicating within their own group. Authors may turn to familiar citation patterns, rather than draw on the broader field (Costanza & Kubiszewski 2012). A lack of interdisciplinarity at this scale may serve to protect the integrity of social science disciplines and attract broader engagement from within. This could be a necessary strategy to build greater social science engagement (Chaudhary et al. 2015). Indeed, our most recent network showed promise of increased interdisciplinarity facilitated by key social science disciplines. In addition to more publications, a greater number of social science disciplines, including geography, environmental studies, and forestry, occupied a more central network position, playing a critical role in connecting otherwise disparate disciplines. As the historical dominance of ecology (Chaudhary et al. 2015) diminished through time, the 2 social science disciplines (geography and environmental studies) among the 10 most productive disciplines increased their share of publications. These 2 disciplines also gained influence in terms of betweenness centrality, suggesting engagement with interdisciplinary research topics.

A caveat of our approach is that we relied heavily on the classification of journals and the subsequent social-natural science distinction. Therefore, our conclusions are necessarily a result of the Clarivate classification method. However, our approach allows for systematically assessing the diversity of the ecosystem services research field, as measured by journal disciplines, and is one that can be tracked through time.

In the ecosystem services literature, a need has been identified for a continued move away from describing ecological patterns toward inclusion of the complexity of underlying social-ecological systems and processes, necessitating an interdisciplinary approach (Nicholson et al. 2009). Specifically, consideration of markets, human behaviors and values, and processes of decision making and conflict resolution have been identified as central to successfully balancing human needs and environmental protection (Mascia et al. 2003; Nicholson et al. 2009; Isbell et al. 2017). Specific disciplines that have been argued as capable of providing analytical tools and knowledge on the human dimension are as follows: political science, anthropology, economics, psychology, sociology, geography, and law (Mascia et al. 2003). Most of these disciplines (with the exception of geography and to a lesser extent law) occurred at the periphery of our citation networks, indicating there is room for improvement in incorporating heterogenous knowledge. Such inclusion can help researchers in the ecosystem services field reflect on common critiques and build the field. Recent contributions toward this goal take human values as the starting point of all efforts into valuing nature (Kenter 2018) and ask what role indigenous knowledge can play in understanding nature’s contributions to people (Díaz et al. 2018).

Continued development toward interdisciplinarity is essential for moving beyond critiques of monetary valuation and commodification toward the exploration of...
noninstrumental relational values of ecosystem services as a more meaningful way of understanding human-nature relations (Jackson & Palmer 2015; Himes & Muraca 2018). Mutual awareness of complementary forms of knowledge can align principles, values, and priorities and promote collaboration in framing and addressing real-world problems (Gould et al. 2020). The importance of nature to people is necessarily subject to diverse worldviews and human-nature relationships (Van Riper & Kyle 2014; Kohler et al. 2019). Therefore, if policy and conservation are to be informed by the study of ecosystem services, an interdisciplinary and relational values-based approach could contribute to both sustainability and justice by providing space for this diversity of relationships (Himes & Muraca 2018). Our results indicated that despite dominance of a few core disciplines, ecosystem services research is increasingly diverse, representing a plurality of disciplinary approaches, including from the social sciences. To improve applicability in policy and practice, this knowledge base can be used to build shared understandings. Researchers in the field of ecosystem services can gain support for conservation (Fisher & Brown 2015) by developing new ways of knowing human-nature relations and thus realizing the potential of inclusion of different perspectives and actors.

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