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How interdisciplinary is sustainability research? Analyzing the structure of an emerging scientific field

Ethan D. Schoolman · Jeremy S. Guest · Kathleen F. Bush · Andrew R. Bell

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Abstract Sustainability research is expected to incorporate concepts, methods, and data from a diverse array of academic disciplines. We investigate the extent to which sustainability research lives up to this ideal of an interdisciplinary field. Using bibliometric data, we orient our study around the "tripartite model" of sustainability, which suggests that sustainability research should draw from the three "pillars" of the environmental, economic, and social sciences. We ask three questions: (i) is sustainability research truly more interdisciplinary than research generally, (ii) to what extent does research grounded in one pillar draw on research from the other two, and (iii) if certain disciplines or pillars are more interdisciplinary than others, then what explains this variation? Our results indicate that sustainability science, while more interdisciplinary than other scientific fields, falls short of the expectations inherent in the tripartite model. The pillar with the fewest articles published on sustainability—economics—is also the most integrative, while the pillar with the most articles—environmental sciences—draws the least from outside disciplines. But interdisciplinarity comes at a cost: sustainability research in economics and the social sciences is centered around a relatively small number of interdisciplinary journals, which may be becoming less valued over time. These findings suggest that, if sustainability research is to live up to its interdisciplinary ideals, researchers must be provided with greater incentives to draw from fields other than their own.

Keywords Sustainability science · Sustainable · Bibliometric · Interdisciplinarity · Academia · Citation analysis

Handled by Arnim Wiek, Arizona State University, USA.

E. D. Schoolman, J. S. Guest, K. F. Bush, and A. R. Bell contributed equally to this work.

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E. D. Schoolman
Department of Sociology, College of Literature, Science, and the Arts, University of Michigan, LSA Building, Room 3001, 500 S. State St., Ann Arbor, MI 48109, USA

J. S. Guest
Department of Civil and Environmental Engineering, College of Engineering, University of Michigan, 1351 Beal Ave., 19 EWRE, Ann Arbor, MI 48109, USA

K. F. Bush
Department of Environmental Health Sciences, School of Public Health, University of Michigan, SPH Tower, 1415 Washington Heights, Ann Arbor, MI 48109, USA

A. R. Bell (✉)
Lamont-Doherty Earth Observatory, Earth Institute, Columbia University, 103 Tree Ring Lab., 61 Route 9W, P.O. Box 1000, Palisades, NY 10964, USA
e-mail: ab3477@columbia.edu

Introduction

The idea of the interconnectedness of natural and socioeconomic systems is fundamental to thinking on sustainability and sustainable development. For this reason, the principle of interdisciplinarity, which calls for the integration of theories, concepts, techniques, and data from diverse bodies of knowledge (Porter et al. 2006; Rafols and Meyer 2010), is equally crucial to the study of sustainability. Indeed, in the decades since the Brundtland Report called for balancing economic growth with ecological integrity (World Commission on Environment and Development [WCED] 1987), the interconnectedness of challenges such as climate change and persistent poverty has become apparent, and the importance of interdisciplinarity to sustainability research has taken on new urgency (Holling 2001; Kates et al. 2001). Recent work depicts sustainability science as a distinct field where researchers, policymakers, and stakeholders can collaborate and learn from each other, without the hindrance of traditional disciplinary boundaries (Kates et al. 2001; Komiyama and Takeuchi 2006; Ostrom 2009; Characklis et al. 2011). As publications on sustainability have surged (Kajikawa et al. 2007), the structure of sustainability science itself has become an object of interest. Many researchers have advocated for knowledge integration to be supported by new institutions and practices (Bäckstrand 2003; Swart et al. 2004; Koehler and Hecht 2006; Jerneck et al. 2011), while others have focused on illuminating the emerging characteristics of the field. Efforts to understand the structure of sustainability science and related fields have mapped well-formed research clusters (Kajikawa et al. 2007), analyzed citation patterns across national boundaries (Yarime et al. 2010), and identified productive institutions and influential publications (Costanza et al. 2004; Janssen et al. 2006; Ma and Stern 2006; Janssen 2007). But the extent to which sustainability science lives up to its interdisciplinary ideals has, so far, not been the object of systematic inquiry.

In this study, we ask whether sustainability science is as integrative of knowledge across disciplines as its subject would appear to require. Specifically, we use bibliometric data to investigate the empirical validity of the particular vision of interdisciplinarity that arises from what we call the “tripartite model” of sustainability. The tripartite model, which envisions sustainability as the union of equitable economic growth, social well-being, and thriving natural systems, has, for years, been a widely accepted way of both describing the subject of, and motivating interdisciplinarity within, sustainability research (Kajikawa 2008). In variations on the idea of a tripartite relationship between complex systems of phenomena, as well as between corresponding areas of knowledge, sustainability has been portrayed as an edifice supported by the “three pillars” of economic growth, environmental protection, and social progress (Kastenhofer and Rammel 2005; United Nations General Assembly 2005; Office of Government Commerce [OGC] 2007), as the union of three overlapping circles representing the economy, the environment, and society (Adams 2006), and as the goal of business and governmental practices that recognize a “triple bottom line” of economic, human, and natural capital (Elkington 1998; Willard 2002). An important consequence of the tripartite model is the idea that sustainability research should draw substantively from three realms of knowledge: the environmental sciences, the social sciences, and the economic sciences. The tripartite model, in addition to having deep roots in the development of sustainability thought, thus offers a relatively clear vision for what knowledge integration ought to look like in sustainability science. In this study, we use the tripartite model as a framework around which to construct specific research questions and hypotheses regarding the putative interdisciplinarity of sustainability research.

Though a widespread and influential heuristic, the tripartite model is not without critics. Alternative theories of the structure and goals of sustainability research have been proposed which, like the tripartite model, give rise to both descriptive and normative claims. Sustainability science has been characterized as a transdisciplinary field concerned more with problem-solving (Jerneck et al. 2011; Wiek et al. 2011) and overcoming challenges than by the disciplines it employs (Clark 2007), while researchers have been urged to focus on the dynamic interactions of the global, human, and social (Komiyama and Takeuchi 2006) or social and ecological systems (Holling 2001; Clark and Dickson 2003; Ostrom 2009). The tripartite model might, therefore, be seen as a reification of the very disciplinary boundaries that sustainability science is expected to transcend. On the other hand, one early inquiry into the possibility of interdisciplinarity across “grand categories” of human knowledge—engineering and the life, natural, and social sciences—found such “distant” connections to be quite rare (Porter and Chubin 1985). Subsequent research into interdisciplinary scholarship has focused on exchanges between fields with overlapping applications in medicine and engineering (Porter et al. 2007; Rafols and Meyer 2010). We want to emphasize, then, that our hypotheses and analyses do not represent an endorsement of the tripartite model as a theory of, or basis for, good sustainability science. Indeed, just the opposite is true. By taking seriously the descriptive claims of the tripartite model, our goal is to address whether the tripartite ideal of knowledge integration in sustainability research has been matched by publishing practice. Our inquiry into the descriptive usefulness of the tripartite model will also expose whether it should continue to be a theoretical mainstay in efforts to shape and support the field of sustainability science.

Research questions and hypotheses

Taking as our starting point the tripartite model of sustainability research, we ask three specific, interrelated questions. First, is sustainability research truly more interdisciplinary than scientific research generally speaking, insofar as its propensity to draw more evenly from each "pillar"—the environmental, economic, and social sciences—is concerned? Second, to what extent does sustainability research grounded in one pillar draw on research from the other two? Third, if certain areas of study, or pillars, are found to be more interdisciplinary than others, what explains this variation? Though knowledge integration in sustainability science is the ideal, many studies have found academia, in general, to be characterized by significant institutional and organizational impediments to interdisciplinary research (Kostoff 2002; Porter et al. 2006). Academic fields and subfields have distinct vocabularies and standards for validity, which can be difficult for "outsiders" to learn (Fujigaki and Leydesdorff 2000; Becher and Trowler 2001). Publishing and competitions for funding rely on a peer review system that is often rigidly mono-disciplinary (Bruhn 1995; Butler 1998; Metzger and Zare 1999). Individuals who wish to draw on concepts and techniques from "outside" fields may find that they have little time to do so on their own, and little institutional support to do so as part of a multidisciplinary team. In recent years, universities, public agencies, and corporations have begun to provide greater support for interdisciplinary research (Sá 2008). However, while the number of centers and degree programs focused on sustainability has increased, decisions about employment and promotion generally remain in the hands of traditional academic departments (Kostoff 2002; Nyhus et al. 2002; Nelson 2011). Indeed, according to a report by major US scientific associations, promotion criteria constitute the number one impediment to interdisciplinary research (Committee on Facilitating Interdisciplinary Research and Committee on Science, Engineering, and Public Policy 2005).

We put forth the following hypotheses regarding the vision of sustainability science that arises from the tripartite model:

H1: Sustainability research is more interdisciplinary than scientific research generally, insofar as sustainability articles are more likely to draw from all pillars of scientific knowledge.

H2: Sustainability research has become more interdisciplinary over time, as interest in—and awareness of obstacles to—interdisciplinary research has increased.

H3: Interdisciplinarity varies across pillars; furthermore, the results of our analyses may offer insight into how much progress different disciplines have made in overcoming impediments to interdisciplinarity in sustainability research.

Data and methods

Data extraction

We analyzed the citation histories of articles on sustainability published between 1996 and 2009 and generated measures of interdisciplinarity for each of the three pillars identified above. In order to investigate whether, with respect to interdisciplinarity, sustainability research is different from scientific research generally, we performed identical analyses on a random sample of all articles published between 1996 and 2009 in relevant categories of the natural, economic, and social sciences. Bibliometric data have been used in a growing number of studies of the structures of, and connections between, subfields in the natural and applied sciences (Porter et al. 2008; Porter and Rafols 2009; Rafols and Meyer 2010) and operations management (Nakamura et al. 2011). We obtained data for our study from Scopus, a database of approximately 16,500 peer-reviewed journals and 41 million records. We chose Scopus over other databases, such as the ISI Web of Knowledge, due to the ease with which citation data for journal articles could be downloaded, and because the set of subject categories into which journals are placed was the most comprehensive (Table S1 of the Supplementary Material). Though most recent bibliometric research has used ISI to obtain data, a comparison of databases has confirmed that Scopus is an acceptable alternative to ISI (Leydesdorff et al. 2010).

Generating a dataset of articles on sustainability

We conducted our analyses on the set of all peer-reviewed journal articles in Scopus that contained the word "sustainability" in either the article title or keywords and that were published between 1996 and 2009. Data were retrieved from Scopus on April 30, 2010, and included records for 17,226 articles. At the time of retrieval, Scopus did not contain records for articles published prior to 1996; these records have recently been added to the database, but only 469 articles answering our query were published between 1973 (one article) and 1995 (127 articles), which would have constituted a relatively small (less than 3%) increase in the number of data points for our study. We elected to make "sustainability" the query term, rather than "sustainable", and we searched for "sustainability" in titles and keywords, but not abstracts, because we wanted to minimize the chance that our final dataset would include articles whose subject matter did not fall within the purview of sustainability science. For instance, using "sustainable" as the query would have returned the article "Effective Employment Brand Equity Through Sustainable Competitive Advantage", published in the *Journal of*

Business Research, but this article's abstract makes it clear that "sustainable" carries a very different connotation in this title than, say, in the phrase "sustainable development" (Kim et al. 2011). Similarly, the abstract for the article "Reaching a Destination by Starting Earlier: Revisited", published in *Transportation Research Part E*, contains the word "sustainability", but in the following sentence: "A theoretical lower bound value to guarantee the sustainability of the FIFO principle in a dynamic traffic network was also derived" (Qian et al. 2011). It was, thus, our view that our search criteria, if resulting in a somewhat smaller dataset of articles, would maximize the probability that this dataset would contain only those articles whose subject matter was directly relevant to sustainability science.

For each article in the dataset, we downloaded information on the article itself (journal, year of publication, etc.) and the complete list of references cited by the article. We wrote an algorithm that linked each article to the Scopus-designated subject category or categories of the journal in which it was published. The algorithm also linked every referenced work in the bibliography of every article to a Scopus category or categories, as long as the referenced work was itself a journal article (see the Supplementary Material for a pseudocode representation of this algorithm). For quality assurance purposes, 100 randomly selected articles and their references (over 850) were manually matched with the journals in which they were published, and the results were compared with the algorithm output. Quality assurance confirmed that 94% of matched references were correctly matched to the appropriate journal and 85% of unmatched references were from conference proceedings, government reports, books, or other gray literature. The remaining 15% of unmatched references consisted of periodicals not indexed by Scopus.

Data categorization

Scopus groups journals into 27 basic categories and 307 subcategories; for instance, the basic category *Chemistry* (*all*) includes the subcategories *Chemistry* (*misc.*), *Analytic Chemistry*, *Electrochemistry*, and so on. Journals may be cross-listed in multiple subcategories, which may, in turn, bridge multiple basic categories. Several recent studies have created maps of citation networks in order to inductively identify research clusters in sustainability science and related fields (Kajikawa et al. 2007; Nakamura et al. 2011). For our study, we used the Scopus basic categories to deductively construct environmental, economic, and social science "composite pillars" corresponding to the three pillars of inquiry at the heart of the tripartite model of sustainability research (Table S1 of the Supplementary Material). For instance, the composite economics pillar includes articles from three basic categories: (1) *Economics, Econometrics, and Finance* (*all*), (2) *Business, Management and Accounting* (*all*), (3) *Decision Sciences* (*all*). Applied to the dataset of sustainability articles, the composite pillar construction captured 11,543 unique articles with 167,605 matched references.

Many articles are published in journals that are cross-listed under multiple Scopus categories and may, thus, appear in more than one pillar (Table S2 of the Supplementary Material). In order to evaluate the role of cross-listed journals as conduits for more interdisciplinary articles, we classified articles as originating from cross-listed journals or single-listed journals and repeated the analyses for each group.

Generating a baseline dataset

We generated a baseline dataset of general research articles for each pillar to serve as a standard of comparison for the interdisciplinarity of sustainability research. This baseline dataset was equivalent to a 5% random sample of all research published in the categories included in our composite pillars (Table S1 of the Supplementary Material) from 1996 to 2009. Due to the fact that Scopus allows a maximum of 2,000 records from a given search to be downloaded, we performed individual searches for each year and pillar, and restricted ourselves to publication dates between January and March. This kept the number of search results below 40,000 for each combination (allowing a 5% sample to be downloaded within the 2,000 record limit), and included journals not published monthly (such as quarterly journals). Data were collected on June 18, 2011 and the final dataset included 52,376 unique articles.

Measuring interdisciplinarity

In recent years, there have been several efforts to develop measures of interdisciplinarity using bibliometric data. Many of these measures are based on a simple proportion of cross-disciplinary connections found between journal articles and works cited (Porter and Chubin 1985; Tomov and Mutafov 1996; van Leeuwen and Tijssen 2000) or between research clusters that have emerged from maps of citation networks (Nakamura et al. 2011). A number of measures also adjust for the fact that not all cross-disciplinary citations are created equal, and that some connect truly disparate academic fields, while others connect fields that are already relatively close (Porter et al. 2007, 2008). In order to quantify the balance of cited references in each of our three pillars, we used the Shannon entropy measure, which has been adopted from thermodynamics and information theory into many fields as a means of characterizing diversity (e.g., Bailey 1983; Gill 2005; Kaufman et al. 2008). For each article, we calculated the fraction f of cited references that fall into each pillar; references from journals listed in one pillar add 1 to the numerator of the fraction for that particular pillar, those cross-listed in two pillars add 0.5 to each numerator, and those cross-listed in three pillars add 0.33. From these fractions, we calculated the Shannon entropy for each article as follows:

$$E = -(f_{\mathrm{econ}} \cdot \ln(f_{\mathrm{econ}}) + f_{\mathrm{soc}} \cdot \ln(f_{\mathrm{soc}}) + f_{\mathrm{env}} \cdot \ln(f_{\mathrm{env}})) \quad (1)$$

With three possible categories for references, the Shannon entropy ranges from a minimum of 0 (all references in one pillar) to a maximum of approximately 1.1 (references evenly distributed among all three pillars). We use the term "bibliographical entropy" to describe the Shannon entropy for each article.

Data analysis

We employed several types of analysis in order to visualize patterns in the data and evaluate the hypotheses outlined above. First, we plotted counts of articles over time in order to show the overall trend toward increasing interest in sustainability. Second, we generated a ternary plot of citation trends in order to provide a visualization of differences in interdisciplinarity both between sustainability and baseline articles, and between sustainability articles across pillars. The position of each data point in this plot represents the fraction of references attributable to each pillar for a particular set of articles (sustainability articles in economics in 1996, baseline articles in economics in 1996, etc.). Fractions were calculated for each set of articles by dividing the number of references associated with each pillar by the total number of references; these fractions sum to 1.

We supported the patterns visible in the ternary plot with statistical analyses of the bibliographical entropy of articles in our dataset. First, we used two-tailed Kolmogorov–Smirnov (K–S) tests to test for differences between the bibliographical entropy distribution functions of sustainability and baseline articles (H1 above) and sustainability articles across pillars (H3). We included side-by-side comparisons of medians for all distributions, as is standard practice for reporting the results of both K–S and Mann–Whitney tests (we also performed Mann–Whitney tests on all data, and obtained nearly identical results as with K–S). Second, we performed simple linear regression of the change in bibliographical entropy over time in order to test whether sets of articles (sustainability articles in economics, baseline articles in economics, etc.) have become more interdisciplinary since 1996. We also tested for differences in trends in interdisciplinarity across article sets by calculating the following Z-score (Paternoster et al. 1998):

$$Z_{\mathrm{ij}} = \frac{\beta_{\mathrm{i}} - \beta_{\mathrm{j}}}{\sqrt{SE_{\beta_{\mathrm{i}}}^2 + SE_{\beta_{\mathrm{j}}}^2}} \quad (2)$$

where β_{i} and β_{j} are the coefficients of change in bibliographical entropy over time for the article sets to be compared and SE is the standard error of each β coefficient.

Results

Increasing interest in sustainability

The percentage increase in sustainability articles has been greater than that of scientific articles generally. From 1996 to 2009, the total number of unique articles per year across the three pillars increased by 71%, from 421,538 to 722,330. By comparison, the number of unique articles published annually that met the search criteria for sustainability increased by 663%, from 241 to 1,838. Measured as the increase in the number of articles per pillar, interest in sustainability has risen the most in economics. Sustainability articles increased by nearly 1,400% (from 35 articles to 520) in the economics pillar, by 680% (from 93 to 722) in the social science pillar, and by 670% (from 226 to 1,749) in the environmental science pillar (Fig. 1).

Interdisciplinarity and sustainability science

The ternary plot provides a visualization of the extent to which articles grounded in a particular pillar—environmental sciences, social sciences, or economics—draw from research in fields other than their own (Fig. 2). Points located in the center of the triangle draw equally from all three pillars; points located along the sides have a mix of two pillars; and points located in any of the corners draw primarily from only one pillar. Since the number of articles published per year has generally increased over time (see Fig. 1), temporal trends can be observed by moving from smaller to larger circles within each pillar (essentially, moving from 1996 to 2009 data).

The ternary plot suggests support for the first hypothesis: that sustainability research is more interdisciplinary than scientific research generally. For each pillar and across all years, points representing sustainability articles are closer to the center of the triangle than points corresponding to baseline sets of general scientific research articles. For instance, baseline social science articles are pinned in the bottom left corner, while sustainability social science articles are clustered about midway between the social and environmental corners and edging close to the midpoint of the triangle (i.e., moving towards economics).

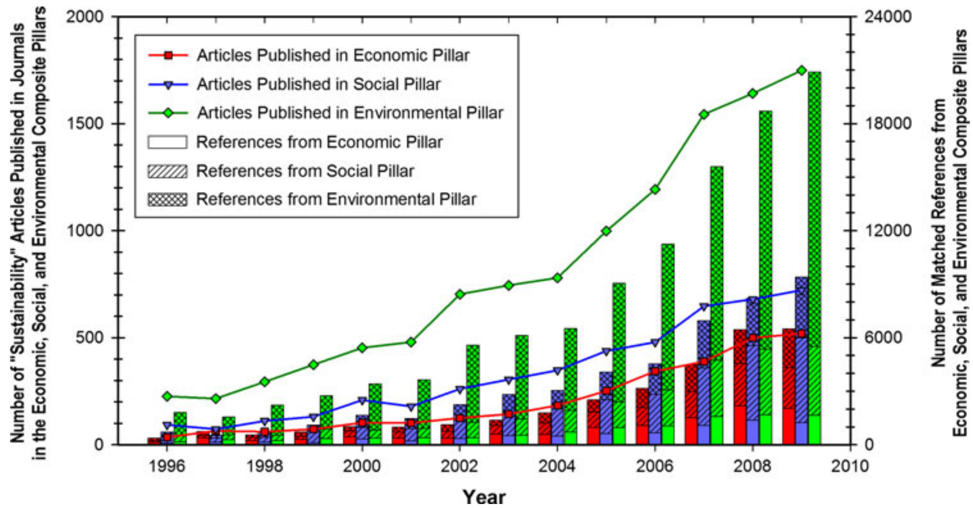

Fig. 1 Number of articles (lines with *filled symbols*, *left axis*) and number of corresponding references (*stacked bars*, *right axis*) from composite sustainability pillars: economic (*left bar*, *squares*); social (*center bar*, *triangles*); environmental (*right bar*, *diamonds*). The classification of references sources are indicated by the *bar hatchings*

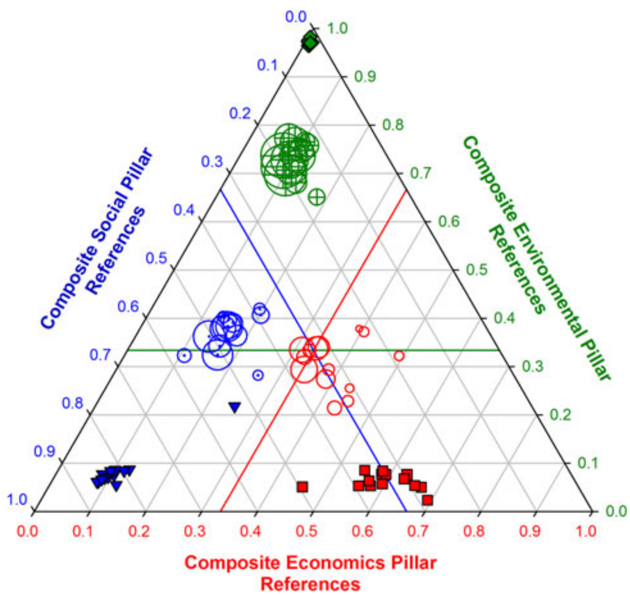

Fig. 2 Plotted circles are annual averages of "sustainability" (*hollow circles*) and "baseline" (*filled symbols*) articles from each pillar: economics (*empty circles* and *filled squares*); social (*dotted circles* and *filled triangles*); environmental (*crossed circles* and *filled diamonds*). The center of each *circle* or *symbol* indicates the relative fraction of references from each of the three composite pillars (fractions have been normalized to add to 1.0). For "sustainability" circles, the area of each circle is proportional to the number of articles published in that year. The intersecting lines are located at reference fractions of 0.333 for economic, social, and environmental composite pillars, respectively

Statistical analyses confirm the significance of the trends and relationships visible in the ternary plot. For each comparison of the bibliographical entropy distribution functions for sustainability and baseline articles in the same pillar and year, the null hypothesis of the K–S test is rejected, indicating that the distance between the two distributions is significantly different from 0 (Table 1). Side-by-side comparisons of the medians for sets of articles for each pillar and year—coupled with the ternary plot—strongly suggest that sustainability research across the academy is, indeed, more interdisciplinary than scientific research generally. There is not a single year when the median bibliographical entropy for a set of sustainability articles does not exceed that of its corresponding set of baseline articles, or when the K–S test fails to return a significant result in the difference between bibliographical entropy distribution functions.

The second set of comparisons in Table 1 excludes articles published in journals that are cross-listed in more than one pillar. Excluding cross-listed articles does not change the outcome of K–S comparisons between sustainability and baseline articles in the social or environmental sciences, though, in most years, the bibliographical entropy median for sustainability articles does decrease. But, in economics, excluding cross-listed articles minimizes the distance between the bibliographical entropy distributions of sustainability and baseline articles, with the result that the differences between these distributions are no longer statistically significant for the years 1996–1997, 1999–2005, and 2007. These results suggest that cross-listed journals may play an important role in sustainability research and publishing within economics, and we come back to this point in our discussion below.

Is sustainability research becoming more interdisciplinary over time, as the second hypothesis proposes? For the environmental and social sciences, the answer is yes: the change in bibliographical entropy from 1996–2009 for sustainability articles in both pillars is positive and statistically significant (Table 2). Moreover, this movement towards greater parity in the works cited of sustainability research cannot be explained by trends in scientific research as a whole. Baseline articles in the environmental and social sciences show much less movement in the

Table 1 Bibliographic entropy medians and Kolmogorov–Smirnov (K–S) tests for differences in entropy distributions (between sustainability and baseline articles in each pillar)

	Econ_Sust	*n*	Econ_Base	*n*	K–S (*D*)	Soc_Sust	*n*	Soc_Base	*n*	K–S (*D*)	Env_Sust	*n*	Env_Base	*n*	K–S (*D*)
Including cross-listed articles															
1996	0.623	35	0.362	248	**0.417****	0.604	93	0.277	438	**0.466****	0.489	226	0.218	1,856	**0.678****
1997	0.693	65	0.383	181	**0.404****	0.637	73	0.290	432	**0.486****	0.387	216	0.193	1,835	**0.675****
1998	0.693	61	0.363	233	**0.450****	0.664	111	0.347	154	**0.366****	0.397	294	0.209	2,727	**0.696****
1999	0.724	73	0.361	116	**0.525****	0.615	131	0.280	388	**0.498****	0.365	374	0.195	2,726	**0.691****
2000	0.646	103	0.367	296	**0.363****	0.627	209	0.317	587	**0.450****	0.329	453	0.179	2,992	**0.657****
2001	0.693	102	0.365	174	**0.520****	0.637	179	0.259	436	**0.521****	0.419	480	0.206	2,304	**0.741****
2002	0.691	125	0.365	226	**0.485****	0.673	261	0.273	378	**0.514****	0.359	703	0.195	2,516	**0.725****
2003	0.681	143	0.377	441	**0.357****	0.669	305	0.318	545	**0.506****	0.368	745	0.176	4,036	**0.757****
2004	0.655	184	0.368	461	**0.435****	0.655	348	0.278	943	**0.516****	0.501	780	0.182	4,552	**0.738****
2005	0.688	252	0.367	483	**0.412****	0.683	438	0.274	1,031	**0.508****	0.373	998	0.187	4,882	**0.700****
2006	0.691	343	0.367	522	**0.448****	0.668	479	0.266	1,258	**0.518****	0.474	1,193	0.212	4,855	**0.723****
2007	0.693	389	0.366	633	**0.447****	0.673	647	0.289	1,415	**0.552****	0.464	1,544	0.208	5,082	**0.761****
2008	0.683	499	0.374	742	**0.367****	0.653	680	0.277	1,476	**0.497****	0.397	1,641	0.216	5,503	**0.689****
2009	0.693	520	0.395	835	**0.399****	0.676	722	0.216	1,805	**0.570****	0.426	1,749	0.232	6,564	**0.719****
Excluding cross-listed articles															
1996	0.562	5	0.338	12	0.467	0.591	22	0.091	101	**0.488****	0.245	64	0.245	219	**0.586****
1997	0.630	12	0.607	11	0.371	0.665	16	0.061	97	**0.481****	0.254	55	0.146	377	**0.603****
1998	0.930	9	0.531	9	**0.778****	0.671	20	0.165	24	**0.583****	0.377	94	0.179	317	**0.687****
1999	0.590	6	0.144	4	0.750	0.347	33	0.133	70	0.238	0.336	120	0.152	393	**0.452****
2000	0.525	10	0.331	12	0.317	0.574	42	0.291	108	**0.431****	0.246	101	0.210	568	**0.650****
2001	0.532	6	0.449	5	0.233	0.587	38	0.195	91	**0.523****	0.305	137	0.238	453	**0.704****
2002	0.525	6	0.183	4	0.500	0.610	41	0.037	69	**0.524****	0.368	163	0.224	409	**0.671****
2003	0.503	26	0.481	10	0.223	0.636	78	0.216	64	**0.539****	0.290	199	0.204	721	**0.700****
2004	0.637	19	0.531	19	0.263	0.500	69	0.192	192	**0.387****	0.304	196	0.183	715	**0.589****
2005	0.532	38	0.441	20	0.342	0.585	80	0.179	241	**0.443****	0.304	207	0.181	770	**0.631****
2006	0.628	47	0.359	27	**0.427****	0.497	99	0.207	268	**0.314****	0.285	276	0.193	736	**0.506****
2007	0.600	60	0.470	17	0.366	0.566	134	0.209	322	**0.426****	0.342	346	0.195	832	**0.613****
2008	0.591	83	0.363	30	**0.471****	0.562	139	0.179	285	**0.462****	0.331	399	0.201	841	**0.562****
2009	0.592	62	0.430	44	**0.379****	0.524	168	0.127	259	**0.431****	0.349	421	0.179	760	**0.524****

* $p < 0.05$, ** $p < 0.01$; significant values for D are in **bold** type (two-tailed Kolmogorov–Smirnov test)

Table 2 Changes in bibliographical entropy, 1996–2009

Article set	n	Beta0	SE Beta0	Beta1	SE Beta1
Including cross-listed articles					
Econ_Sust	2,894	**0.682**	0.018**	−0.001	0.002
Soc_Sust	4,676	**0.586**	0.014**	**0.003**	0.001*
Env_Sust	11,396	**0.388**	0.010**	**0.005**	0.001**
Econ_Base	5,591	**0.375**	0.009**	**0.003**	0.001**
Soc_Base	11,286	**0.312**	0.006**	**−0.004**	0.001**
Env_Base	52,430	**0.182**	0.002**	**0.001**	0.000**
Excluding cross-listed articles					
Econ_Sust	389	**0.585**	0.058**	−0.002	0.005
Soc_Sust	979	**0.549**	0.033**	−0.004	0.003
Env_Sust	2,778	**0.325**	0.018**	**0.003**	0.002*
Econ_Base	224	**0.386**	0.043**	0.002	0.004
Soc_Base	2,191	**0.229**	0.015**	0.000	0.001
Env_Base	8,111	**0.185**	0.005**	0.001	0.000

* $p < 0.05$, ** $p < 0.01$; significant values for B are in **bold** type (two-tailed test)

Table 3 Z-scores for comparing change in bibliographical entropy (beta 1) between article sets

Article set	Econ_Sust	Soc_Sust	Env_Sust	Econ_Base	Soc_Base	Env_Base
Including cross-listed articles						
Econ_Sust	0	**2.038**	**2.933**	**2.140**	**1.814**	1.413
Soc_Sust	**2.038**	0	0.768	0.185	**5.073**	1.469
Env_Sust	**2.933**	0.768	0	1.179	**7.600**	**3.299**
Econ_Base	**2.140**	0.185	1.179	0	**6.509**	**1.811**
Soc_Base	**1.814**	**5.073**	**7.600**	**6.509**	0	**8.512**
Env_Base	1.413	1.469	**3.299**	**1.811**	**8.512**	0
Excluding cross-listed articles						
Econ_Sust	0	0.359	1.012	0.626	0.346	0.499
Soc_Sust	0.359	0	**2.152**	1.224	1.170	1.507
Env_Sust	1.012	**2.152**	0	0.314	1.616	1.618
Econ_Base	0.626	1.224	0.314	0	0.523	0.373
Soc_Base	0.346	1.170	1.616	0.523	0	0.479
Env_Base	0.499	1.507	1.618	0.373	0.479	0

* Significant results are in **bold**; >1.64 significant at 95%; >2.33 significant at 99%

direction of interdisciplinarity, and the differences between the coefficients of change in bibliographical entropy for sustainability and baseline articles in both pillars are statistically significant (Table 3). Sustainability articles in economics, however, have not experienced a statistically significant increase in bibliographical entropy; the yearly entropy median has hovered near 0.69 for 14 years, despite the fact that interdisciplinarity in economics articles generally during this time has increased at a statistically significant rate. This finding is tempered, though, by the trends suggested by the ternary plot: sustainability research in economics may not have had much room for improvement, as it has existed near the center of the triangle for some time.

Excluding cross-listed articles from the analysis leads to a loss in statistical significance for all but the set of sustainability articles in the environmental science pillar, which retains a slight movement in the direction of interdisciplinarity over time. Again, it appears that cross-listed journals play an important role in publishing trends for sustainability research.

The third hypothesis holds that, even if sustainability research on the whole is relatively interdisciplinary compared with other scientific fields, this propensity for knowledge integration varies across pillars. Statistical analysis supports this hypothesis and mirrors the hierarchy visualized by the ternary plots. The most unambiguous results involve sustainability articles in the economics pillar, all of whose yearly bibliographic entropy distributions are significantly different from those of sustainability articles rooted in either the social or the environmental sciences (Table 4). Moreover, for each year, the median bibliographic entropy of sustainability articles in economics is the highest of any of the three pillars. K–S tests also

Table 4 Bibliographic entropy medians and Kolmogorov–Smirnov (K–S) tests for differences in entropy distributions (between sustainability articles across pillars)

	Econ_Sust	*n*	Soc_Sust	*n*	K–S (*D*)	Econ_Sust	*n*	Env_Sust	*n*	K–S (*D*)	Soc_Sust	*n*	Env_Sust	*n*	K–S (*D*)
Including cross-listed articles															
1996	0.623	35	0.604	93	**0.176***	0.623	35	0.489	226	**0.359****	0.604	93	0.489	226	0.221
1997	0.693	65	0.637	73	**0.267****	0.693	65	0.387	216	**0.365****	0.637	73	0.387	216	0.155
1998	0.693	61	0.664	111	**0.272****	0.693	61	0.397	294	**0.345****	0.664	111	0.397	294	**0.219***
1999	0.724	73	0.615	131	**0.277****	0.724	73	0.365	374	**0.398****	0.615	131	0.365	374	**0.243****
2000	0.646	103	0.627	209	**0.304****	0.646	103	0.329	453	**0.368****	0.627	209	0.329	453	0.116
2001	0.693	102	0.637	179	**0.272****	0.693	102	0.419	480	**0.326****	0.637	179	0.419	480	**0.187***
2002	0.691	125	0.673	261	**0.292****	0.691	125	0.359	703	**0.395****	0.673	261	0.359	703	**0.160***
2003	0.681	143	0.669	305	**0.335****	0.681	143	0.368	745	**0.363****	0.669	305	0.368	745	0.072
2004	0.655	184	0.655	348	**0.222****	0.655	184	0.501	780	**0.288****	0.655	348	0.501	780	0.090
2005	0.688	252	0.683	438	**0.290****	0.688	252	0.373	998	**0.295****	0.683	438	0.373	998	0.058
2006	0.691	343	0.668	479	**0.218****	0.691	343	0.474	1193	**0.261****	0.668	479	0.474	1,193	0.078
2007	0.693	389	0.673	647	**0.281****	0.693	389	0.464	1544	**0.311****	0.673	647	0.464	1,544	**0.091***
2008	0.683	499	0.653	680	**0.247****	0.683	499	0.397	1641	**0.336****	0.653	680	0.397	1,641	**0.101****
2009	0.693	520	0.676	722	**0.261****	0.693	520	0.426	1749	**0.314****	0.676	722	0.426	1,749	**0.087***
Excluding cross-listed articles															
1996	0.562	5	0.591	22	**0.334***	0.562	5	0.245	64	0.500	0.591	22	0.245	64	0.209
1997	0.630	12	0.665	16	**0.389***	0.630	12	0.254	55	**0.488***	0.665	16	0.254	55	0.250
1998	0.930	9	0.671	20	0.310	0.930	9	0.377	94	**0.500***	0.671	20	0.377	94	0.456
1999	0.590	6	0.347	33	0.111	0.590	6	0.336	120	**0.575***	0.347	33	0.336	120	0.545
2000	0.525	10	0.574	42	**0.403****	0.525	10	0.246	101	**0.452***	0.574	42	0.246	101	0.276
2001	0.532	6	0.587	38	**0.371****	0.532	6	0.305	137	0.394	0.587	38	0.305	137	0.228
2002	0.525	6	0.610	41	**0.271***	0.525	6	0.368	163	0.269	0.610	41	0.368	163	0.183
2003	0.503	26	0.636	78	**0.429****	0.503	26	0.290	199	**0.369****	0.636	78	0.290	199	0.269
2004	0.637	19	0.500	69	**0.246****	0.637	19	0.304	196	**0.415****	0.500	69	0.304	196	0.244
2005	0.532	38	0.585	80	**0.287****	0.532	38	0.304	207	0.212	0.585	80	0.304	207	0.141
2006	0.628	47	0.497	99	**0.218****	0.628	47	0.285	276	**0.408****	0.497	99	0.285	276	0.229
2007	0.600	60	0.566	134	**0.271****	0.600	60	0.342	346	**0.319****	0.566	134	0.342	346	0.098
2008	0.591	83	0.562	139	**0.260****	0.591	83	0.331	399	**0.382****	0.562	139	0.331	399	0.165
2009	0.592	62	0.524	168	**0.171****	0.592	62	0.349	421	**0.295****	0.524	168	0.349	421	0.143

* $p < 0.05$, ** $p < 0.01$; significant values for *D* are in **bold** type (two-tailed Kolmogorov–Smirnov test)

find the bibliographic entropy distributions of sustainability articles in the social science and environmental science pillars to be significantly different in 7 out of 14 years. In each of these years, sustainability articles in the social sciences have a higher median entropy. These results, overall, echo the impression of the ternary plot. Sustainability articles rooted in economics and the social sciences approach a more even distribution of references than do articles in the environmental sciences, which draw mostly from research based in their home pillar.

The second set of comparisons in Table 4, as in Table 1, excludes articles published in journals cross-listed in more than one pillar. In these analyses, economics largely retains its distinction in interdisciplinarity over the environmental sciences. Yearly bibliographic entropy medians in economics, however, are no longer consistently higher than those in the social sciences (though medians in both pillars tend to be lower when cross-listed articles are excluded). Differences in the yearly bibliographic entropy distributions of sustainability articles in the social sciences, as compared to those in the environmental sciences, are no longer statistically significant.

Discussion

Sustainability science, as embodied in the distribution of references in peer-reviewed journal articles from 1996 to 2009, satisfies the predictions and ideals of the tripartite model to a greater extent than scientific research generally speaking. But there are also significant disparities within sustainability science itself. Moreover, these disparities fit an intriguing pattern: there is an inverse relationship between the number of sustainability articles within a pillar and its interdisciplinarity as measured by bibliographical entropy. The economics pillar, which has the fewest articles on sustainability and the largest proportional increase in sustainability publishing, is the most interdisciplinary. The environmental science pillar is richest in terms of articles and the poorest in terms of connections to other pillars. Why is this the case?

We suggest that it is precisely because sustainability research is less widespread within economics and the social sciences that researchers affiliated with these pillars reach out, through citations, both to each other and to the environmental sciences. By broadening their citation networks beyond their home pillar, we speculate that economists and social scientists are able to accomplish several things. Substantively, they draw on less familiar theory, research strategies, and findings that have already undergone a vetting process by peer review. Pragmatically, they broaden their potential audience to include researchers who are interested in sustainability in general. Moreover, stretching sustainability research in economics and the social sciences to include references from environmental science may help to bolster subfields that, until recently, have not been central to the field of sustainability science.

On the other hand, sustainability researchers based in the environmental sciences enjoy a wider readership within their own pillar, and so have less incentive to incorporate ideas and approaches from outside disciplines into their published work. It is also possible that the palpable connection between the environmental sciences and many sustainability challenges, such as climate change, reduces incentives to cite across pillars: environmental scientists do not have to go beyond traditional boundaries to link their research to sustainability.

Our findings support the theory that researchers in areas of academia where sustainability science is relatively peripheral have an incentive to establish connections, through citations, with areas where sustainability science is better established. But analyses also find disparities in interdisciplinarity within pillars: specifically, articles published in cross-listed journals (journals that bridge pillars) appear to be more interdisciplinary than those which are published in single-pillar journals. Examples of cross-listed journals include *Ecological Economics*, which accounts for 15% of the sustainability articles in economics and 4% of those in the environmental sciences, and the *Journal of Sustainable Agriculture*, which accounts for 2% of the sustainability articles in the social sciences and 1% of those in the environmental sciences (Table S2 of the Supplementary Material). When articles published in cross-listed journals like these are excluded from the dataset, the yearly median bibliographical entropy for sustainability articles decreases by an average of 12% in economics, 13% in the social sciences, and 23% in the environmental sciences. These decreases in bibliographic entropy occur despite the fact that the sustainability articles which remain in the dataset—those published in journals listed only under one pillar—are still "free" to cite from cross-listed journals or from journals that are not associated with their home pillar at all. The results suggest that the remaining articles continue to do so, but at a reduced rate. In other words, interdisciplinarity in referencing, as defined by the standards of the tripartite model, is not evenly spread among all journals in each pillar, but, rather, is more closely associated with journals that are themselves interdisciplinary. How might this be explained?

We would argue that the relationship between journal and article interdisciplinarity suggests that there is less of an incentive to establish connections across pillars when the reputation of the journal itself is not tied to interdisciplinarity. It may also be true that authors of articles without the cover of an interdisciplinary journal are less likely to risk citing outside of their pillar. These explanations are consistent with studies that have found that explicitly interdisciplinary journals often play an important role in building bridges between fields and subfields whose citation networks are otherwise unconnected (Leydesdorff and Schank 2008).

In our study, pillars with smaller bodies of sustainability-oriented research appear to be more interdisciplinary, with much of this work being published in a relatively small number of explicitly interdisciplinary journals. Nearly 70% of sustainability articles in the economics pillar and 68% of those in the social science pillar are from journals cross-listed with at least one other pillar, while the same is true for just 34% of the articles in the environmental science pillar. But if sustainability publishing in economics and the social sciences is centered around cross-listed journals (when the majority of journals are not cross-listed), then it seems possible that interest in sustainability science may have difficulty growing beyond these journals, and reaching a wider audience.

In order to investigate the possibility that the dependence of sustainability science on cross-listed journals in economics and the social sciences might be detrimental to its growth and development in these pillars, we used Scopus' in-house metrics to analyze how the impact and prestige of various journals has changed over the study period. Source-Normalized Impact per Paper (SNIP) measures impact for a particular journal by finding a body of recent literature that cites the journal in question, and then examining the fraction of citations in that literature that point back to the target journal (Elsevier 2010). In contrast, the SCImago Journal Rank (SJR) evaluates journals through a more complicated, iterative "prestige transfer" algorithm: citations from prestigious journals contribute to a higher SJR for the target journal than those from less prestigious journals, and articles citing many articles transfer less prestige than those citing fewer (ibid.). Released in early 2010 for the years 1999–2009, both metrics are designed to overcome and normalize the differences in citation behavior that exist across disciplines, increasing their suitability for the comparisons that we wish to make in the current study.

Investigation of the integration of sustainability science into economics and the social sciences gives some cause for concern. The SNIP for the set of journals represented in our study has paralleled the rise in (and remained above) the average SNIP across all journals covered by Scopus (Fig. 3a). On the other hand, the average SJR of those journals in our study from the economics and social science pillars (in which many of the most important journals are highly interdisciplinary and cross-listed) has actually declined slightly and steadily, over a period during which the overall average SJR value rose slightly (Fig. 3b). In other words, while journals publishing on sustainability in these pillars are being cited more often and have higher-than-average impact, the prestige of these same journals remains lower than average, and may be declining. This may reflect some mathematical consequences of growth in the number of publications (Fig. 1) on the SNIP and SJR metrics: more publications means more citations and higher impacts, but more citations also means lower prestige transfer per citation, and lower contributions to the SJR. However, this finding might also contain a cautionary message: while interdisciplinary journals publishing on sustainability are gaining impact overall, they are being outpaced by other journals in their respective disciplines. Sustainability has gained popularity as a topic, as measured

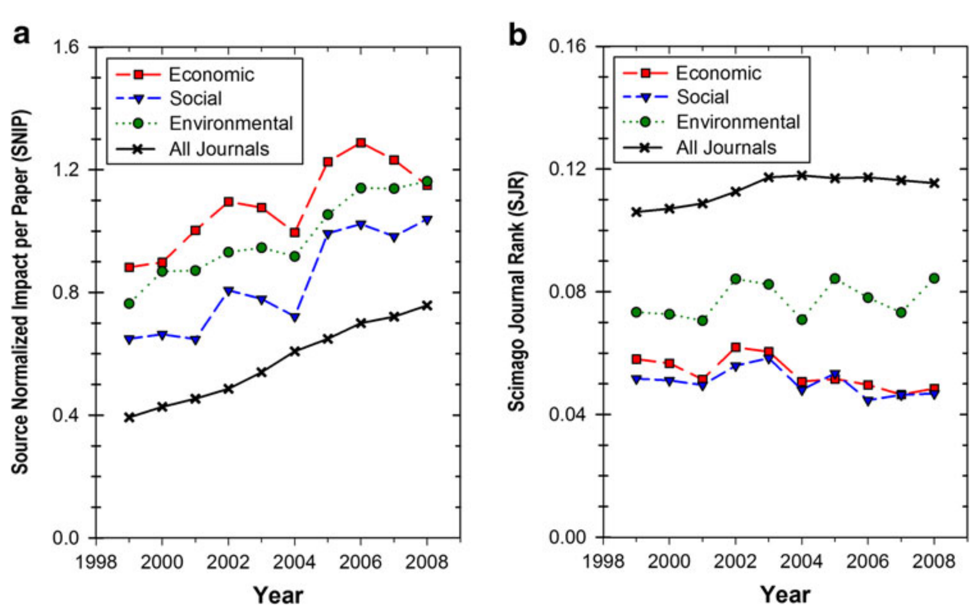

Fig. 3 Trends in the **a** Source-Normalized Impact per Paper (SNIP) and **b** SCImago Journal Rank (SJR) values. Average **a** SNIP and **b** SJR values for composite pillars and all Scopus journals (for which these values are calculated) over time are shown. Averages are calculated as the sum of the SNIP or SJR values for journals represented in a year, weighted by the number of articles from that journal appearing in the year, divided by the total number of articles appearing in the year

by increases in the absolute number of articles published. But the interdisciplinary venues in which issues surrounding sustainability are most prominently discussed, particularly in the economics and social science pillars, may be becoming less valued over time.

Conclusions and future research

As we consider the implications of interdisciplinary journals' sliding SJR values in their respective disciplines, it seems appropriate to return to a discussion of sustainability science and academic institutions. Despite the fact that scholars in the US and abroad have acknowledged the need for sustainability research, the genuine pursuit of sustainability requires a degree of interdisciplinarity that hiring, funding, and promotion processes are often ill equipped to accommodate. The results of our study are consistent with the idea that institutional obstacles to interdisciplinary work have had an impact on the structure of sustainability science. Where sustainability research has the widest audience—in the environmental sciences—incentives to establish connections across "pillars" of knowledge are likely reduced, and we find that fewer such connections are, indeed, made. Where the number of sustainability publications is still relatively small—in economics and the social sciences—researchers have strong reasons to establish connections with scholars across academia. But the relatively insular nature of interdisciplinary work on sustainability in these latter two pillars may be contributing to a decline in its perceived value over time.

Our study offers qualified support for, and suggests amendments to, the tripartite model of sustainability science, an influential and historically important framework for the exchange of ideas across the academic landscape. Moreover, our study has implications not just for the tripartite model, but also for theories of sustainability science in general. Sustainability science more successfully integrates knowledge from the environmental, social, and economic sciences than scientific research generally speaking. But sustainability science itself is not uniformly interdisciplinary. The finding that the environmental sciences, relative to the economic and social sciences, are significantly less interdisciplinary with respect to knowledge integration across pillars might be seen as troubling. But this variation across pillars also creates opportunities for comparative research into the institutional and social mechanisms underlying interdisciplinarity. We put forth one explanation: that readership size in an author's home field shapes incentives to make connections to other fields. But our study does not directly address the topic of causal mechanisms, and cannot conclusively test this hypothesis. Future studies should examine not just the extent to which interdisciplinarity characterizes different fields of research, but why interdisciplinarity varies across fields. In particular, increased understanding of why economics and the social sciences appear to differ from the environmental sciences with respect to knowledge integration could potentially support the efforts of funding agencies and centers of learning to advance sustainability science.

Finally, our finding that journals for sustainability research in the most interdisciplinary pillars have declined in prestige over time suggests that quantitative analyses and bibliometric data can play a role investigating how interdisciplinarity, and especially knowledge integration across pillars, influences the reach and impact of sustainability science. Recent studies have found that knowledge transfer, even between neighboring subfields, occurs in small steps (Porter and Rafols 2009), and that the gap between the social and natural sciences can be a "bridge too far" for journals to cross (Leydesdorff and Schank 2008, p. 1817). Our study indicates that connections across pillars are often associated with cross-listed journals. In light of these findings, it may be necessary to revise theories of sustainability science to take into account the possibility that different levels of interdisciplinarity are not only characteristic, but ought to be characteristic of different kinds of publications. Perhaps, for instance, it is mainly those publications directly concerned with the application of scientific knowledge to policy-making and problem-solving that should be expected to cite and integrate knowledge from disparate academic areas. If this is the case, then publications in the "gray"—non-peer-reviewed—literature of public agencies and non-governmental organizations may do a disproportionate amount of the work of aggregating across realms of knowledge. But it could also be that a lack of cross-pillar integration in the peer-reviewed literature, and particularly in the environmental sciences, is hindering sustainability science from accomplishing its goals. Additional research is needed in order to answer these and other questions.

The paper trail left by the scientific literature represents a unique opportunity to study how incentives, motivations, and constraints underlying research in sustainability ultimately manifest in published products. If knowledge integration has proven to be challenging for scholars working in relatively closely related subfields, then the task of bridging whole realms of academia would seem to involve particular difficulties. Yet, such are the demands on an emerging scientific field that seeks to solve some of the most pressing problems facing society today. The future of sustainability science will depend on both the continued efforts of researchers to share their work across traditional academic boundaries and on increased awareness that institutional structures surrounding promotion and funding may be out of alignment with the ideals and requirements of sustainability research.

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