Are social sciences becoming more interdisciplinary? Evidence from publications 1960–2014

Reference:
Zhou Hongyu, Guns Raf, Engels Tim.- Are social sciences becoming more interdisciplinary? Evidence from publications 1960–2014
Journal of the Association for Information Science and Technology / Association for Information Science and Technology - ISSN 2330-1643 - 73:9(2022), p. 1201-1221
Full text (Publisher's DOI): https://doi.org/10.1002/ASI.24627
To cite this reference: https://hdl.handle.net/10067/1862090151162165141

Are social sciences becoming more interdisciplinary? Evidence from publications 1960-2014.

Hongyu Zhou[1], Raf Guns[1], and Tim C. E. Engels[1]

[1] *Hongyu.Zhou@uantwerpen.be, Raf.Guns@uantwerpen.be, Tim.Engels@uantwerpen.be*

Centre for R&D Monitoring (ECOOM), Faculty of Social Sciences, University of Antwerp
Middelheimlaan 1, 2020 Antwerp (Belgium)

This is the final peer-reviewed accepted manuscript for our article under the same name on JASIST. The official published version can be found via the following link: https://asistdl.onlinelibrary.wiley.com/doi/full/10.1002/asi.24627

Are social sciences becoming more interdisciplinary? Evidence from publications 1960-2014.

ABSTRACT

Interdisciplinary research is widely recognized as necessary to tackle some of the grand challenges facing humanity. It is generally believed that interdisciplinarity is becoming increasingly prevalent among STEM fields. However, little is known about the evolution of interdisciplinarity in the Social Sciences. Also, how interdisciplinarity and its various aspects evolve over time has seldom been closely quantified and delineated. This paper answers these questions by capturing the disciplinary diversity of the knowledge base of scientific publications in nine broad Social Sciences fields over 55 years. The analysis considers diversity as a whole and its three distinct aspects, namely variety, balance, and disparity. OLS regressions are also conducted to investigate whether such change, if any, can be found among research with similar characteristics. We find that learning widely and digging deeply have become one of the norms among researchers in Social Sciences. Fields acting as knowledge exporters or independent domains maintain a relatively stable homogeneity in their knowledge base while the knowledge base of importer disciplines evolves towards greater heterogeneity. However, the increase of interdisciplinarity is substantially smaller when controlling for several author and publication related variables.

INTRODUCTION

Interdisciplinary research (IDR) is recognized as a necessary condition to tackle complex and pressing societal problems that cannot be truly resolved by a single discipline (Carayol & Thi, 2005; Frodeman & Mitcham, 2016). In a review article, Jacobs and Frickel (2009) characterized two sources of promoting efforts towards interdisciplinarity, namely top-down initiatives and bottom-up support. Top-down initiatives include various grants, seed projects, training programs, and job opportunities that are dedicated to supporting IDR by federal agencies, private foundations, and universities. Bottom-up support roots deeply in the acceptance and confidence of IDR held by many individual researchers that "interdisciplinary knowledge is better than knowledge by a single discipline" (Jacobs & Frickel, 2009, p. 46) or in their willingness to conduct IDR (Milman et al., 2017).

To closely monitor and evaluate the aforementioned supporting initiatives and understand mechanisms behind IDR, recent studies have examined its different aspects (Rousseau et al., 2019), such as **input** (e.g. disciplinary diversity in team assembly; Abramo et al., 2017; Schummer, 2004; Zhang et al., 2018), **process** (e.g. disciplinary diversity in reference; Mugabushaka et al., 2016; Porter & Rafols, 2009; Zhang et al., 2016), **outputs** (e.g. topic diversity in the full text; Bu et al., 2020; Evans, 2016; Nichols, 2014), and **outcomes** (e.g. research impact; Larivière et al., 2015; Larivière & Gingras, 2010; Rinia et al., 2004; J. Wang et al., 2015; Yegros-Yegros et al., 2015). Among all, quantitative measurements to evaluate the intensity of IDR process, i.e., how interdisciplinary one's research is, is one of the most discussed research topics (Wagner et al., 2011). Although such indicators have been criticized as confusing and unable to achieve universally convergent validity at the micro-level (Q. Wang & Schneider, 2020), each of them individually can still effectively quantify the diversity of knowledge and serves to infer interdisciplinarity from a macro perspective. Given that the purpose of this study is to investigate general patterns and dynamics of interdisciplinarity as a social phenomenon, we reckon the aforementioned defects of the indicators do not compromise the validity of this study.

One of the frequently referenced macroscopic statements by researchers, policy-makers, and the media is "science is becoming more interdisciplinary". A consensus seems to have formed that scientists working in dissimilar knowledge bases or mastering different skills have been increasingly crossing disciplinary borders to collaborate with unconventional partners; this leads to more interdisciplinary and scientifically significant outcomes. Empirical evidence, however, is still limited to STEM fields; a detailed summary and comparison for related literature are available in Appendix regarding data, classification scheme, measurement, discipline/region, and results. Porter and Rafols (2009) investigated the change of interdisciplinarity (embodied by Rao-Stirling diversity) between 1975 and 2005 over six research domains from STEM and reported a modest increase. Another group of publications is devised to capture the evolution of IDR in certain fields such as biochemistry and molecular biology (Chen et al., 2015), physics (Pan et al., 2012), biodiversity science (Craven et al., 2019), and library and information science (Chang & Huang, 2012); for specific regions

(Karlovčec & Mladenić, 2015; Lužar et al., 2014); or for science in general (Gates et al., 2019; Larivière & Gingras, 2014). One article specifically analyzing the temporal trends (1980-2010) in Social Sciences and its sub-fields is conducted by Levitt et al. (2011) using the percentage of cross-disciplinary citing documents. They reported a declining trend in the 1980s and a sharp rise in the 1990s. However, their chosen indicator can only shed light on partial aspects of interdisciplinarity according to recent developments of the theoretical framework of IDR measurements. Hence we conclude from our literature review that temporal change in IDR in Social Sciences has not been thoroughly studied so far.

We would like to emphasize that IDR in Social Sciences is as important and prevailing, if not more, as in any discipline in STEM. Many disciplines from Social Sciences that are now perceived as independent and established knowledge territory used to be the direct result of knowledge "interdisciplined" (Frodeman, 2010). According to Frodeman (2010)'s book on interdisciplinarity, Science and Technology Studies (STS), which originally emerged in the 1960s, was "included for the first time in the International encyclopedia of social and behavioral sciences…as an intersecting field rather than a discipline" (p. 191) in 2001. Nowadays, there are multiple STS programs taught in academic institutions from more than 20 countries, several professional associations around the world, and at least 16 notable peer-reviewed journals focusing on STS according to Wikipedia[1]. On the other hand, many established disciplines in Social Sciences such as sociology achieved significant progress and exciting reinvention after being "interdisciplined" with previously remote disciplines and developed new and thriving achievements. For instance, sociologists are inspired to use large-scale social media datasets and network theories to study collective behavior and politics from a new computational perspective and have achieved considerable quality progress (Edelmann et al., 2020). Social Sciences could be one of the most fertile grounds to observe and understand how IDR has evolved, where we are now, and where it is going to be.

In this study, we attempt to delineate the evolution of interdisciplinarity in Social

[1] Wikipedia, "Science and Technology Studies."

Sciences over 55 years and contribute to a more comprehensive answer to the question "is science becoming more interdisciplinary".

The rest of the paper is organized as follows: we first introduce the dataset and methodology we adopt. The following section presents the results and discussions and the last section concludes.

METHODOLOGY

Data

The Microsoft Academic Graph (MAG) is adopted in our empirical study. MAG differs from other bibliographic databases in that it adopts a bottom-up approach (individual paper level) for the field categorization process. MAG quantifies the semantic distance between two textual paragraphs representing two publications and then clusters the retrieved semantic representations to form the basis of *concepts*, which are *de facto* fields, domains, or disciplines in practice. Six levels of concepts are clustered automatically on different granularities. The top two levels of concepts (L0 and L1) are manually defined into a unique hierarchical structure to be compatible with most of the categorization systems (K. Wang et al., 2020), where L0 is comprised of 19 fields (e.g., chemistry and economics) and L1 consists of 294 subfields (e.g., biochemistry and macroeconomics).

To draw a comprehensive view of IDR in Social Sciences, we include as many subfields from Social Sciences as possible. However, the highest level of field hierarchy in MAG (L0) does not list Social Sciences as one of the 19 main fields in their setting, let alone the mapping relationships between Social Sciences and its corresponding subfields. Furthermore, the granularity of the discipline setting in L1 might be too trivial and needlessly specific to embody the major subfields or research areas. To address this issue, we identified 60 subfields from L1 that are classified under Social Sciences according to the OECD Fields of Science (OECD, 2015) and mapped them into nine broader subfield groups[2], namely *Psychology*, *Economics & Business*, *Educational*

[2] The classification scheme provided by the OECD defines a three-level hierarchical structure having

Sciences, *Sociology*, *Law*, *Political Science*, *Social & Economic Geography*, *Media & Communications*, and *Other Social Sciences.* The details of the mapping are available in Appendix Table A1. The remapped sub-field labels assigned to each paper are only used in the process of recognizing scientific publications affiliated with Social Sciences and presenting the results. When calculating IDR indicators, the original subfield labels (L1) are employed instead of our re-assigned labels to maintain the accuracy and integrity of the dataset. An example to clarify the terms we used for knowledge domains at different levels: Social Sciences is termed as the main field, consisting of Psychology and eight other fields. Applied Psychology is one of the subfields (or discipline) listed under the field of Psychology.

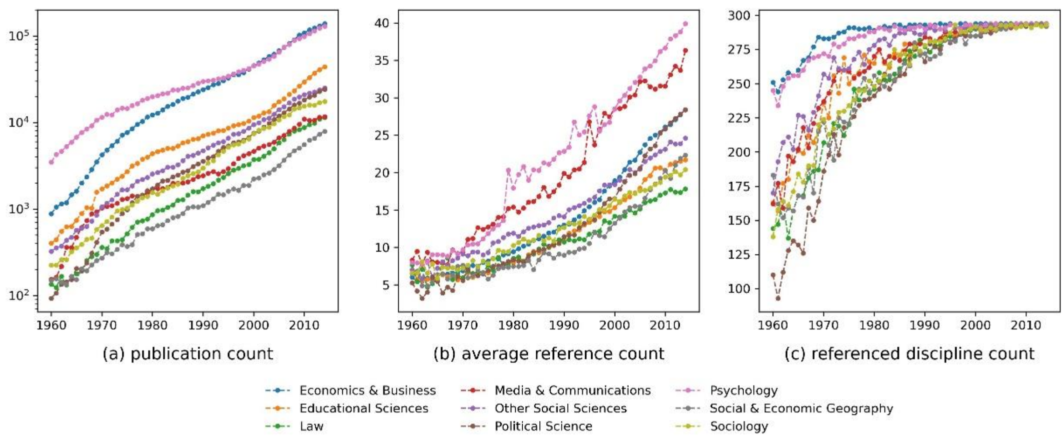

Figure 1. Descriptive statistics of the selected MAG subset by regrouped L1-level domains: (a) Number of publications over years; (b) Average number of references over years; and (c) Number of disciplines referenced over years.

The dataset comprises 3,989,221 journal/conference publications, published between 1960 and 2014, labeled with at least one of the subfields from our earlier defined Social Sciences structure, and having at least one recorded reference. Publications labeled with more than one category will be assigned to each category respectively. Fractional counting is adopted in this study to cope with the multi-labeling in the field categorization of publications. As shown in Figure 1(a), all nine fields achieved almost exponential growth in publications, with Psychology and Economics & Business

---

social science at the top level, e.g.. social science – educational sciences – education (general). The selection and mappings from 60 subfields in MAG to nine social sciences disciplines are made manually, with reference to both the OECD classification scheme and other resources, for instance Wikipedia and Web of Science.

continuing to be the largest fields in Social Sciences. Besides, 90,673,766 references (9,903,133 unique cited papers) and their corresponding discipline labels are retrieved. Figure 1(b) illustrates the temporal change of the average number of references for all publications in the dataset. Economics & Business, Psychology, Political Science and Media & Communications increased more than threefold in 55 years, while the other fields also achieved more than 200% growth, except Law which grew by 132%. In addition, more disciplines that were previously weakly related or even unrelated to Social Sciences are now referenced as shown in Figure 1(c). For instance, Political Science cited only 110 out of 294 disciplines in 1960, whereas this number increased to 294 in 2014. Almost all 294 disciplines are cited by Social Sciences in their annual production by the end of 2014.

Methods

<u>Framework</u>

To answer the question "Are social sciences becoming more interdisciplinary", we first need to decipher what it actually entails and what people might expect of it. Two interpretations can be drawn from this question: 1) Is more IDR observed in social sciences over time? 2) Are researchers in social sciences designing and conducting their research in a more interdisciplinary way? The first interpretation focuses on the change in the overall distribution of interdisciplinarity, while the latter taps into researchers' cognition and mentality regarding interdisciplinarity. In a more static setting where other variables such as the total number of publications, team size, and reference count do not exhibit significant change, the two interpretations would converge and an increase in value of a certain IDR indicator would also provide strong evidence for a corresponding change in people's willingness to conduct IDR. However, other variables *de facto* keep evolving and interacting with interdisciplinarity. Hence, a positive answer to the first question does not necessarily imply a positive answer to the second one. Examining the change in the distribution of interdisciplinarity can only deliver us partial answers or incomplete interpretations of the research question. To gain a thorough understanding, one must also try to exclude the effect of other confounding variables. In this study, we, therefore, investigate the evolution of IDR from two perspectives. First, we quantify and observe the evolution of IDR via multiple proposed indicators. Then, ordinary least squares (OLS) regressions are conducted to examine the evolution of IDR by controlling for several related variables. In the next section, we will first introduce the indicators of our selection for the observational analysis and then move on to the design of the OLS regression.

Quantifying IDR

Stirling (2007) pointed out that diversity consists of three basic concepts, namely variety, balance, and disparity, each of which is a necessary but insufficient property of diversity as a whole. This notion and a generic indicator of diversity were then introduced and modified by Rafols and Meyer (2010) to Information Science as a quantitative measurement of knowledge integration to infer interdisciplinarity. A significant proportion of research is devoted to devising indicators that integrate two or three components (dimensions) of diversity to achieve a reliable metric and assess/ compare IDR for different entities. In this study, we aim to work as comprehensively as possible so that information loss caused by dimension reduction or integration can be minimized. Therefore, to quantify the evolution of IDR processes, we employed single-component (variety, balance, and disparity themselves) indicators as well as three multi-component indicators: Rao-Stirling (RS) diversity (Rafols & Meyer, 2010; Stirling, 2007), DIV (Leydesdorff, Wagner, & Bornmann, 2019), ${}^2D^s$ (Zhang, Rousseau, & Glänzel, 2016). We believe that the involvement of single-component measurements may provide more contextual implications, for instance, the number of disciplines referenced, and that the multi-component measurements shed more insights into the evolution of IDR.

Table 1 provides notations and mathematical definitions of each indicator we employed in this study. Variety (n_c) is operationalized as the number of disciplines referenced by each publication, which reveals information regarding the **broadness of the knowledge base**. Its variant, relative variety (n_c/N), is used in DIV representing variety in a relative scale. Balance (B), representing the **evenness of the knowledge base**, is quantified using two indicators of evenness (Beisel et al., 2003), namely, the Shannon Evenness Index ($H/\ln n_c$) and $1 - Gini_c$ (Gini coefficient), where B = 1 indicates maximum evenness and B = 0 shows extreme imbalance. Disparity (D) captures the average dissimilarity (or distance, explained further on) between every two disciplines referenced for each publication, which can be utilized to examine the cognitive distance and **heterogeneity of the knowledge base**.

Three indicators integrating a part of or all of the above-mentioned three components are also employed (i.e., multi-component indicators). RS calculates the sum of dissimilarities between every two disciplines referenced multiplied by the product of proportions each discipline accounts for in the reference list. DIV is the multiplication of relative variety, balance, and disparity ranging from zero to one. ${}^{2}D^{s}$ can be regarded as a variant of RS that possesses greater discriminatory power, satisfies the properties proposed in Leinster and Cobbold (2012), and employs similarity among categories instead of disparity directly, yielding $1/(1-RS)$.

Table 1. Selected measures of IDR.

Notation			
n_c	number of disciplines referenced	d_{ij}	dissimilarity between categories *i* and *j*
p_i	proportion of elements in category i	N	number of categories in total
x_i	number of references to the i-the category in an ascending order		
Indices			
Variety	n_c	Rao-Stirling (RS)	$\sum_{i,j(i\neq j)} d_{ij}(p_i p_j)$
Balance (B)	$H/\ln n_c = -\sum_{i=1}^{n_c}(p_i \ln p_i)/\ln n_c$	DIV	$(n_c/N) * Gini_c * D$
Disparity (D)	$\frac{\sum_{i\neq j} d_{ij}}{n_c(n_c-1)}$	${}^{2}D^{s}$	$1/(1-RS)$
Gini coefficient ($Gini_c$)	$\frac{\sum(2i-n_c-1)x_i}{n_c\sum_{n_c} x_i}$		

Four out of seven measures (i.e. disparity, RS, DIV, ${}^{2}D^{s}$) employ the dissimilarity between two categories d_{ij} in their calculation, which is operationalized as $1 - cosine\ similarity$ in a cross-citation matrix, as shown to be valid and efficient in Zhang, Rousseau, and Glänzel (2016). The temporal perspective of this paper makes a few modifications to the cosine similarity necessary, that is, the application of a time window on similarity calculation. As the distance or reference strength among disciplines may be changing over time (Frank et al., 2019), potential structural changes to the similarity matrix cannot be ignored when performing temporal analysis. To account for this, we construct eleven similarity matrices with a five-year time window for each to capture the dynamic distance change between disciplines in 55 years. This yields the following equation:

$$d_{ijt} = 1 - \frac{R_{ij}+R_{ji}}{\sqrt{\left(TC_i^t + TR_i\right)\left(TC_j^t + TR_j\right)}} \quad (1)$$

where i and j refer to two sets of publications from two different categories published during the period t, R_{ij} denotes the number of times set i publications cite set j publications, TC_i^t denotes the total number of citations set i publications received from other categories overtime during the period t, and TR_i denotes the total number of references from papers in set i to other categories.

When examining balance and disparity, publications with variety equal to 1, 3.36 % of the dataset, are excluded since they deliver null implication on interdisciplinarity in a unit with only one category. These publications are accordingly not included in the analysis of integrated interdisciplinarity as well.

Regression analysis

To answer the second interpretation of our research question, we used OLS regressions to control for other confounding variables and observe the effect of time on interdisciplinarity values. Specifically, publications from 2005-2009 and 2010-2014 constitute the dataset for regression analysis. The investigated independent variable, time, is set to be 0 if a publication is published in the first period, or 1 if published in the second. Nine confounding (control) variables are identified that might directly or indirectly influence interdisciplinarity or the calculation of the chosen indicators. Among them, four variables relate to the characteristic of publications, as follows:

- ***Number of references:*** References and their disciplinary affiliations are the ingredients for quantifying interdisciplinarity in this study. A greater number of references would directly affect the calculation of interdisciplinarity. For instance, Wang et al. (2015) reported a positive correlation between the number of references and RS values in their study. On the other hand, publications are found to have a greater number of references over time (Nicolaisen & Frandsen, 2021).
- ***Reference age:*** The average year of difference between the publishing year of referenced articles and the citing article. Rinia et al. (2004) discovered interdisciplinary citations are relatively more attributed to the older literature.
- ***Two-year citation after publication ($\ln C_2$):*** The relationship between citations and

interdisciplinarity is studied by many studies, although with different, sometimes opposite, findings (Glänzel & Debackere, 2021). Here we use number of citations as a proxy for latent research quality or potential. We take the natural logarithm of two-year citations into the regression model since citation is unevenly distributed.

- ***Two-year Journal Impact factor (JIF):*** This variable takes into account the citation impact of publishing venues of publications.

In addition, teams assembly, or collaboration, as another important aspect of IDR, would also affect the interdisciplinarity of the knowledge base (Zhang et al., 2018). Five variables controlling for the effect of authors (or teams) are included as follows:

- ***Team size:*** The number of co-authors in the publication byline. More members in a team may be associated with a greater probability of introducing external knowledge to research.
- ***Author average productivity:*** Average number of publications each coauthor published within the five years before the focal publication.
- ***Author average impact (log scale):*** Average number of citations each coauthor received within the five years before the focal publication.
- ***Author average connection:*** Average number of coauthors each coauthor had within the five years before the focal publication.
- ***Author average seniority:*** Average academic age of each coauthor by the time the focal publication was published.

The regression analysis is conducted in two steps. First, we examine only the effect of the time variable on interdisciplinarity, which is equivalent to the change in average interdisciplinarity value from the observational study perspective. Second, both time and all the other control variables are added to the regression to determine the effect of time. The coefficients of regressions are retrieved for comparison between the two models to offer a holistic answer to both interpretations of the research question. The regression models are constructed for each of the nine disciplines to arrive at detailed disciplinary understandings of the social sciences. Around 30% of the publications from the investigated period cannot be matched with detailed author information. Therefore, a sub-sample of 1,516,119 publications is adopted in the regression analyses.

RESULTS AND DISCUSSION

In this section, we will first present the results of the observational studies and then dive into the results of the regression analyses.

The evolution of IDR: A descriptive perspective

<u>The broadness of the knowledge base</u>

Figure 2 illustrates the evolution of variety for all fields in 55 years (1960-2014). For the nine selected fields, the number of subfields each publication has cited (i.e. variety) on average keeps increasing over time, which can be seen from the continuous right-shift of dashed lines. Publications between 2010 and 2014 from all fields generally cited 5-8 more disciplines than contributions that appeared between 1960 and 1965. Despite unanimous growth, several differences in the level of increase and changes in rank should be noted. Political Science gained the largest increase in variety from 4.2 to 12.8, yielding a 206.7% growth over 55 years, which also pushed it from 9th to 2nd position in terms of variety rank among fields. The smallest growth in variety can be found in Sociology (90.3%) whose rank slipped from 2nd to 7th at the end of 2014. Other fields doubled their variety and remained at a similar rank. By the end of 2014, Psychology, Political Science, and Media & Communications were the top three interdisciplinary fields in Social Sciences in terms of variety, while Law, Educational Sciences, and Sociology showed the least variety.

Also, the dominance of low variety publications has weakened over time as opposed to the rise of high variety publications. For instance, the percentage of publications with variety no larger than 2 accounted for more than 30% in Economics & Business, Educational Sciences, Law, Other Social Sciences, Social & Economic Geography, and Sociology and more than 40% in Political Science from 1960 to 1964; that percentage universally decreased to less than 15% (less than 9% for Economics & Business, Educational Sciences, Media & Communications, Other Social Sciences, Political Science, Psychology) from 2010 to 2014. Such a weakening tendency can also be observed from the change of peak for several fields. The mode increased in five out of nine fields, which shows that the majority of recent researchers tend to situate their study on a more diverse knowledge base. However, such a right-shifting peak did not occur for Social & Economic Geography, Sociology, and Law as their peaks of variety remained at the same level. Such consistency over time might be explained by the specialized nature of a field like Law. An alternative explanation is that these fields are in a nascent state of interdisciplinarity and will eventually become dominated by high variety publications like the others. In any case, a clear increasing trend of the high-variety research is apparent from the uplift of the right tail of the distribution for all nine fields.

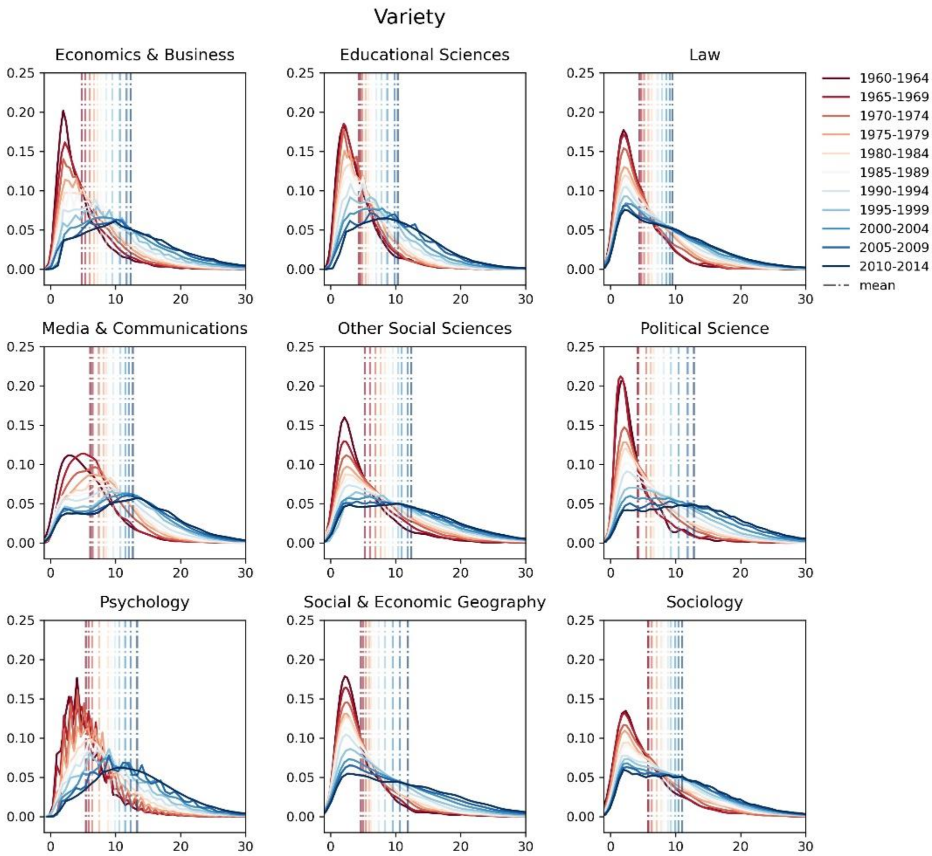

Figure 2. Evolution of variety. Each subplot represents a field and each solid curve shows the kernel density distribution of variety for all publications in the corresponding period. The vertical dashed lines denote the mean of variety for each period. The same color for a solid curve and a dashed line means that they are describing the same period.

The aforementioned findings illustrate the ever-increasing broadness of the knowledge base for research in Social Sciences, more significantly in less-specialized fields. Furthermore, such multi-discipline-sourced studies have become the mainstream of science production. Clearly, researchers in Social Sciences are absorbing more and more external knowledge or skills to advance their study.

Evenness of the knowledge base

Contrary to variety, the mean balance exhibits a decreasing trend for all fields, which holds for both two indicators of evenness (Pearson coefficient = 0.975 for mean values). The largest drop can be found in Economics & Business, Psychology, and Political Science for more than 30% during the past 55 years. The average balance for Sociology, Law and Social & Economic Geography declined the least for around 20%. Psychology and Media & Communications continued to be the fields with the lowest balance (9th and 8th respectively) throughout the period, while Law remained in the top 3 fields of this parameter.

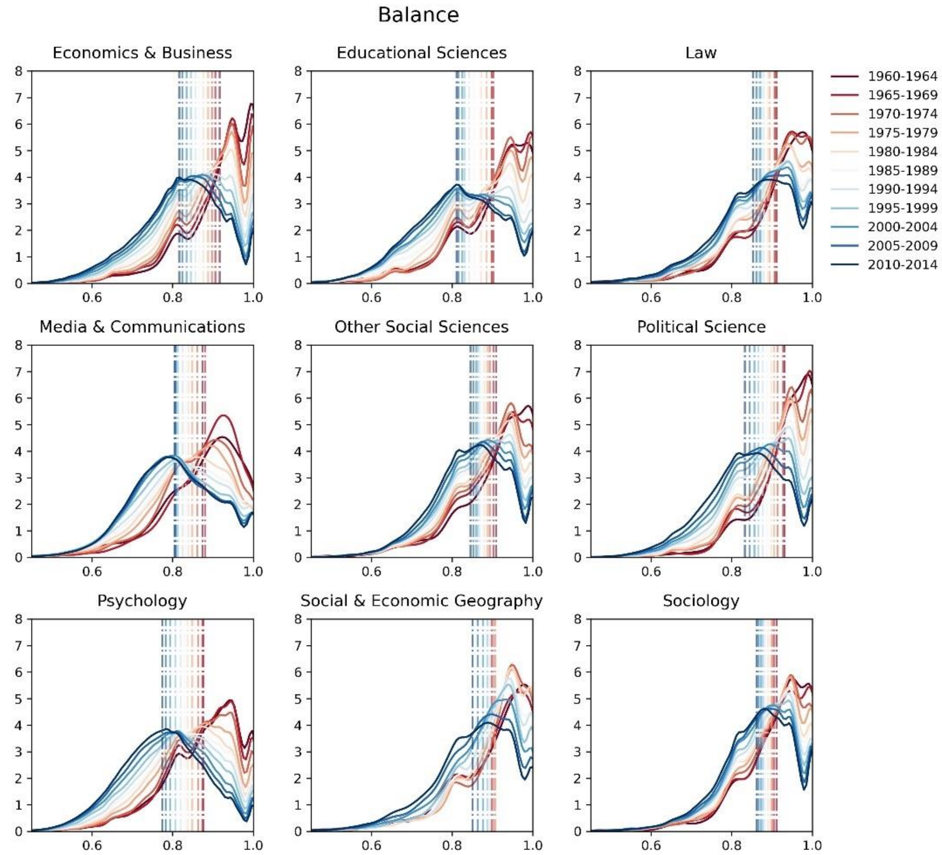

Figure 3. The evolution of balance (Shannon Evenness Index). (See captions in Figure 2 for description. Results for balance using Gini coefficient are available in Appendix.)

Furthermore, changes in the peaks and skewness of the distribution are worthy to be closely examined. The peaks for all fields continued to evolve towards lower balance sections, which indicates the ever-growing unbalance in the knowledge base of scientific research. This statement can be strengthened by the shift of skewness from right to left for some fields, which also illustrates the increasing population of lower-balance publications. As a robustness check, we also examined the temporal trends in balance with a controlled value for variety since an increasing variety might naturally cause a decrease in the value of balance. The results confirmed the original findings by comparing publications with equal value for variety (for example V = 5, see Appendix

A1) over time.

The decreasing trend of balance is tightly related to knowledge base specialization (Foster et al., 2015). The formation of new research topics might result in clusters of disciplines that are more frequently and intensely referenced together which yielding a dominant knowledge combination. Such tendency indicates that researchers active in the Social Sciences tend to have a clearer and more strategic agenda in terms of how to situate their research and how to learn from their peer scientists. Furthermore, we suppose that the increasing broadness in knowledge base (i.e., variety) might as well be associated with the decrease in evenness (i.e., balance) to some extent. The occurrences of new disciplines (an increase of the value of variety) in the knowledge base might be naturally weak in intensity and proportions, which leads to an imbalanced knowledge base. What's more, a decreasing balance, i.e. more specialized knowledge base, could serve researchers better in boosting research impact as balance is claimed to be negatively associated with long-term citations (J. Wang et al., 2015). Research that learns widely (high variety) and digs deeply (low balance) has greater potential to achieve more significant impact and visibility through interdisciplinarity. The increasing variety and decreasing balance indicate that researchers are wisely choosing their knowledge base so that they can benefit both from interdisciplinarity and specialization.

Heterogeneity of the knowledge base

Figure 4 shows the evolution of disparity. Unlike previous findings, the change of average disparity varies fundamentally and the universal increasing trend did not reappear. The largest increase in mean disparity can be found in Psychology with a 13.2% increase over 55 years, followed by Media & Communications and Educational Sciences in 2nd and 3rd place with an increase of around 5.5%. Sociology, however, maintains a similar level of disparity over the entire period. Based on the temporal trend in central tendency, we can separate all fields into two groups, the increasing ones, and the stable (fluctuating) ones. The increasing group, including Educational Sciences, Social & Economic Geography, Media & Communications, and Psychology, has achieved consistent growth over the time period considered, while those in the stable (fluctuating) group – Economics & Business, Sociology, Political Science, Law, and Other Social Sciences – fluctuates around a certain value and alters little.

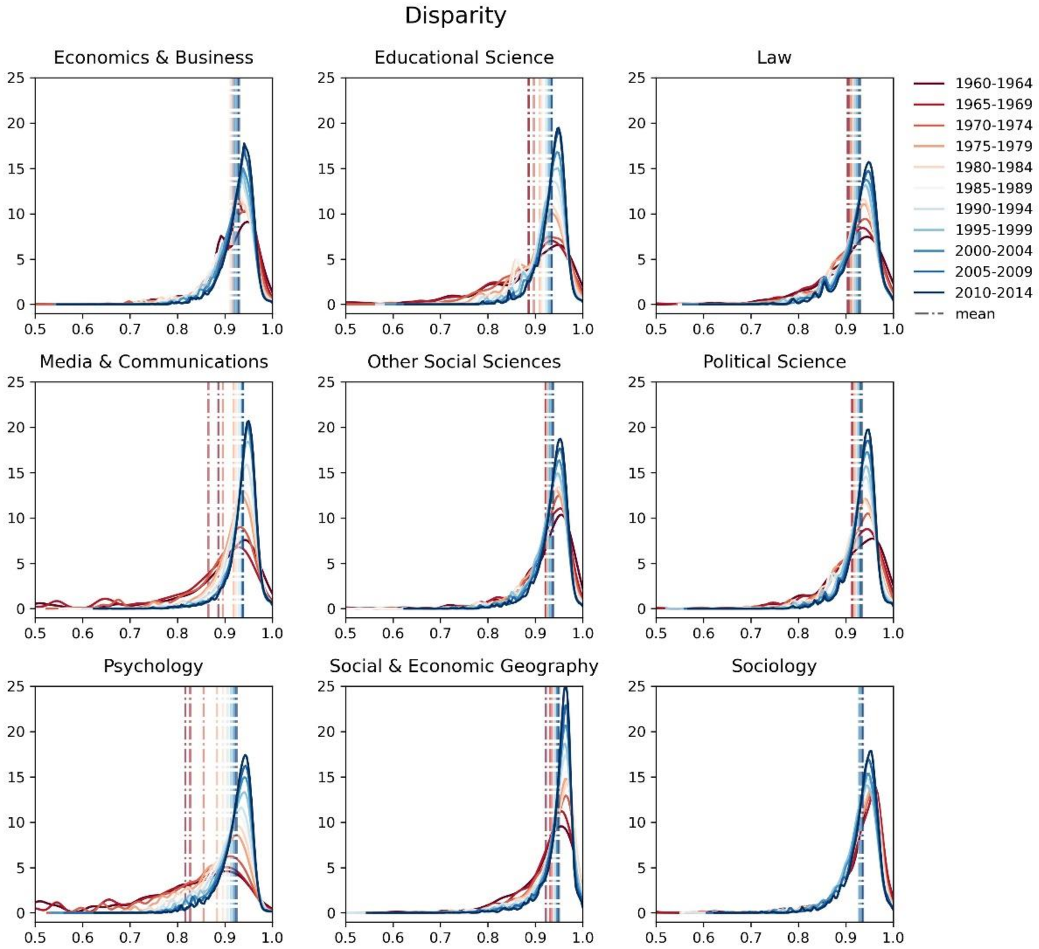

Figure 4. The evolution of disparity. (see captions in Figure 2 for description)

We believe this distinction is related to their role in the scientific trading systems, i.e. knowledge importer/exporter, and knowledge dependent/independent fields. According to Yan et al. (2013), economics, business, and sociology are found to act as important knowledge exporters in Social Sciences. Political Science and Law exhibit high self-citation rates indicating their relative knowledge independence. By contrast, fields with increasing disparities appear to be more dependent on other disciplines with either a low export/import ratio or a low self-citation rate, or both. Additionally, a stable heterogeneity in knowledge base for some fields, such as Economics, could also attribute to their reservations and skepticism towards research in other disciplines (Pieters & Baumgartner, 2002).

An increasing heterogeneity indicates that researchers in these fields are referencing more "remote" or previously less connected disciplines to constitute their knowledge bases. As for the other group, the relatively stable distribution suggests that fields in this group did not experience a significant change in the heterogeneity of their knowledge base, that is to say, the newly cited disciplines, if any, are not cognitively remote or exhibit a similar level of cognitive distance to the original knowledge base.

Integrated IDR trends

We calculated the evolution of integrated IDR using three indicators, namely DIV, ${}^{2}D^{s}$, and RS to investigate how the diversity of references as a whole evolves over time. Similar temporal trends are found in results for all three so here we only present one, namely ${}^{2}D^{s}$ (see Appendix Figure A2 for the other two). The distribution of ${}^{2}D^{s}$ for all nine fields is shown in Figure 5.

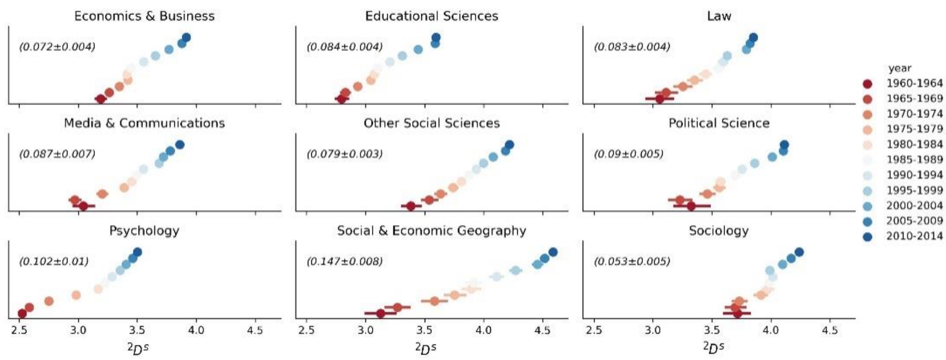

Figure 5. Temporal trends in integrated IDR measurements for nine fields. Dots represent mean values and bars indicate their 99% confidence intervals. Different periods are indicated with different colors. The slope and its 95% confidence interval of a linear fit on the dots are shown in the top left of each subplot.

It is obvious that publications from all fields in Social Sciences are, generally speaking, becoming increasingly interdisciplinary over time, with a few distinctions for each. Social & Economic Geography achieved the greatest rise (51.5%) and became the field with the highest average interdisciplinarity, replacing Sociology which used to occupy first place in 1960-1964. Psychology and Educational Science, both of which accomplished a significant rise (40.2% and 32.6%, respectively), are still the two least interdisciplinary fields. The increase of interdisciplinarity for Educational Sciences, Economics & Business, and Political Science seems to have accelerated from 1990 to 2009, while that of Psychology, Social & Economic Geography, Sociology, and Law is slowing down in the 21st century. Almost all fields experienced the smallest increase in the most recent period compared to the increase in 2005-2009.

In previous work by Porter and Rafols (2009), they reported a 5% increase for six research fields in STEM from 1975 to 2005 measured by the Rao-Stirling on journals. The increase for this same indicator over the same period is 6.65% on average for nine fields in Social Sciences we study here. Even though a direct comparison is not viable due to different datasets and different measured subjects, this seems to corroborate with their findings and extend it from STEM to Social Sciences.

What should be additionally pointed out is that interdisciplinarity is not ever-increasing for all fields and all periods. In the 1960s, Media & Communications and Political Science exhibit a temporal drop in interdisciplinarity on average. Something similar happened for Political Science and Economics & Business in the period 1980-1984. On the other hand, certain synchronicity in change for certain periods can be observed and might lead to some interesting implications. In addition to the simultaneous decrease mentioned above, a rather large increase in interdisciplinarity can be observed in the early 1970s and 2000s for many fields, for instance, Law, Social & Economic Geography, and Political Science. The increasing interdisciplinarity for almost all fields slowed down in the 1980s. Although the developments in interdisciplinarity are realized by each individual field itself with their own pace or characteristics, they might be synchronously facilitated or hindered by historical contexts. For example, internationalization, digitalization, mobility of researchers, and interdisciplinary programs in higher education may have provided a better infrastructure fostering scholarly communication and knowledge integration, eventually leading to increasing interdisciplinarity.

The evolution of IDR: regression model

As explained in *Methods*, we choose to compare the actual (raw) change in mean interdisciplinarity values with the controlled change excluding the effects of other confounding variables; the latter is embodied as the coefficient of the time variable in an OLS regression controlling 9 other variables. We take the logarithm of ${}^{2}D^{s}$ as inputs for dependent variable since its distribution is log-normal upon visual inspection. Through the Variance Inflation Factor test, the regression models do not suffer from serious multicollinearity issues. In Table 2, we report the raw change and controlled change of interdisciplinarity values from 2005-2009 to 2010-2014 in our sub-sample. For instance, while (the log of) average interdisciplinarity has increased by .0159 (raw change) for Economics & Business between 2005-2009 and 2010-2014. After controlling for these variables, the average interdisciplinarity remains virtually stable, with a very slight decrease (-.0031), which shows the observed increase in interdisciplinarity might be related to change in publication and author characteristics. Detailed results of regression for the field Economics & Business are presented in the Appendix as a demonstration.

Table 2. Comparison between raw and controlled change in average interdisciplinarity from 2005-2009 to 2010-2014.

Results for integrated IDR indicators ($^{2}D^{s}$)

	Raw change (log)	*Controlled change (log)*
Economics & Business	+.0159	-.0031***
Educational Sciences	-.0007	-.0175***
Law	+.0287	+.0079*
Media & Communications	+.0233	+.0080***
Other Social Sciences	+.0091	-.0129***
Political Science	+.0139	-.0188***
Social & economic geography	+.0266	-.0103*
Sociology	+.0102	-.0047
Psychology	+.0153	+.0129***

Regression: ***p<0.01. **p<0.05. *p<0.1.

Results for single-component IDR indicators

	Variety		***Balance***		***Disparity***	
	Raw	*Controlled*	*Raw*	*Controlled*	*Raw*	*Controlled*
Economics & Business	+0.863	+0.015	-0.016	+0.004***	+0.003	-0.003***
Educational Sciences	+0.476	+0.006	-0.011	+0.002***	-0.001	-0.005***
Law	+0.530	+0.038	-0.019	-0.006***	+0.010	+0.003*
Media & Communications	+0.788	+0.206***	-0.011	+0.005***	+0.004	-0.002
Other Social Sciences	+0.516	-0.127***	-0.014	-0.001	+0.004	-0.002**
Political Science	+1.099	-0.179***	-0.027	+0.003***	+0.004	-0.005***
Social & economic geography	+1.278	+0.099*	-0.032	-0.005***	+0.010	+0.000
Sociology	+0.336	-0.081*	-0.008	+0.001	+0.001	-0.003**
Psychology	+0.964	+0.416***	-0.018	-0.001***	+0.004	+0.001***

Regression: ***p<0.01. **p<0.05. *p<0.1.

After controlling for several confounding variables, the level of increase for average interdisciplinarity shrank in all nine fields, and that of Economics & Business, Educational Sciences, Political Science, Social & Economic Geography, and Sociology shifts from positive to negative. Such a shrinking effect is less prominent in Law, Media & Communications, and Psychology. As suggested by one of the reviewers, a second group of regressions are conducted for robustness check which use year directly as an independent variable. Our observations are robust and the regression coefficients for year are in the same direction (positive or negative) and similar scales for most of the fields. The aforementioned shrinking effect did not only occur for results of integrated indicators but also single-component indicators such as variety and balance. The growth of mean variety is lessened in the regression analyses for all fields, the same for the change of average disparity and balance.

Two special cases, namely, Psychology and Social & Economic Geography, are noteworthy in revealing two different patterns of evolutions of interdisciplinarity. The latter achieved the most significant increase in average interdisciplinarity. However, after controlling for several variables, a negative change is found for the most recent five years. On the other hand, Psychology, although not recognized as the most interdisciplinary field, achieved an increasing level of interdisciplinarity from both the perspective of the observational studies and the regression analyses. We believe these cases may relate to the two different interpretations as we highlighted in the research framework. An increasing level of interdisciplinarity can be induced either by the widening adoption of a certain interdisciplinary knowledge combination across different researcher demographics or by the novel knowledge combination introduced by a small group of researchers that eventually obsoletes established methodology. Nonetheless, it is important to differentiate which mode of interdisciplinary evolution disciplines are heading towards.

Porter and Rafols (2009) claimed a modest increase in interdisciplinarity in STEM. In our opinion, it is hard to evaluate the level of such an increase due to the lack of ground truth (what quantifies as a large or small increase). Even so, based on the results from this section, the actual rise in interdisciplinarity may be even smaller than the one observed. The observed increase in the level of diversity in the knowledge base is likely inflated by other endogenous variables that are significantly associated with our current measurement of IDR.

Implications

Understanding the evolution of interdisciplinarity plays a crucial role in deciphering the formation mechanism, characteristics, and potential drivers of IDR. As the result of knowledge integration, interdisciplinarity emerged from a dynamic process and should be thoroughly investigated from a temporal perspective.

In this paper, we show that research from nine fields in Social Sciences has come to rely on a more interdisciplinary knowledge base over the past 55 years. This increase in interdisciplinarity poses opportunities as well as challenges to the research enterprise, for example, in terms of research assessment in different contexts. Among others, the compatibility or cognitive distance between evaluators and evaluatees is a crucial element for an unbiased, professional, and competent evaluation (Rahman et al., 2015), especially for interdisciplinary research. To ensure the quality and equality of evaluation, many funding agencies established extra guidelines and evaluative entities specifically for IDR. For instance, the Australian Research Council (ARC) allows researchers to identify their research proposal as interdisciplinary by assigning two or multiple distinct Field of Research (FoR) codes (Australian Research Council, 2018). ARC will then appoint relevant College of Expert (CoE) members with interdisciplinary expertise or broad disciplinary expertise to conduct a multi-panel evaluation. Nevertheless, most of the evaluation practices for scientific research today are still conducted within disciplinary silos and are more dependent on the expertise of domain experts. Based on the findings in this study, we argue that nowadays interdisciplinary knowledge integration is not merely the ingredient of IDR anymore but for disciplinary research as well. Evaluative entities equipped with diverse expertise will become increasingly necessary to cope with the increasing interdisciplinarity in regular research. In addition, evaluation by experts from different knowledge domains is a tricky practice in itself. As pointed out by Huutoniemi (2010, p. 311), quality of research is not "a unitary concept" and has "a distinct meaning within each discipline". Significant cognitive differences or even contradictions would be expected for experts from disparate disciplines regarding their epistemic and practical views towards the "originality, soundness, feasibility, and relevance" of research (Huutoniemi, 2010). More discussions are necessary regarding how to ensure the quality and impartiality of the peer-review process under the rise of IDR.

Besides the evaluation process, the increase in interdisciplinarity also prompts us to consider the epistemology of Social Sciences in greater depth. Taking humans or human social activities as research subjects, Social Sciences are traditionally believed to follow the interpretation model, as opposed to the explanation model for STEM. Interpretation delivers "wisdom and practical knowledge, but has no scientific validity" because it lacks the "formulation of a regularity" (e.g. mathematical formulations) and rigorous reproducibility, and thus cannot enjoy conditions of cumulativeness (Bonaccorsi, 2022). Nowadays, some interdisciplinary movements in Social Sciences, for instance, the emergence of computational social science (CSS), may call into question the established epistemology. Much recent research in CSS utilizes large-scale datasets and advanced quantitative methodologies such as machine learning and causal inference to characterize, model, and even predict human activities. Their efforts seem to challenge the traditional conception of Social Sciences and create, at least, an illusion of explanation for human endeavors. Besides methodology, more research in Social Sciences is becoming more dependent on knowledge from STEM fields for validation or supplementation (e.g. psychology and neuroscience), making them partly situated on results from the explanation model. Will changes like these evoke a paradigm shift in Social Sciences and fundamentally change the way we understand research within these fields? If so, how should researchers and relevant stakeholders prepare for such a different epistemology?

Finally, we would also like to highlight the significant heterogeneity within interdisciplinarity, as indicated by the complex temporal patterns of variety, balance, and disparity. In the current effort of quantifying interdisciplinarity, researchers are desperate to find a unified metric to gauge its intensity and hope to filter out the most IDR for additional decision-making. The level of interdisciplinarity is often regarded as a value in a continuous range that can purely move along a single axis (more or less interdisciplinary). However, much more variations and complexities can be found in different elements of interdisciplinarity. Interdisciplinarity might be increasing in variety but decreasing (or remain stable) in disparity, as found in the case of Economics & Business. Fields might have different trajectories of developing and embracing IDR and cannot be compared directly using the same scale. We should not reduce it to a single value and ignore the tremendous contextual information embedded in the practice of interdisciplinarity.

CONCLUSIONS

This paper examines the evolution of interdisciplinarity in the knowledge base of nine broad fields from Social Sciences over a 55-year-long time window. The diversity of the knowledge base, as one aspect of interdisciplinarity, is observed and analyzed from a temporal perspective. Through regression models, we check whether such change, if any, can still be discovered among publications from different periods but with similar characteristics. We find that research from Social Sciences is nowadays on average reliant on 5-8 more disciplines than in the '60s, which contributes to growth in the overall level of interdisciplinarity. Yet, the increasing level of specialization in knowledge base, i.e. decrease in evenness, is also significant and universal, which could be influenced by the formation or emergence of specific research topics. Trends in the heterogeneity of the knowledge base vary among fields. The overall level of interdisciplinarity in the knowledge base appears to be generally increasing for all fields in these 55 years, although with different speeds and temporal drops for some. On the other hand, when controlling for several confounding variables, such an increase is smaller, even reversed, and nonuniversal among disciplines.

An important implication that can be drawn here for researchers and policymakers is to understand what kind of interdisciplinarity that Social Sciences is marching toward. Becoming interdisciplinary exposes researchers to multiple knowledge sources that can potentially facilitate their research or inspire out-of-box thinking, but that does not necessarily lead to the eclipse of specialization. Learning widely and digging deeply is the new norm to achieve IDR and appears to be the most common approach in the Social Sciences.

This study has several limitations. First, we investigated the temporal trends in interdisciplinarity using aggregated indicators. More contextual information regarding what kind of knowledge is integrated to fields in Social Sciences, i.e. from other Social Science fields or STEM fields, and temporal patterns of the preference of knowledge source are not explored. In addition, for the regression analysis, although we try to include as many variables as possible, there might still exist variables that explicitly or implicitly affect interdisciplinarity. In future studies, we will continue to unveil the dynamics of interdisciplinarity in Social Sciences and provide a contextualized understanding of the formation of interdisciplinarity.

ACKNOWLEDGEMENTS

A previous version of this study was presented at the occasion of the 18th International Conference on Scientometrics & Informetrics (ISSI) (Zhou et al., 2021).

We thank the Flemish Government for its support to the Centre for R&D Monitoring (ECOOM), which made possible this research as part of the program on the study of interdisciplinarity and impact.

We thank the reviewers for their constructive comments. We thank Joshua Eykens for valuable discussions and insights.

REFERENCES

Abramo, G., D'Angelo, C. A., & Di Costa, F. (2017). Do interdisciplinary research teams deliver higher gains to science? *Scientometrics*, *111*(1), 317–336. https://doi.org/10.1007/s11192-017-2253-x

Australian Research Council. (2018). *ARC Statement of Support for Interdisciplinary Research*. Australian Research Council. https://www.arc.gov.au/policies-strategies/policy/arc-statement-support-interdisciplinary-research

Beisel, J.-N., Usseglio-Polatera, P., Bachmann, V., & Moreteau, J.-C. (2003). A Comparative Analysis of Evenness Index Sensitivity. International Review of Hydrobiology, 88(1), 3–15. https://doi.org/10.1002/iroh.200390004

Bonaccorsi, A (2022). An epistemic approach to research assessment in the social sciences. In Engels, T.C.E. & Kulczycki, E. (in press). Handbook on Research Assessment in the Social Sciences. Edward Elgar Publishing, ISBN 9781800372542

Bu, Y., Li, M., Gu, W., & Huang, W. (2020). Topic diversity: A discipline scheme-free diversity measurement for journals. Journal of the Association for Information Science and Technology, n/a(n/a). https://doi.org/10.1002/asi.24433

Carayol, N., & Thi, T. U. N. (2005). Why do academic scientists engage in interdisciplinary research? Research Evaluation, 14(1), 70–79. https://doi.org/10.3152/147154405781776355

Chang, Y.-W., & Huang, M.-H. (2012). A study of the evolution of interdisciplinarity in library and information science: Using three bibliometric methods. Journal of the American Society for Information Science and Technology, 63(1), 22–33. https://doi.org/10.1002/asi.21649

Chen, S., Arsenault, C., Gingras, Y., & Larivière, V. (2015). Exploring the interdisciplinary evolution of a discipline: The case of Biochemistry and Molecular Biology. Scientometrics, 102(2), 1307–1323. https://doi.org/10.1007/s11192-014-1457-6

Craven, D., Winter, M., Hotzel, K., Gaikwad, J., Eisenhauer, N., Hohmuth, M., König-Ries, B., & Wirth, C. (2019). Evolution of interdisciplinarity in biodiversity science. Ecology and Evolution, 9(12), 6744–6755. https://doi.org/10.1002/ece3.5244

Edelmann, A., Wolff, T., Montagne, D., & Bail, C. A. (2020). Computational Social Science and Sociology. Annual Review of Sociology. https://doi.org/10.1146/annurev-soc-121919-054621

Evans, E. D. (2016). Measuring Interdisciplinarity Using Text. Socius, 2, 2378023116654147. https://doi.org/10.1177/2378023116654147

Frank, M. R., Wang, D., Cebrian, M., & Rahwan, I. (2019). The evolution of citation graphs in artificial intelligence research. Nature Machine Intelligence, 1(2), 79–85. https://doi.org/10.1038/s42256-019-0024-5

Frodeman, R. (Ed.). (2010). The oxford handbook of interdisciplinarity. Oxford University Press.

Frodeman, R., & Mitcham, C. (2016). New Directions in Interdisciplinarity: Broad, Deep, and Critical: Bulletin of Science, Technology & Society. https://doi.org/10.1177/0270467607308284

Gates, A. J., Ke, Q., Varol, O., & Barabási, A.-L. (2019). Nature ’s reach: Narrow work has broad impact. Nature, 575(7781), 32–34. https://doi.org/10.1038/d41586-019-03308-7

Glänzel, W., & Debackere, K. (2021). Various aspects of interdisciplinarity in research and how to quantify and measure those. Scientometrics. https://doi.org/10.1007/s11192-021-04133-4

Huutoniemi, K. (2010). Evaluating interdisciplinary research. The Oxford Handbook of Interdisciplinarity, 309–320.

Jacobs, J. A., & Frickel, S. (2009). Interdisciplinarity: A Critical Assessment. Annual Review of Sociology, 35(1), 43–65. https://doi.org/10.1146/annurev-soc-070308-115954

Karlovčec, M., & Mladenić, D. (2015). Interdisciplinarity of scientific fields and its evolution based on graph of project collaboration and co-authoring. Scientometrics, 102(1), 433–454. https://doi.org/10.1007/s11192-014-1355-y

Larivière, V., & Gingras, Y. (2010). On the relationship between interdisciplinarity and scientific impact. Journal of the American Society for Information Science and Technology, 61(1), 126–131. https://doi.org/10.1002/asi.21226

Larivière, V., & Gingras, Y. (2014). Measuring Interdisciplinarity. In Beyond bibliometrics: Harnessing multidimensional indicators of scholarly impact (pp. 187–200). Cambridge MA: MIT Press.

Larivière, V., Haustein, S., & Börner, K. (2015). Long-Distance Interdisciplinarity Leads to Higher Scientific Impact. PLOS ONE, 10(3), e0122565.

https://doi.org/10.1371/journal.pone.0122565

Leinster, T., & Cobbold, C. (2012). Measuring diversity: The importance of species similarity. Ecology, 93, 477–489. https://doi.org/10.2307/23143936

Levitt, J. M., Thelwall, M., & Oppenheim, C. (2011). Variations between subjects in the extent to which the social sciences have become more interdisciplinary. Journal of the American Society for Information Science and Technology, 62(6), 1118–1129. https://doi.org/10.1002/asi.21539

Lužar, B., Levnajić, Z., Povh, J., & Perc, M. (2014). Community Structure and the Evolution of Interdisciplinarity in Slovenia's Scientific Collaboration Network. PLoS ONE, 9(4), e94429. https://doi.org/10.1371/journal.pone.0094429

Milman, A., Marston, J. M., Godsey, S. E., Bolson, J., Jones, H. P., & Weiler, C. S. (2017). Scholarly motivations to conduct interdisciplinary climate change research. Journal of Environmental Studies and Sciences, 7(2), 239–250. https://doi.org/10.1007/s13412-015-0307-z

Mugabushaka, A.-M., Kyriakou, A., & Papazoglou, T. (2016). Bibliometric indicators of interdisciplinarity: The potential of the Leinster–Cobbold diversity indices to study disciplinary diversity. Scientometrics, 107(2), 593–607. https://doi.org/10.1007/s11192-016-1865-x

Nichols, L. G. (2014). A topic model approach to measuring interdisciplinarity at the

National Science Foundation. Scientometrics, 100(3), 741–754. https://doi.org/10.1007/s11192-014-1319-2

Nicolaisen, J., & Frandsen, T. F. (2021). Number of references: A large-scale study of interval ratios. Scientometrics, 126(1), 259–285. https://doi.org/10.1007/s11192-020-03764-3

OECD. (2015). Frascati Manual 2015: Guidelines for Collecting and Reporting Data on Research and Experimental Development. OECD. https://doi.org/10.1787/9789264239012-en

Pan, R. K., Sinha, S., Kaski, K., & Saramäki, J. (2012). The evolution of interdisciplinarity in physics research. Scientific Reports, 2(1), 551. https://doi.org/10.1038/srep00551

Pieters, R., & Baumgartner, H. (2002). Who Talks to Whom? Intra- and Interdisciplinary Communication of Economics Journals. Journal of Economic Literature, 40(2), 483–509. https://doi.org/10.1257/002205102320161348

Porter, A. L., & Rafols, I. (2009). Is science becoming more interdisciplinary? Measuring and mapping six research fields over time. Scientometrics, 81(3), 719–745. https://doi.org/10.1007/s11192-008-2197-2

Rafols, I., & Meyer, M. (2010). Diversity and network coherence as indicators of interdisciplinarity: Case studies in bionanoscience. Scientometrics, 82(2), 263–

287. https://doi.org/10.1007/s11192-009-0041-y

Rahman, A. I. M. J., Guns, R., Rousseau, R., & Engels, T. C. E. (2015). Is the expertise of evaluation panels congruent with the research interests of the research groups: A quantitative approach based on barycenters. Journal of Informetrics, 9(4), 704–721. https://doi.org/10.1016/j.joi.2015.07.009

Rinia, E., Leeuwen, T. V., Bruins, E., Vuren, H. V., & Raan, A. V. (2004). Citation delay in interdisciplinary knowledge exchange. Scientometrics, 51(1), 293–309. https://doi.org/10.1023/a:1010589300829

Rousseau, R., Zhang, L., & Hu, X. (2019). Knowledge Integration: Its Meaning and Measurement. In W. Glänzel, H. F. Moed, U. Schmoch, & M. Thelwall (Eds.), Springer Handbook of Science and Technology Indicators (pp. 69–94). Springer International Publishing. https://doi.org/10.1007/978-3-030-02511-3_3

Schummer, J. (2004). Multidisciplinarity, interdisciplinarity, and patterns of research collaboration in nanoscience and nanotechnology. Scientometrics, 59(3), 425–465. https://doi.org/10.1023/B:SCIE.0000018542.71314.38

Stirling, A. (2007). A general framework for analysing diversity in science, technology and society. Journal of The Royal Society Interface, 4(15), 707–719. https://doi.org/10.1098/rsif.2007.0213

Wagner, C. S., Roessner, J. D., Bobb, K., Klein, J. T., Boyack, K. W., Keyton, J., Rafols, I., & Börner, K. (2011). Approaches to understanding and measuring interdisciplinary scientific research (IDR): A review of the literature. Journal of Informetrics. https://doi.org/10.1016/j.joi.2010.06.004

Wang, J., Thijs, B., & Glänzel, W. (2015). Interdisciplinarity and Impact: Distinct Effects of Variety, Balance, and Disparity. PLOS ONE, 10(5), e0127298. https://doi.org/10.1371/journal.pone.0127298

Wang, K., Shen, Z., Huang, C., Wu, C.-H., Dong, Y., & Kanakia, A. (2020). Microsoft Academic Graph: When experts are not enough. Quantitative Science Studies, 1(1), 396–413. https://doi.org/10.1162/qss_a_00021

Wang, Q., & Schneider, J. W. (2020). Consistency and validity of interdisciplinarity measures. Quantitative Science Studies, 1(1), 239–263. https://doi.org/10.1162/qss_a_00011

Yan, E., Ding, Y., Cronin, B., & Leydesdorff, L. (2013). A bird's-eye view of scientific trading: Dependency relations among fields of science. Journal of Informetrics, 7(2), 249–264. https://doi.org/10.1016/j.joi.2012.11.008

Yegros-Yegros, A., Rafols, I., & D'Este, P. (2015). Does Interdisciplinary Research Lead to Higher Citation Impact? The Different Effect of Proximal and Distal Interdisciplinarity. PLOS ONE, 10(8), e0135095. https://doi.org/10.1371/journal.pone.0135095

Zhang, L., Rousseau, R., & Glänzel, W. (2016). Diversity of references as an indicator of the interdisciplinarity of journals: Taking similarity between subject fields into account. Journal of the Association for Information Science and Technology, 67(5), 1257–1265. https://doi.org/10.1002/asi.23487

Zhang, L., Sun, B., Chinchilla-Rodríguez, Z., Chen, L., & Huang, Y. (2018). Interdisciplinarity and collaboration: On the relationship between disciplinary diversity in departmental affiliations and reference lists. Scientometrics, 117(1), 271–291. https://doi.org/10.1007/s11192-018-2853-0

Zhou, H., Guns, R., & Engels, T. C. E. (2021). The evolution of interdisciplinarity in five social sciences and humanities disciplines: relations to impact and disruptiveness. In Proceedings of the 18th international conference on scientometrics and informetrics (p.1381-1392).

APPENDIX

Table A1. Mapping of original discipline labels in MAG to nine Social Sciences fields

Remapped fields	**Original L1 labels in MAG**
Psychology	applied psychology, clinical psychology, cognitive psychology, developmental psychology, psychoanalysis, psychotherapist, social psychology,
Economics & Business	accounting, advertising, business administration, classical economics, commerce, development economics, econometrics, economic history, economic policy, economic system, economy, environmental economics, finance, financial economics, financial system, industrial organization, international economics, international trade, keynesian economics, labour economics, law and economics, macroeconomics, management, market economy, marketing, mathematical economics, microeconomics, monetary economics, neoclassical economics, political economy, positive economics, public economics, socioeconomics, welfare economics
Educational Sciences	mathematics education, medical education, pedagogy
Sociology	gender studies, anthropology, ethnology, demography
Law	law, criminology
Political Science	public administration, public relations
Social & Economic Geography	economic geography, environmental planning, environmental protection, environmental ethics
Media & Communications	communication, library science, media studies
Other Social Sciences	social science

Figure A1. Temporal trends in balance for publications with variety=5

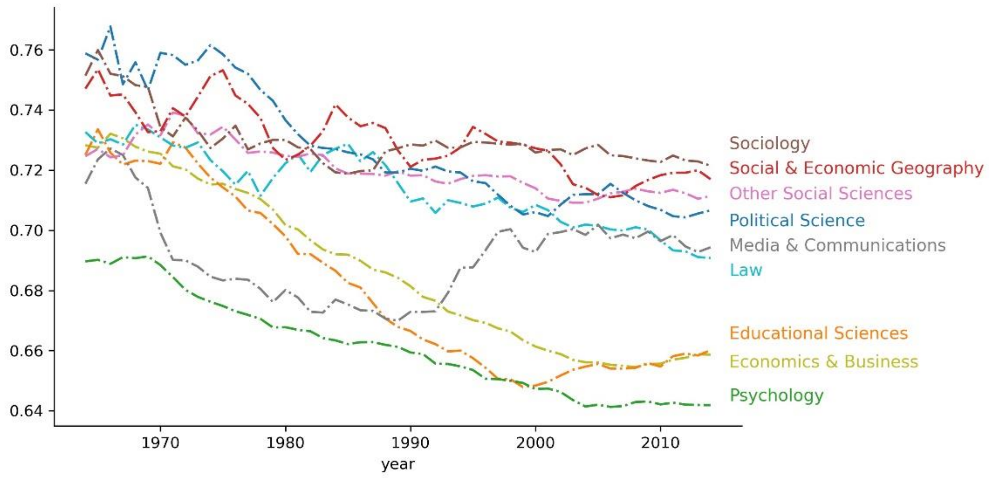

Figure A2. Temporal trends in integrated IDR measurements.

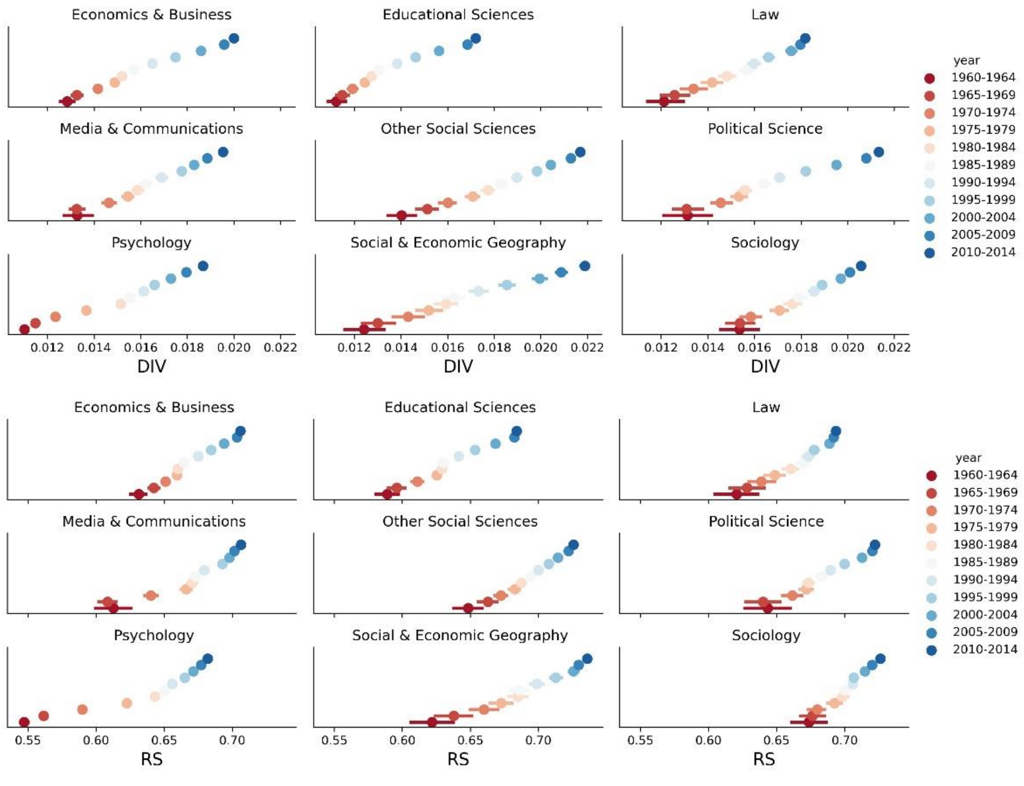

Table A2. OLS regression results on interdisciplinarity

Field: Economics and Business

	True Diversity: ln ($^2D^s$)		Variety		Balance		Disparity	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Time	0.0159 (0.001)	-0.0031 (0.001)	0.8634 (0.017)	0.0154# (0.013)	-0.0164 (0.000)	0.0041 (0.000)	0.0027 (0.000)	-0.0033 (0.000)
Reference count		0.0041 (0.000)		0.2204 (0.002)		-0.0040 (0.000)		0.0008 (0.000)
Reference age		0.0041 (0.000)		0.0362 (0.001)		0.0017 (0.000)		0.0019 (0.000)
ln(C_2)		0.0325 (0.001)		0.4121 (0.016)		-0.0145 (0.000)		0.0072 (0.000)
JIF		-0.006 (0.000)		0.0073# (0.007)		-0.0015 (0.000)		-0.0009 (0.000)
Team Size		0.0131 (0.000)		0.1132 (0.006)		-0.0036 (0.000)		0.0037 (0.000)
AVG(author productivity)		0.0016 (0.000)		0.0127 (0.001)		0.0006 (0.000)		0.0001# (0.000)
AVG(author impact)		-0.0069 (0.000)		-0.0594 (0.006)		-0.0119 (0.000)		0.0025 (0.000)
AVG(author connection)		0.0006 (0.000)		0.0078 (0.001)		-0.0000 (0.000)		0.0001 (0.000)
AVG(author seniority)		0.0015 (0.000)		0.0165 (0.001)		0.0017 (0.000)		-0.0003 (0.000)
Constant	1.2615 (0.001)	1.0466 (0.002)	12.2507 (0.013)	5.2889 (0.025)	0.5488 (0.000)	0.7111 (0.001)	0.9143 (0.000)	0.8526 (0.001)
Log-likelihood	-3.98e+05	-3.63e+05	-2.63e+06	-2.31e+06	2.95e+05	5.29e+05	5.60e+05	5.85e+05
F-statistic	279	3587	2567	21890	1793	22650	98	2009

Standard errors are in parentheses
not statistically significant at 0.10 level. The rest are statistically significant at 0.01 level.

Data validation tasks

Task 1: Is MAG assigning more discipline labels to recent publications than older ones, which could nullify the discovered increasing trends in variety by claiming the observed increase is an artefact of the dataset?

Figure A3 shows the distribution of avearage number of L1 labels for referenced publications investigated in this study. It indicates that publications published in recent years are indeed assigned more L1 labels than those in earlier periods. But the level of difference (increase) is minor and not substantial enough to overturn our findings.

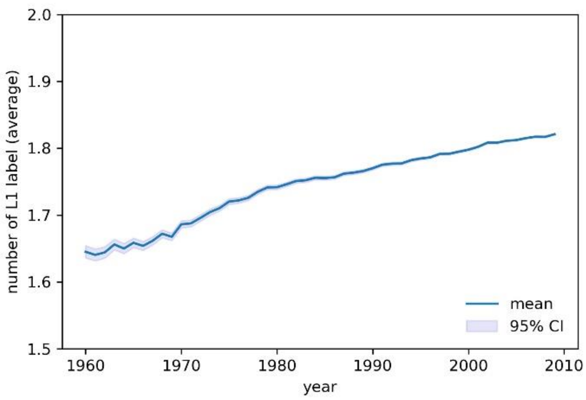

Figure A3. Average number of discipline labels (L1) for investigated references.

Task 2: Are some disciplines relatively new and did they therefore not appear in the earlier periods?

All 60 studied disciplines are present throughout our selected time span. We present cases for two disciplines, namely gender studies (rise in prominence around 1990s) and media studies (first M.A. program around 1975). In Figure A4, we can see that they both have been present in our dataset since the 1960s.

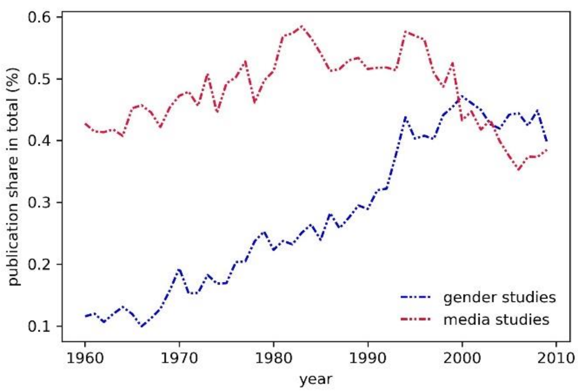

Figure A4. Temporal trends of publications share for two research domains.

Table A3. Summary for publications studying temporal trends of interdisciplinarity

Source	Data & Classification Scheme	Measurement	Discipline/Region	Period	Main Results
Porter and Rafols, 2009	*Data:* Web of Science Sampling 1000 articles on average for each categories and year (1975, 1985, 1995, and 2005) *Classification Scheme:* Web of Science subject category	Disciplinary diversity in reference; Rao-Stirling index;	Six research field from STEM • Biotechnology & Applied Microbiology • Engineering, Electrical & Electronic • Mathematics • Medicine – Research & Experimental • Neurosciences • Physics – Atomic, Molecular & Chemical	1975-2005	"Modest increase (mostly around 5% growth);" *(p. 719)* "Science is indeed becoming more interdisciplinary, but in small steps." *(p. 719)*
Levitt et al. 2011	*Data:* Web of Science *Classification Scheme:* Web of Science subject category	Percentage of cross-disciplinary citing documents (PCDCD)	Social Sciences and its subfields	1980-2000	Decrease in the 1980s, sharp rise in the 1990s.
Chang & Huang, 2012	*Data:* SSCI, Thomson Reuters 1,536 articles published in 10 journals from LIS *Classification Scheme*: Library of Congress classification (LCC)	Disciplinary diversity in reference and author affiliation; Brillouin index;	Library and Information Science (LIS)	1978-2007	"The degree of LIS interdisciplinarity increased between 1978 and 2007." *(p. 28)*
Raj Kumar Pan et al., 2012	*Data:* All published articles in Physical Review journals *Classification Scheme*: Physics and Astronomy Classification Scheme (PACS)	Interconnections between its subfields; Average number of links per code and average link weight, new links from dissimilar branches of the hierarchy;	Physics	1985–2009	"Steady increase, indicating increased connectivity between different subfields of physics;" *(p. 7)* "increase in interdisciplinarity between the subfields of physics, as dissimilar branches of the PACS hierarchy are becoming increasingly connected;" *(p. 3)*
Lužar et al., 2014	*Data:* SICRIS national database (Slovenia) Classification Scheme: SICRIS field labels for researcher	Disciplinarity diversity within communities of collaboration network; Proposed new measurement;	Slovenia	1960-2010	Modest increase in 1970s and 1980s, minor decrease in 1985 to 1990, and remain stable afterwards. "The frequency of interdisciplinary research is only proportional with the overall growth of the network." (p. 1)
Larivière & Gingras, 2014	*Data:* Web of Science *Classification Scheme:*	References to journals in a different discipline	General Science	1900-2010	Increase since the mid-1980s

	Web of Science subject category				
Chen et al., 2015	*Data:* Web of Science 1,539,526 publications in the field of BMB *Classification Scheme*: Web of Science subject category	Disciplinary diversity in reference; Rao-Stirling index;	Biochemistry and Molecular Biology (BMB)	1910-2010	"Doubles over the century with a 32% increase during 1975-2005"; *(p. 1315)* "The rise in interdisciplinarity is stronger in BMB than in the six disciplines which Porter and Rafols investigated." *(p. 1315)*
Karlovčec & Mladenić, 2015	*Data:* SICRIS national database and COBISS national bibliographic database (Slovenia) *Classification Scheme*: SICRIS field labels for researcher	Disciplinarity diversity of collaboration network; Proposed new measurement, an extension of Stirling's diversity index;	Slovenia	1996-2013	Increasing trend.
Craven et al., 2019	*Data:* Web of Science 97,945 articles related to biodiversity *Classification Scheme:* Web of Science subject category Extracted terms from the title and abstract, via a continuous dynamic topic model (LDA-cDTM)	Concept diversity and subdiscipline diversity; " species richness and the effective number of species for the probability of interspecific encounter…(1/Simpson's index)" *(p.6747)*	Biodiversity Science	1990-2012	"either stable or declining concept or subdiscipline diversity" (p.6752)
Gates et al., 2019	*Data:* Web of Science 19,252,639 publications *Classification Scheme:* Web of Science subject category	Disciplinary diversity in reference; Rao-Stirling index;	General Science	1900-2017	Increasing. " a typical article is inspired by and impacts three times more disciplines this decade than it did 50 years ago." (p. 34)