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A bird's-eye view of scientific trading: Dependency relations among fields of science

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ABSTRACT

We use a trading metaphor to study knowledge transfer in the sciences as well as the social sciences. The metaphor comprises four dimensions: (a) *Discipline Self-dependence*, (b) *Knowledge Exports/Imports*, (c) *Scientific Trading Dynamics*, and (d) *Scientific Trading Impact*. This framework is applied to a dataset of 221 Web of Science subject categories. We find that: (i) the Scientific Trading Impact and Dynamics of materials science and transportation science have increased; (ii) biomedical disciplines, physics, and mathematics are significant knowledge exporters, as is statistics and probability; (iii) in the social sciences, economics, business, psychology, management, and sociology are important knowledge exporters; and (iv) Discipline Self-dependence is associated with specialized domains which have ties to professional practice (e.g., law, ophthalmology, dentistry, oral surgery and medicine, psychology, psychoanalysis, veterinary sciences, and nursing).

1. Introduction

In economics, trade refers to the transfer of ownership of goods or services from one entity to another. The notion of trade has also been applied to the transfer of things other than goods or services, such as knowledge. Since knowledge transfer cannot be observed directly (Jaffe, Trajtenberg, & Fogarty, 2000), one relies on proxy measures, notably citations. Citation linkages between articles imply a flow of knowledge from the cited to the citing entity (Jaffe, Trajtenberg, & Henderson, 1993; Mehta, Rysman, & Simcoe, 2010; Nomaler & Verspagen, 2008; Van Leeuwen & Tijssen, 2000). Several studies have used the trading metaphor to explore knowledge transfer between different disciplines (Cronin & Davenport, 1989; Cronin & Meho, 2008; Cronin & Pearson, 1990; Goldstone & Leydesdorff, 2006; Hessey & Willett, in press; Larivière, Sugimoto, & Cronin, 2012; Lockett & McWilliams, 2005; Stigler, 1994).

The application of the trading metaphor to citations takes us beyond typical bibliometric studies where the focus is on clustering disciplines (e.g., Glänzel & Schubert, 2003; Janssens, Zhang, De Moor, & Glänzel, 2009; Leydesdorff & Rafols, 2009; Rafols & Leydesdorff, 2009; Zhang, Liu, Janssens, Liang, & Glänzel, 2010), mapping disciplines (e.g., Klavans & Boyack, 2011; Leydesdorff & Rafols, 2009; Moya-Anegón et al., 2004; Rafols, Porter, & Leydesdorff, 2010) or evaluating disciplines/specialties (e.g., Bensman, 2008; Morillo, Bordons, & Gomez, 2003; Porter, Roessner, Cohen, & Perreault, 2006; Porter, Roessner, & Heberger, 2008; Rafols & Meyer, 2010; Rinia, Van Leeuwen, Bruins, Van Vuren, & Van Raan, 2002; Zhang et al., 2010). Knowledge flows in the past 20 years have become more inter-sectoral, inter-organizational, inter-disciplinary, and international in character (Autant-Bernard, Mairesse, & Massard, 2007; Buter, Noyons, & Van Raan, 2010; Gazni, Sugimoto, & Didegah, 2011; Lewison, Rippon, & Wooding, 2005; Ponds, Van Oort, & Frenken, 2007; Wagner & Leydesdorff, 2009).

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Trading Metaphor		
International Trade	**Scientific Trading**	**Citation Representation**
Country	Discipline	Subject category
Currency	Credit	Citation
Goods	Knowledge	Paper
Export	Sending knowledge	Cited
Import	Receiving knowledge	Citing
Exporter	Knowledge exporter/distributor	Receiving incoming citations
Importer	Knowledge importer/collector	Sending outgoing citations
Trade surplus	Knowledge surplus	Incoming citations > Outgoing citations
Trade deficit	Knowledge deficit	Outgoing citations > Incoming citations
Net capital outflow (positive)	Knowledge flow (positive)	From A to B if B cites A more than A cites B
Net capital outflow (negative)	Knowledge flow (negative)	From A to B if B cites A less than A cites B
Trading dependence	Discipline dependence	Self-citation rate
Trading dynamics	Scientific trading dynamics	Growth in citations
Trading size	Scientific trading impact	Number of citations

Fig. 1. Concepts in scientific trading.

Perhaps the first attempt to study knowledge trading was by Xhignesse and Osgood (1967) who addressed the "problem of information exchange in psychology" (p. 778) through journal citation analysis. A receiver of information was defined as a journal whose articles cited articles published by other journals, and a source as a journal whose articles were cited by other journals. Early studies of knowledge trading were limited in terms of their scope, focusing on either a single field or small number of disciplines (Cronin & Meho, 2008; Cronin & Pearson, 1990; Goldstone & Leydesdorff, 2006; Larivière et al., 2012; Lockett & McWilliams, 2005; Xhignesse & Osgood, 1967; Stigler, 1994). The present study is designed to provide a comprehensive overview of trends in scientific trading across disciplines.

We begin with a formal elaboration of the trading metaphor. Fig. 1 lists the terminology used in international trade (first column), the key concepts in scientific trading (second column), and their citation representations (third column). In scientific trading, for example, each *discipline* can be considered as a trading entity, the thing being transferred is *knowledge*, and the exchange currency is *citations*. A discipline *exports* its domain knowledge by *sending knowledge* through *incoming citations* and *imports* other disciplines' knowledge by *receiving knowledge* through *outgoing citations*. A discipline is thus both an *exporter* and an *importer*, to a greater or lesser extent. A *knowledge deficit* occurs if a discipline imports more knowledge than it exports; and a *knowledge surplus* occurs if a discipline exports more knowledge than it imports. Of course, not all citations are equal and thus it is impossible to quantify with precision the actual volume or heft of exported/imported knowledge.

Table 1
Scientific trading impact.

Year	No. of journals	No. of citation links	Scientific Trading Impact (total citations)
2007	7940	1,460,847	24,979,391
2008	8207	1,580,178	26,809,415
2009	9216	1,899,373	30,150,625

Table 2
Scientific Trading Impact and Dynamics.[a]

Year range	Increment of citable (exportable) knowledge	No. of fields that export knowledge more than the increment	No. of fields that export knowledge less than the increment
2007–2008	7.33%	144	77
2008–2009	12.46%	125	96
2007–2009	20.70%	133	88
Union of 2007–2008 and 2008–2009		98	61

[a] Multidisciplinary sciences is excluded, as it is not considered a discipline.

For two disciplines A and B, a *positive knowledge flow* from A to B is defined as B citing A more than A cites B; a *negative knowledge flow* is defined as B citing A less than A cites B. *Discipline Self-dependence* is based on self-citation rates: a discipline is said to be independent if it has a relatively high self-citation rate and dependent if it has a relatively low self-citation rate. *Scientific Trading Impact* and *Scientific Trading Dynamics* are calculated based on the number of incoming citations (measures of impact) and the dynamics of change (Garfield, 1972; Glänzel & Moed, 2002). Note that unlike international trade, where one thing is exchanged for another, in scientific trading, knowledge is shared not given away. To be consistent with the terminology of previous studies, the term scientific trading is used here.

The concepts in Fig. 1 are used to examine all 221 subject categories indexed in the Web of Science (WoS); subject categories are referred to as WoS categories (WCs) in version 5 of the WoS launched in August 2012 (Leydesdorff et al., in press). With this framework we are able to examine disciplinary developments and interactions in a novel fashion, in the process providing a bird's-eye view of scientific trade routes.

2. Methods

2.1. Data

Thomson Reuters' (formerly ISI's) Web of Science is one of the most comprehensive citation databases.[1] It is a well-established tool within the worlds of research evaluation and science policy making. The company assigns journals to subject categories (SCs, here also referred to as fields) based on journal-to-journal citation patterns and editorial judgment (Garfield, Pudovkin, & Istomin, 2002). The subject categories signify classes of specialized knowledge. Although the accuracy of the subject categories has been questioned repeatedly (e.g., Boyack, Klavans, & Börner, 2005; Rafols & Leydesdorff, 2009), the categories remain the most widely used and accessible journal classification scheme. The SCs provide a clear and consistent means of tracking knowledge flows among scientific disciplines (Van Raan, 2008; Zitt, 2005). We refer the reader to Rafols and Leydesdorff (2009) for procedures on data collection. Data were harvested from the CD-ROM version of the Journal Citation Reports (JCR) of the Science Citation Index (SCI) and the Social Sciences Citation Index (SSCI) for 2007, 2008, and 2009.

At the field level, since a journal can be assigned to more than one subject category, "multiple counting" is considered in that citations from a multi-assigned journal are counted toward all assigned subject categories. "Multiple counting" avoids the arbitrariness of assigning a multi-assigned journal to either one subject category. For all fields collectively, since we calculated the total number of citations for all journals (but not fields), "multiple counting" can therefore be avoided. Thus, except for Tables 1 and 2, the rest of the tables (including supplementary tables) use "multiple counting".

Table 1 shows the total scientific trading size for all 220 science and social sciences subject categories (221 in 2009) for the three years. For example, 30,150,625 is the number of times articles published in 2009 cited articles published in all 221 subject categories.

[1] Nonetheless, there are several features of WoS that one cannot overlook: it is highly skewed toward English-language publications, covers journal articles and indexes a relatively higher number of biomedical journals.

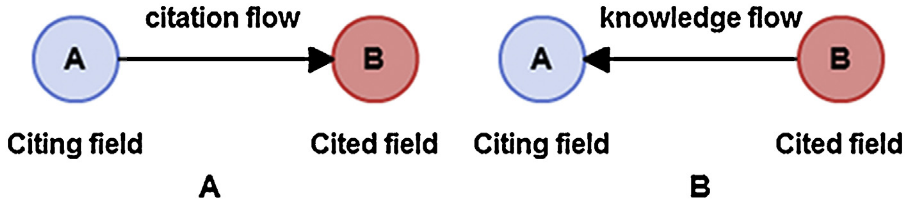

Fig. 2. Citation flow vs. knowledge flow.

2.2. Citation flow vs. knowledge flow

We distinguish between citation flow and knowledge flow. Knowledge flows into a field via outgoing links and a field's own knowledge is disseminated via incoming links (Borgman & Rice, 1992; Buter, Noyons, & Van Raan, 2011; Cronin & Meho, 2008; Levitt, Thelwall, & Oppenheim, 2011; Leydesdorff, 2011; Leydesdorff & Probst, 2009; Wouters, 1998). Fig. 2 provides a simple illustration of the difference between citation flow and knowledge flow. For two fields A and B, if A cites B, then A distributes citations to B (citation flow) and B diffuses knowledge to A (knowledge flow).

2.3. Scientific disciplines: dimensions and characteristics

Disciplinary trading can be captured along four dimensions: (i) *Discipline Self-dependence*, (ii) *Knowledge Exports/Imports*, (iii) *Scientific Trading Dynamics*, and (iv) *Scientific Trading Impact*. The interrelationship of these dimensions is shown in Section 4. Fig. 3 provides visualizations. For two fields A and B,

- *Discipline Self-dependence* is represented by the size of the inner circle area; the higher the self-citation rate, the greater the area (Fig. 3A).
- *Knowledge Exports/Imports* are represented by the size of the outgoing and incoming arrows. Arrow size indicates the amount of imported and exported knowledge (Fig. 3B).
- Circles represent *Scientific Trading Dynamics*. The circle area size mirrors the amount of knowledge exported by a discipline in different years (Fig. 3C).
- *Scientific Trading Impact* shows the sum of exported knowledge for different fields during the same time period (Fig. 3D).

To illustrate, we provide two examples. The first compares two fields in the same year: Field A has a lower Scientific Trading Impact, higher Discipline Self-dependence, and a lower Export/Import ratio than field B (Fig. 3E). The second compares the same field over time: the field at the second point in time has a higher Scientific Trading Impact, a lower Discipline Self-dependence, and a lower Export/Import ratio than it had at the first (Fig. 3F). We applied these four dimensions to the 221 subject categories to reveal the nature and scale of knowledge trading across disciplines.

3. Results

3.1. The acceleration of science (Scientific Trading Impact and Dynamics)

Human knowledge, in the form of scholarly publications, is growing apace. Earlier knowledge trading studies did not take the acceleration of science into account. As more and more scientific papers are published each year, the amount of citable (exportable) knowledge increases. In other words, a field may show a year-on-year increase in exports, but that growth rate may actually be less than the rate at which the overall citable (exportable) knowledge stock is increasing.

The overall acceleration rate of science is shown in Table 2. Total Scientific Trading Impact increased by 20.70% from 2007 to 2009. A 133 fields exported knowledge at a rate greater than the overall increment. Ninety-eight fields exported more knowledge than the overall acceleration rate in both time periods – from 2007 to 2008 and from 2008 to 2009, while 61 exported less. The former have, in our terms, an increased Scientific Trading Impact, the latter a reduced Scientific Trading Impact.

Fig. 4 illustrates the distribution of Scientific Trading Dynamics for all 221 fields. The distribution did not pass the normal significance test with Kolmogorov–Smirnov's asymptotic significance equal to 0.004 ($p < 0.05$). The distribution is positively skewed (statistic is 1.2 which is more than three times larger than its standard error 0.16) and leptokurtic (statistic is 4.65 which is more than three times larger than its standard error 0.33). The mean for the distribution is 0.31 and standard deviation is 0.24.

Tables 3 and 4 show the top-10 fields ranked by their Scientific Trading Dynamics. "C" denotes the number of incoming citations (exported knowledge) and "P" the number of publications. Dynamic export changes for all 221 fields are included in the supplementary materials (Supplementary Table 1). The rate of increase should be used for benchmarking purposes: a research unit (be it an author, journal, or institution) in a given field may have increased its rate of knowledge exports but less than its field average, in which case it is lagging behind the overall pace of scientific development of its field.

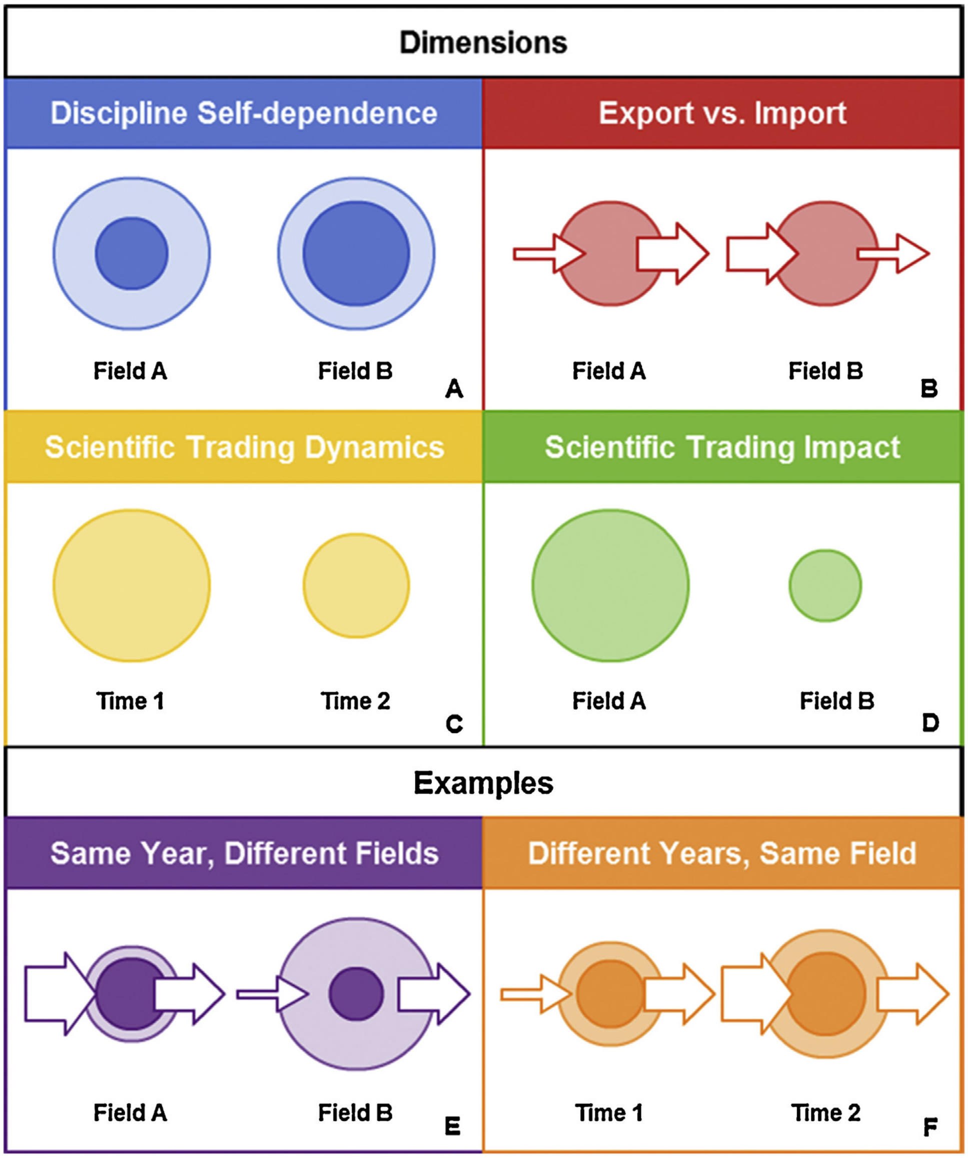

Fig. 3. Disciplinary dimensions.

The Scientific Trading Impact of a field tells us whether its domain knowledge is recognized and valued – the idea of citations as endorsements (Cronin, 1984; Merton, 1968). We can see from Table 3 that materials science (including Nanoscience & Nanotechnology, Materials Science, Biomaterials, and Materials Science, multidisciplinary) and transportation (including Transportation Science & Technology and Transportation) have increased their Scientific Trading Impact in recent years, which means that they are becoming more visible and valued by other fields.

By way of contrast, the 10 fields listed in Table 4 have acceleration rates below the overall rate, which may mean that they are becoming somewhat less central, influential, or popular among other fields of science. Note, too, that some closely related fields appear in both Table 3 (e.g., Psychology, Mathematical and Ethics) and Table 4 (e.g., Psychology, Biological, Psychology and Psychology, Psychoanalysis). This would seem to suggest that sub-field analysis is needed to ensure that we don't draw false conclusions about a field's waxing and waning. For some fields (e.g., Nanoscience & Nanotechnology and Materials Science, Biomaterials), the increased Scientific Trading Impact is due largely to the increase in the number of publications; for other fields (e.g., Psychology, Mathematical and Social Sciences, Biomedical) the increase can be attributed to greater per publication impact (as reflected in citation counts).

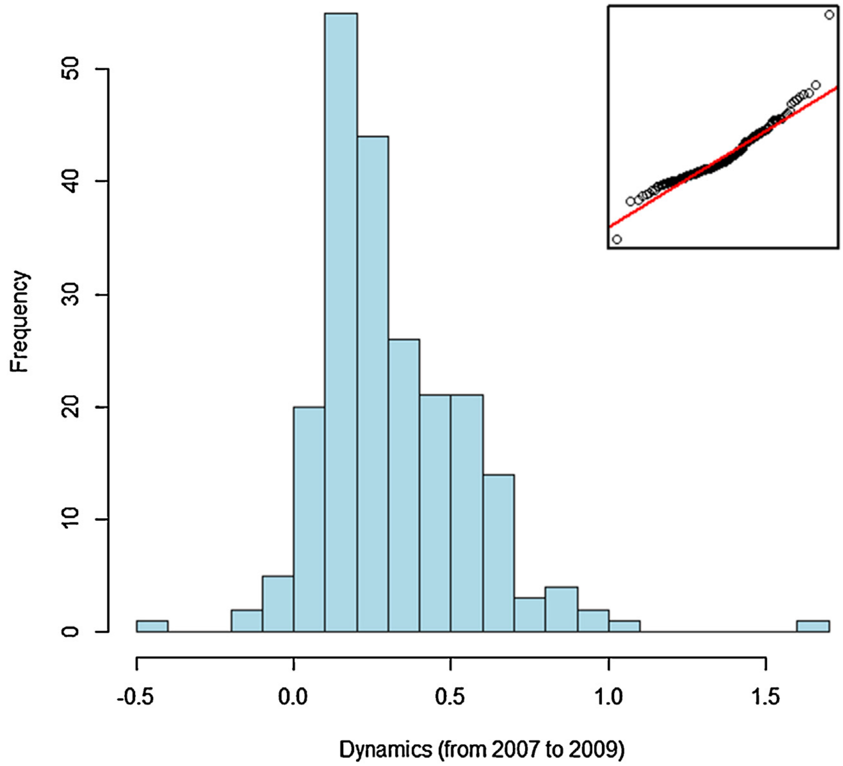

Fig. 4. Distribution of Scientific Trading Dynamics (from 2007 to 2009) with normal quantile–quantile plot.

3.2. Exporters and importers

If a field's outgoing citations exceed its incoming citations, it's a net importer of knowledge; if incoming citations exceed outgoing citations, it's a net exporter (see Table 5).

Fig. 5 shows the distribution of Export/Import Ratios for all 221 fields for 2009. The distribution follows a normal distribution with Kolmogorov–Smirnov's asymptotic significance equal to 0.18 ($p > 0.05$). The mean for the distribution is 0.95 and the standard deviation is 0.19. The results indicate that a majority of fields have a balanced knowledge economy, and only a few play a salient role as knowledge importers (ratio below 0.77) or knowledge exporters (ratio above 1.13).

Table 3
Top-10 fields based on export increases (2007–2009).

Subject categories[a]		Exports in 2007	Exports in 2009	Increase (%)
Nanoscience & Nanotechnology	C	241,198	646,645	168.10
	P	10,000	17,747	77.47
Materials Science, Biomaterials	C	92,103	184,584	100.41
	P	2665	4159	56.06
Transportation Science & Technology	C	19,330	37,110	91.98
	P	1321	2394	81.23
Health Policy & Services	C	10,101	19,331	91.38
	P	2499	3330	33.25
Psychology, Mathematical	C	8584	16,156	88.21
	P	506	596	17.79
Agricultural Engineering	C	37,841	70,511	86.33
	P	1351	2103	55.66
Social Sciences, Biomedical	C	25,874	47,574	83.87
	P	1793	1989	10.93
Transportation	C	7963	14,493	82.00
	P	757	873	15.32
Materials Science, Multidisciplinary	C	1,080,221	1,890,081	74.97
	P	40,905	51,853	26.76
Ethics	C	7415	12,833	73.07
	P	1049	1501	43.09

[a] C: number of citations; P: number of publications.

Table 4
Top-10 fields in terms of reduced exports (2007–2009).

Subject categories[a]		Exports in 2007	Exports in 2009	Change (%)
Psychology, Biological	C	2699	1369	−49.28
	P	1014	1149	13.31
Medical Ethics	C	8014	7028	−12.30
	P	416	592	42.31
History & Philosophy of Science	C	14,033	12,418	−11.51
	P	1007	1162	15.39
Psychology	C	335,943	310,887	−7.46
	P	3984	4923	23.57
Psychology, Psychoanalysis	C	7153	6755	−5.56
	P	467	438	−6.21
Medical Laboratory Technology	C	86,805	82,734	−4.69
	P	2559	2707	5.78
Statistics & Probability	C	269,364	262,307	−2.62
	P	6512	6844	5.10
Ornithology	C	33,466	32,680	−2.35
	P	1135	956	−15.77
Agricultural Economics & Policy	C	9130	9317	2.05
	P	424	549	29.48
Psychiatry	C	692,904	790,573	2.19
	P	10,258	11,829	15.31

[a] C: number of citations; P: number of publications.

Table 5
Exporter vs. importer.

Role	2007	2008	2009
Export > Import	79	88	81
Import > Export	141	132	140

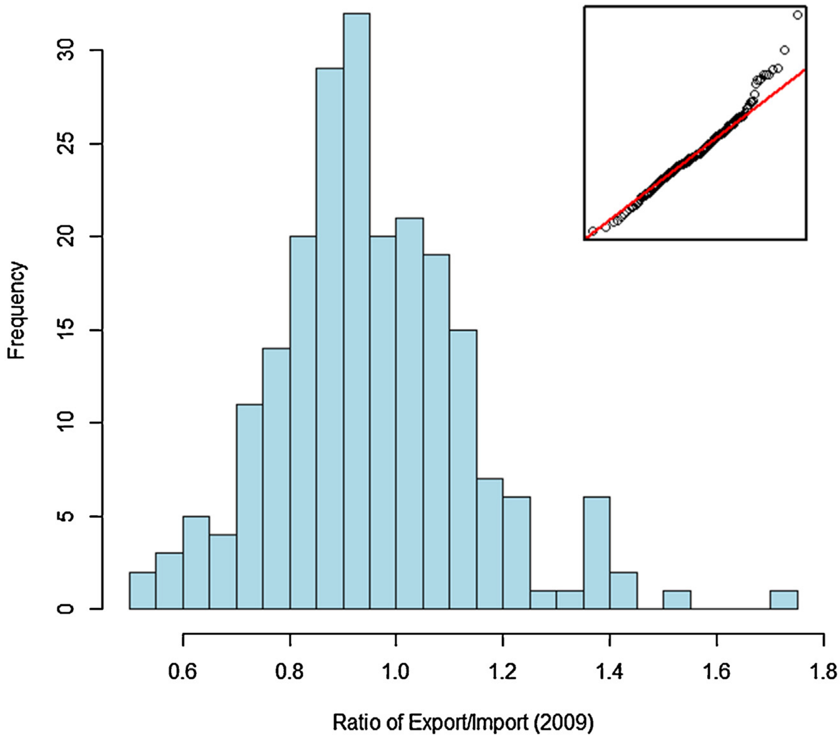

Fig. 5. Distribution of Export/Import Ratios (2009) with normal quantile–quantile plot.

Table 6
Top-10 significant exporters based on export/import ratios (2009).

Subject categories	Imports	Exports	Exports/imports
Medicine, General & Internal	635,835	1,100,441	1.73
Statistics & Probability	171,231	262,307	1.53
Social Sciences, Mathematical Methods	14,974	21,421	1.43
Computer Science, Hardware & Architecture	58,952	83,897	1.42
Psychology, Mathematical	11,596	16,156	1.39
Hematology	564,113	785,838	1.39
Psychology, Social	111,371	155,045	1.39
Physics, Multidisciplinary	714,276	978,353	1.37
Cell Biology	1,407,519	1,918,916	1.36
Peripheral Vascular Disease	478,743	651,799	1.36

Table 7
Top-10 significant importers based on export/import ratios (2009).

Subject categories	Imports	Exports	Exports/imports
Ethics	25,144	12,833	0.51
Biology	666,711	354,614	0.53
Health Policy & Services	34,627	19,331	0.56
Nursing	102,797	58,721	0.57
Parasitology	186,396	110,826	0.59
Materials Science, Characterization & Testing	34,469	20,960	0.61
Medical Ethics	11,295	7028	0.62
Information Science & Library Science	19,987	12,728	0.64
Integrative & Complementary Medicine	51,941	33,208	0.64
Veterinary Sciences	395,908	256,961	0.65

The marketplace of ideas is largely barrier-free—we leave aside here issues relating to tolls and open access publishing. Since knowledge is traded freely, successful exporters are most likely to be those scholars with the highest quality and/or most useful goods to offer. Table 6 lists the most significant exporters in the sciences and social sciences. These fields are the engines that power science and technology development. For example, Medicine, General & Internal, Hematology, Cell Biology, and Peripheral Vascular Disease power biomedical research; Statistics & Probability and Computer Science, Hardware & Architecture, and Physics, Multidisciplinary power physical, mathematical, and engineering research; Social Sciences, Mathematical Methods, and Psychology, Social power social sciences research. Export/import ratios for all 221 fields are included in the supplementary material (Supplementary Table 2).

The fields in Table 7 are significant importers. Their Export/Import ratios are less than one, indicating a knowledge trading deficit.

3.2.1. *Knowledge flow and knowledge surplus*

We next zoom in to capture the extent to which any given subject category is a net exporter to other SCs; that is to say, we identify the fields that have the largest number of trading partners. Table 8 lists the top-10 science SCs and the top-10 social sciences SCs. Table 9 lists the top-10 science subject categories and top-10 social sciences subject categories based on (positive) knowledge surplus.

Statistics & Probability functions as a knowledge exporter to almost all other subject categories (211 in total). It provides useful methodological applications to many scientific and social scientific disciplines. As for knowledge surplus, the top-10 SCs in science comprise the biomedical sciences, chemistry, and physics. In the social sciences, Economics is the leading knowledge exporter, followed by Business, Psychology, Management, and Sociology. There are at least two possible interpretations. First, these fields may be more mature than other social sciences disciplines and thus attract the attention of less established, less cognitively assured fields. Second, these SCs tend to preferentially cite their own literature because

Table 8
Top-10 science and social sciences exporters.

Science subject categories	No. of SCs	Social sciences subject categories	No. of SCs
Statistics & Probability	211	Economics	153
Medicine, General & Internal	196	Psychology, Social	139
Biochemistry & Molecular Biology	186	Business	138
Mathematical & Computational Biology	177	Sociology	136
Genetics & Heredity	170	Social Sciences, Mathematical Methods	134
Cell Biology	169	Management	120
Peripheral Vascular Disease	166	Psychology, Clinical	117
Cardiac & Cardiovascular Systems	166	Psychology, Educational	115
Hematology	162	Psychology, Experimental	115
Psychology	161	Psychology, Multidisciplinary	106

Table 9
Top-10 science and social sciences SCs in terms of knowledge surplus.

Science subject categories	Knowledge surplus	Social sciences subject categories	Knowledge surplus
Biochemistry & Molecular Biology	898,501	Economics	75,406
Cell Biology	526,045	Business	48,305
Medicine, General & Internal	465,714	Psychology, Social	47,841
Chemistry, Multidisciplinary	431,493	Management	37,653
Physics, Multidisciplinary	279,577	Sociology	27,741
Genetics & Heredity	247,151	Psychology, Clinical	19,827
Oncology	238,465	Business, Finance	16,465
Hematology	235,656	Psychology, Educational	15,168
Immunology	230,924	Psychology, Developmental	12,901
Physics, Condensed Matter	210,996	Psychology, Experimental	12,508

they have less permeable boundaries and less need to borrow tools, methods or theories from other fields (see Klein, 1996) on disciplinary boundaries and boundary crossing). The top social science fields measured by knowledge surplus include economics, business, management, and psychology.

3.2.2. Science hubs

Hubs are the most connected nodes in a network. In terms of scientific trading, the fields with the largest volume of exported and imported knowledge are hubs. Similar to the busiest airports in the world, science hubs interconnect smaller fields. Two fields may not have direct trading connections, but they can always link indirectly via hubs. These science hubs function as knowledge processors, absorbing and distributing value-added knowledge to other fields.

Figs. 6 and 7 show the distributions of the sizes of imported and exported knowledge for all 221 fields for 2009. The two distributions display a noticeable power–law distribution pattern (Kolmogorov–Smirnov's asymptotic significance equals zero) in that most fields are limited in the size of imported or exported knowledge and only a few fields function as science hubs.

The top-10 science hubs are shown in Table 10.

According to Lenoir (1997), the creation of domain knowledge reflects the dominant relations of economic, social, and political power in society. The prominence of biomedical fields as science hubs underscores his point: biomedical products have high market value (economic power), are important to the well-being of society (social power), and are sensitive to

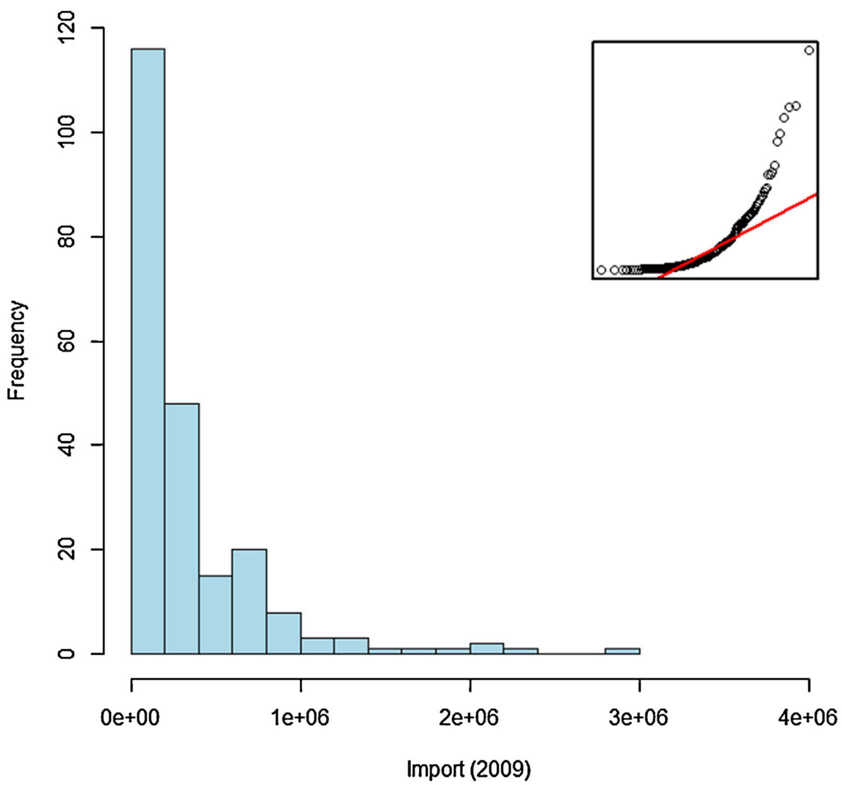

Fig. 6. Distribution of imports (2009) with normal quantile–quantile plot.

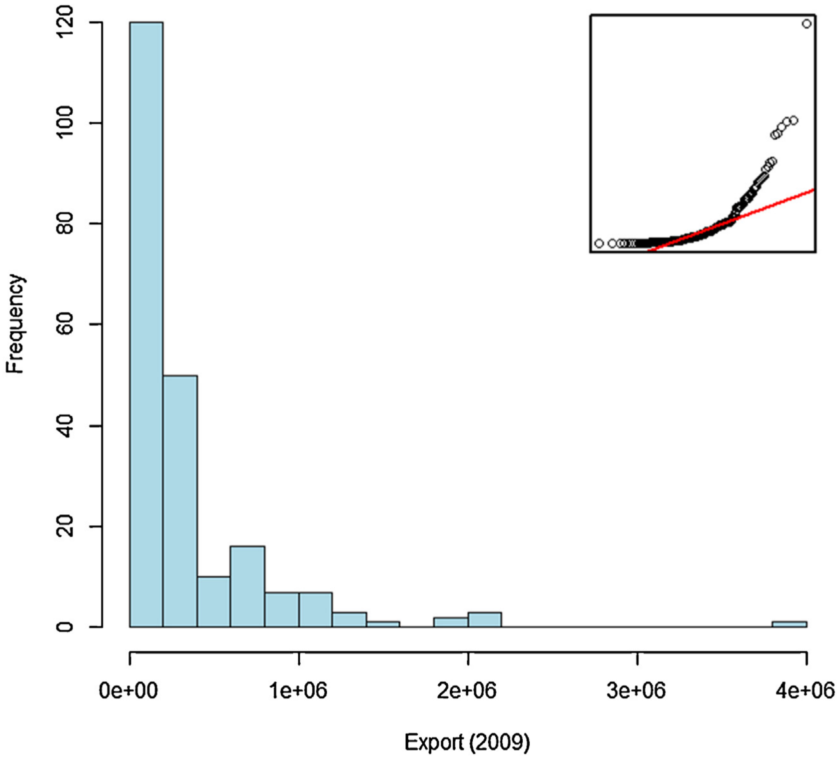

Fig. 7. Distribution of Exports (2009) with normal quantile–quantile plot.

science policy decisions (political power). The importance of this SC is reflected in the magnitude of the funds allocated to biomedical research every year and the vastness of the research literature.

3.3. Discipline Self-dependence

Disciplines vary greatly in terms of their permeability, cognitive autonomy and self-dependence (Klein, 1996). Some are interdisciplinary and porous while others are self-contained and have a quite distinct core. Bourdieu (1977), for instance, considered sociology to be less autonomous than biomedical fields, and the latter less autonomous than physics. The assumption is that an independent field preferentially cites its own publications; the higher the rate of self-citation, the more self-contained a field is (e.g., Borgman & Rice, 1992; Buter et al., 2011; Cronin & Meho, 2008; Guerrero-Bote, Zapico-Alonso, Espinosa-Calvo, Gomez-Crisostomo, & Moya-Anegon, 2007; Levitt et al., 2011; Leydesdorff, 2011; Leydesdorff & Probst, 2009; Lillquist & Green, 2010; Porter & Rafols, 2009; Rafols & Meyer, 2010; Rinia et al., 2002).

It can be seen from Table 11 that most fields are predominantly self-citers, i.e., self-reliant, even though self-dependence is decreasing overall. Some, however, depend on sources other than themselves for ideas. Several factors come into play. It is possible that a new or emerging field draws significantly on the literatures of more established fields as it develops and consolidates its own intellectual base (Larivière et al., 2012). A smaller field may also lie at the intersection of two (or several) larger fields and such an interstitial field may draw heavily on the bookending fields (Leydesdorff & Probst, 2009).

Table 10
Top-10 science hubs.

Name	Imports	Exports	Imports + exports
Biochemistry & Molecular Biology	2,969,848	3,820,866	6,790,714
Chemistry, Physical	2,196,028	2,029,046	4,225,074
Neurosciences	2,062,891	2,129,998	4,192,889
Materials Science, Multidisciplinary	2,216,953	1,890,081	4,107,034
Chemistry, Multidisciplinary	1,843,270	2,140,721	3,983,991
Cell Biology	1,407,519	1,918,916	3,326,435
Pharmacology & Pharmacy	1,745,816	1,339,498	3,085,314
Physics, Applied	1,294,934	1,428,746	2,723,680
Oncology	1,294,057	1,397,783	2,691,840
Environmental Sciences	1,327,559	1,150,162	2,477,721

Table 11
Discipline self-dependence.

	2007	2008	2009
Primarily depends on itself	174	171	161
Primarily depends on others	46	49	60

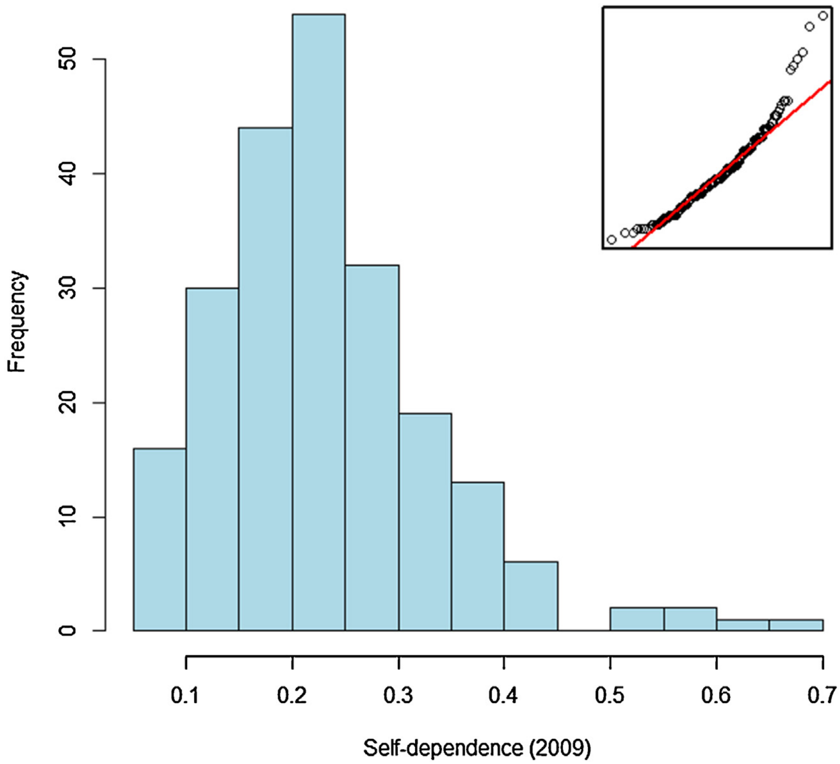

Fig. 8. Distribution of Self-dependence (2009) with normal quantile–quantile plot.

Fig. 8 shows the distribution of Self-dependence for all 221 fields for 2009. The distribution did not pass the normal significance test with Kolmogorov–Smirnov's asymptotic significance equal to 0.002 ($p < 0.05$). The distribution is positively skewed (statistic is 1.2 which is more than three times larger than its standard error 0.16) and leptokurtic (statistic is 2.68 which is more than three times larger than its standard error 0.33). The mean for the distribution is 0.23 and the standard deviation is 0.10, suggesting that although most fields are predominantly self-citers, the combination of cited knowledge from all other fields may account for a higher percentage.

Table 12 shows the most independent disciplines in both the sciences and social sciences. Self-citation ratios for all 221 fields are included in the supplement material (Supplementary Table 2).

Each is highly specialized and strongly reliant on its own knowledge base. Specialized disciplines include vocational and professional fields, for example, Law, Ophthalmology, Dentistry, Oral Surgery & Medicine, Psychology, Psychoanalysis, Veterinary Sciences, and Nursing. These disciplines typically have institutional arrangements (formal educational

Table 12
Top-10 independent disciplines (2009).

Name	Exports	Self-citations	Ratio
Law	61,809	42,025	0.68
Astronomy & Astrophysics	686,519	448,998	0.65
Ophthalmology	232,581	134,928	0.58
Dentistry, Oral Surgery & Medicine	206,287	115,870	0.56
Mathematics	307,136	164,870	0.54
Psychology, Psychoanalysis	6755	3599	0.53
Veterinary Sciences	256,961	114,065	0.44
Linguistics	37,672	16,654	0.44
Nursing	58,721	25,714	0.44
Education & Educational Research	65,164	27,790	0.43

Table 13
Top-10 dependent disciplines (2009).

Name	Exports	Self-citations	Ratio
Psychology, Biological	1369	66	0.05
Social Sciences, Mathematical Methods	21,421	1419	0.07
Medicine, Research & Experimental	615,899	43,815	0.07
Biology	354,614	28,967	0.08
Anatomy & Morphology	50,740	4195	0.08
Microscopy	29,219	2436	0.08
Psychology, Mathematical	16,156	1348	0.08
Biophysics	672,529	56,720	0.08
Limnology	107,229	9327	0.09
Andrology	11,723	1041	0.09

programs, faculties, accrediting agencies, learned/professional societies, etc.) and paraphernalia (meetings, textbooks, scholarly journals, prizes, etc.) that newer, small, less established fields may lack or be unable to put in place.

Most dependent disciplines (see Table 13) are located at the intersection of two or more main disciplines. For example, Psychology, Biological is at the intersection of Psychology and Behavioral Sciences, and thus it cites these two fields most (more than 40%) but does not cite many of its own publications (<5%). BIOLOGY is a well-established field but since the second half of the 20th century it has become increasingly dependent on Biochemistry & Molecular Biology (23%), followed by Cell Biology (14%), Neurosciences (11%), Genetics & Heredity (10%), and Biology (8%).

4. Discussion

4.1. Interrelationship of the scientific trading dimensions

In order to test the reliability of the scientific trading dimensions, Spearman's rank correlation coefficients were calculated for Scientific Trading Dynamics, Ratio of Export/Import, Import, Export, and Self-dependence for 2009, with scatter plot visualizations (Fig. 9).

In Fig. 9, except for the correlation coefficient ($R^2 = 0.9917$) between Import and Export, the strength of the other correlation coefficients ranges from mild to weak. This indicates that the dimensions are not susceptible to multicollinearity and that each one works independently and is thus capable of describing a particular characteristic of disciplines. Combined, the dimensions provide a comprehensive perspective on disciplinary characteristics.

4.2. Applying the scientific trading dimensions to a variety of fields

Using the dimensions we introduced, we highlight ten characteristic types and illustrate each one with a number of SCs (Fig. 10). In general, scientific fields have a higher *Scientific Trading Impact* than social science fields. Biomedical sciences (Biochemistry & Molecular Biology and Medicine, General & Internal), physics, and chemistry have higher levels of dependence and higher *Export/Import* ratios. Interdisciplinary science fields, such as Chemistry, Physics, Material Science, Multidisciplinary, and Environmental Sciences, have lower *Discipline Self-dependence* and lower *Export/Import* ratios. Specialized biomedical sciences, such as Neurosciences and Oncology have higher *Discipline Self-dependence* and higher *Export/Import* ratios. The social sciences (e.g., Information Science & Library Science, Law, Education & Educational Research, Political Science, Management, and Business) tend to have higher levels of *Discipline Self-dependence.*

4.3. Characteristics of the sciences and the social sciences

We visualized the distributions for trading dynamics (Fig. 4), export/import ratios (Fig. 5), import (Fig. 6), export (Fig. 7), and self-dependence (Fig. 8); and found that except for the distribution of export/import ratios, the rest of the trading dimensions did not follow a normal distribution—in particular, the import and export distributions displayed a power law pattern. Such power law properties have been found for different research entities, such as paper citations (e.g., Redner, 1998), author productivity (e.g., Lotka, 1926), journal productivity (e.g., Bradford, 1934), or institutional citations (e.g., Carvalho & Batty, 2006; Yan & Sugimoto, 2011), i.e., only a limited number of these entities have high scientific productivity and/or impact while the majority have low scientific productivity and/or impact. In our study, at the field level, there is an apparent difference between the science and the social science in their scientific trading impact (see Tables 9 and 10). Given this difference, do the social sciences, due to their size, suffer from the preferential attachment effect (Barabási & Albert, 1999; Merton, 1968)? To address this question, we calculated the increment rate for all social science fields as well as the percentage of trading impact for all social science fields in Table 14.

Table 14 shows that the knowledge increment rates for social science fields grew faster than for all fields, while the percentage of trading impact for all social science fields have increased from 3.15% in 2007 to 3.84% in 2009. The results

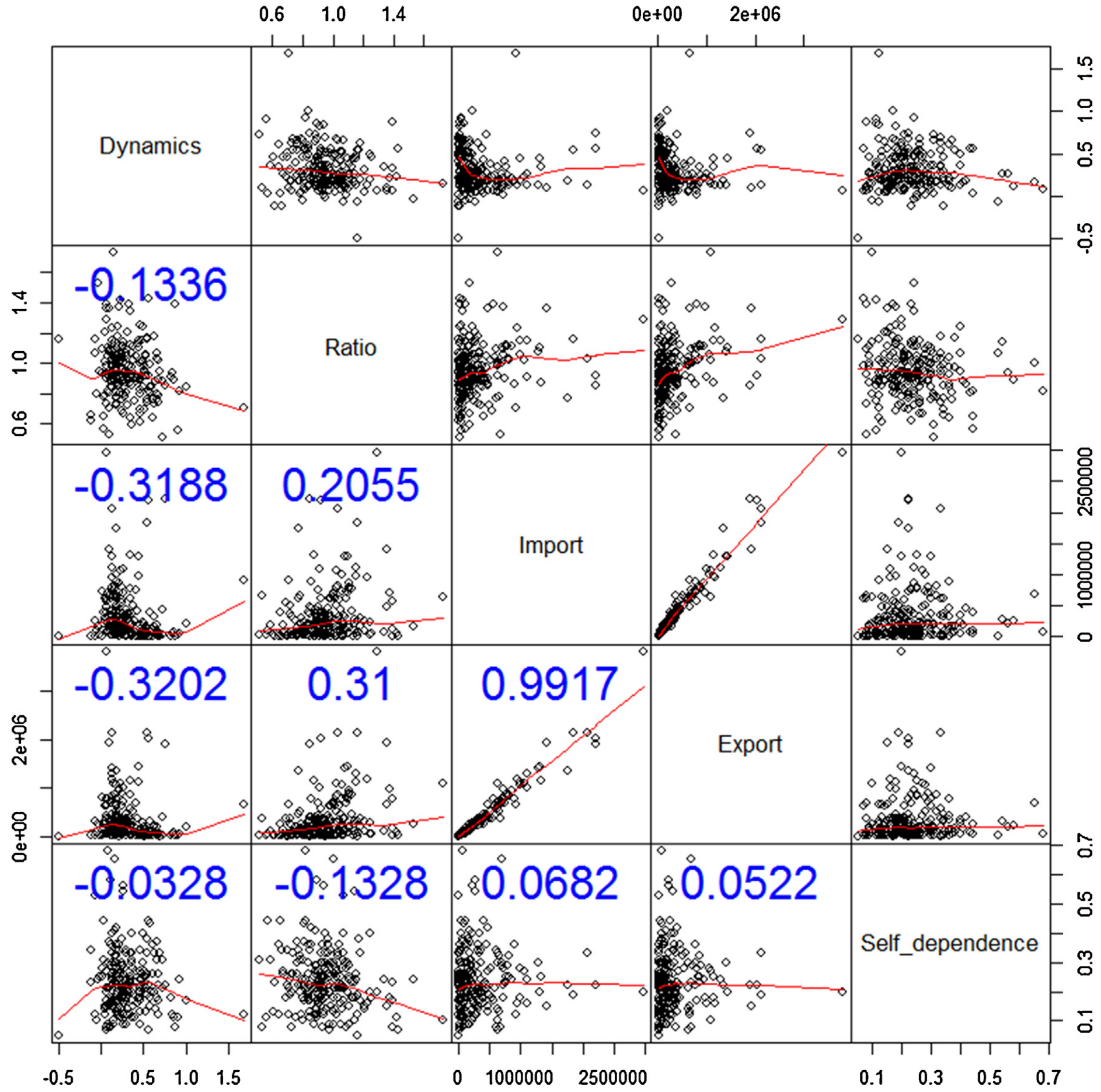

Fig. 9. Spearman's rank correlation coefficients and scatter plots for pairs of indicators.

suggest that despite the power law pattern for knowledge import and export distributions, social science fields may not be susceptible to the preferential attachment effect in that these fields are becoming more visible by exporting more knowledge and having a higher share of scientific trading. The results indicate that the sciences and social sciences are quite different (Nederhof, 2006; Suppes, 1984). In future research we intend to develop fine-grained indicators to study in more detail how knowledge is disseminated.

Table 14
Scientific Trading Impact and Dynamics for the social sciences.

Year range	Increment of citable knowledge for all fields (from Table 2) (%)	Increment of citable knowledge for social science fields (%)	Year	Percentage of trading impact for all social science fields against all fields (%)
2007–2008	7.33	15.4	2007	3.15
2008–2009	12.46	30.51	2008	3.34
2007–2009	20.70	50.61	2009	3.84

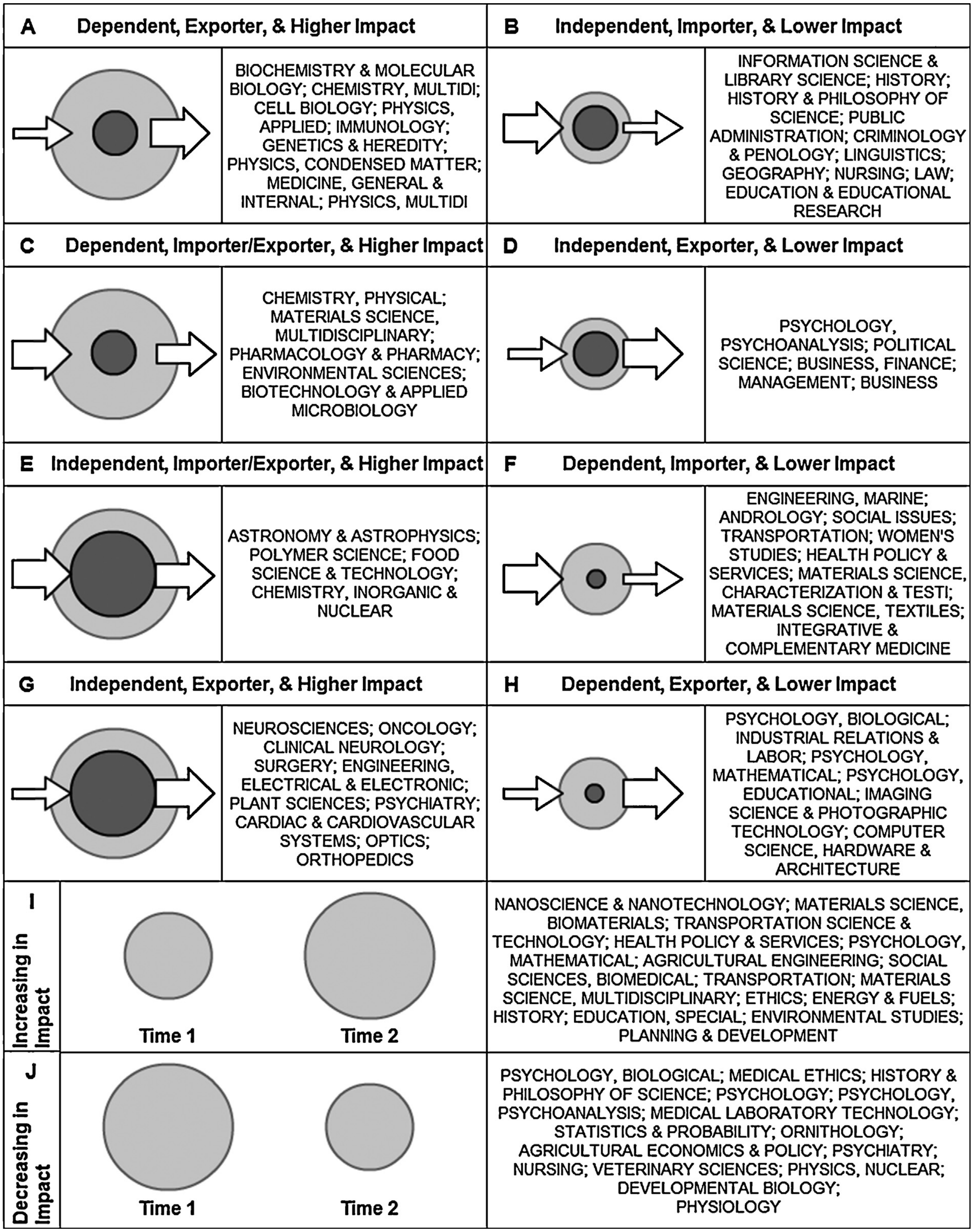

Fig. 10. Characteristics of subject categories.

5. Conclusion

We developed a set of concepts to describe scientific trading. Using these concepts, we fashioned a framework comprising four dimensions: (a) *Discipline Self-dependence*, (b) *Exports/Imports*, (c) *Scientific Trading Dynamics*, and (d) *Scientific Trading Impact*. This framework enabled us to develop a unique, data-rich bird's-eye view of trends in knowledge trading between disciplines and fields. Our study reveals the permeability and self-sufficiency of different scientific and social scientific disciplines. The findings should stimulate further research into the nature and dynamics of disciplinarity and interdisciplinarity and also help inform science policy making.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.joi.2012.11.008.

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