The Structure and Evolution of Sustainability Science

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THE EVOLUTION AND STRUCTURE OF SUSTAINABILITY SCIENCE

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ABSTRACT. The concepts of sustainable development have experienced extraordinary success since their advent in the 1980s. They are now an integral part of the agenda of governments and corporations and their goals have become central to the mission of research laboratories and universities worldwide. However, it remains unclear how far the field has progressed as a scientific discipline, especially given its ambitious agenda of integrating theory, applied science and policy, making it relevant for development globally and generating a new interdisciplinary synthesis across fields as diverse as ecology, the social sciences and engineering. To address these questions we assembled a corpus of scholarly publications in the field and analyzed its temporal evolution, geographic distribution, disciplinary composition and collaboration structure. We show that sustainability science has been growing explosively since the late 1980s when foundational publications in the field increased its pull to new authors and intensified their interactions. The field has an unusual geographic footprint, combining contributions and connecting through collaboration cities and nations at very different levels of development. Its decomposition into traditional disciplines reveals its emphasis on the management of human, social and ecological systems seen primarily from an engineering and policy perspective. Finally we show that the integration of these perspectives has created a new field only in recent years as judged by the emergence of a giant component of scientific collaboration. These developments demonstrate the existence of a growing scientific field of sustainability science as an unusual, inclusive and ubiquitous scientific practice and bode well for its continued impact and longevity.

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1. Introduction

The concepts of sustainable development have experienced an extraordinary rise over the past two decades, and now pervades the agenda of governments, corporations as well as the mission of educational and research programs worldwide. Although there are some antecedents in the 1970s, these ideas had their formal beginning in the 1980s with several important policy documents, primarily the *World Conservation Strategy* [2] and the now famous *Brundtland commission report* [1], issuing a call to arms for new policy and for the advent of a new scientific discipline capable of responding to the challenges and opportunities of sustainable development.

The main obstacle to the creation of a science of sustainability, however, is its universal (systems-level) mandate [3, 4, 5, 6]. A science of sustainability necessarily requires collaboration between perspectives in developed and developing human societies, among theoretical and applied scientific disciplines and must bridge the gap between theory, practice and policy. There is arguably no example in the history of science of a field that from its beginnings could span such distinct dimensions, and achieve at once ambitious and urgent goals of transdisciplinary scientific rigor and tangible socio-economic impact. So an important question is whether sustainability science has indeed become a field of science? And if so, how has it been changing, and who are its contributors in terms of geographic and disciplinary composition. Most importantly is the field fulfilling its ambitious program of generating a new synthesis of social, biological and applied disciplines and is it spanning locations that have both the capabilities and needs for its insights? As we show below the answers to all these questions are positive. The detailed analysis of the scholarly literature of sustainability science provided below paints a detailed picture of an unusual, fast growing, and varied field, which has only recently become a unified scientific practice.

In order to understand the advent and development of a new field of science we have to place its dynamics and structure in the light of broader studies covering many traditional disciplines over time. In his celebrated and still relevant account of the rise of new science [7] Thomas Kuhn characterized the advent of new fields in terms of two main events: *discovery* and *invention*. The moment of *discovery* deals with the realization by a small group of researchers of a new concept or technique. In contrast, the moment of *invention* is characterized by the understanding and practice of the uses of discoveries. If discovery is the source of original knowledge, it is invention that creates science as we know it, as collaborative fields of activity characterized by shared practices and concepts. In one well-known example Kuhn describes the discovery of Oxygen (independently by Scheele and Priestley in 1773-4) as a constituent element of air. However, it was only with the realization of its role in combustion by Lavoisier a few years later that Oxygen acquired a functional role as the key ingredient to a large set of laboratory techniques used universally in chemistry and biology.

It is hard to sketch an exacting parallel between the advent of new fields in the natural sciences and sustainability science. However, it is clear that early policy documents [1, 8, 9] on the need for sustainable development, most notably the 1987 UN Bruntland report *Our Common Future* [1], provided the first articulated concepts of economic and social development that could occur without irreversible damage to the Earths natural environment or the depletion of non-renewable resources. This was still a long way from a clear-cut instrument of science and technology. As we show below, it took the best part of the next twenty years for practical perspectives to arise and for common methodologies to connect knowledge and methods from a variety of traditional disciplines into a new conceptual and practical whole.

To characterize sustainability science we develop here an extensive analysis of the fields literature. We construct and analyze time series for the number of publications and authors in the field and model them using population models that proved useful for the development of other scientific fields. This reveals the founding events in the field that triggered the first flurry of publications. In particular we show that a structural change in collaboration in the late 1980s was an essential ingredient in setting out the field on a path of growth, geographic ubiquity and ultimate unification. We show the field's geographic and disciplinary makeup and how this has changed over time. Finally we show how the field of sustainability science has evolved as a collaboration network that became unified in terms of a giant cluster of co-authorship only around the year 2000.

2. Results

We assembled a large corpus of publications in sustainability science via keyword searches, including journal articles and conference proceedings written in english over the period of 1974-2009. Details are given in Materials and Supplementary Information. The corpus analyzed below consists of about 37 thousand distinct authors of over 20 thousand papers, from 174 countries and territories and 2206 cities worldwide.

2.1. **Temporal evolution.** Figure 1A shows the temporal evolution of the field in terms of the cumulative number of distinct authors. Two main fact are immediately apparent. First the field is currently growing exponentially (linearly on the semi-log plot), with a doubling period of 8.3 years. Secondly this rate of growth was achieved after a dynamical transient in the late 1980s, when the field's pace of growth accelerated to present levels.

These trends can be interpreted in terms of changes in the population dynamics of the field, specifically as changes in its pull for new authors and its collaborative interaction rates. In past publications [10, 11] we have found it useful to infer characteristics of different scientific fields from data analogous to that of Fig. 1A using a family of population models that account for these factors. These models assume that the current active authors in a field are instrumental in spreading its working knowledge, and that as such a field can be characterized by a certain recruitment rate Λ at which new individuals become susceptible to the idea, and rates of interaction β, ϵ, κ that statistically transform these individuals into active authors, who eventually may also leave the field at some given exit rate γ, see Fig. 1B and Materials. Perhaps most importantly, these models were motivated by very general considerations for the dynamics of science [12, 13, 14, 15] in analogy to population dynamics in ecology and epidemiology, and were developed and tested for fields for which we have detailed ethnographic information [16, 10].

The most critical parameters, shown in Fig 1B, are the recruitment rate Λ, the contact rate β and the exit rate γ. The temporal trend of number of authors in sustainability science is well modeled by $\Lambda = 0.460$ (or 46%) through the period 1976-2009, indicating that the number of people susceptible to enter the field has been growing explosively. Susceptible and exposed population are difficult to measure but these numbers are at least qualitatively plausible as measures of the impact of the field in terms of internet pages and general documents suggest [17].

The other fundamental parameter is the ratio $R_0 = \beta/\gamma$, often known in ecology as the basic reproductive number [18]. Its interpretation is as a branching ratio, which characterizes the average number of new authors than an active author will lead to through contact with susceptible and exposed, over his or her time in the field. $R_0 > 1$ means that the field will grow and the magnitude of R_0 is a measure of the initial growth rate of the field (directly related to the eigenvalue of the growing mode around the birth of the field). The most important feature of the temporal trend in the field's growth is that it cannot be modeled accurately with a constant contact rate β, see Fig. 1C. Instead a sharp 36% increase of the contact rate from $\beta = 1.50$ to 2.04 must occur over the period 1985 to 1990 in order to account for the trend of Fig. 1A.

This also means a commensurate increase in R_0 ensuring that the field has grown not only in numbers of susceptible individuals but also in terms of the rate of contacts between these and the population of practicing scientists. This will be apparent more directly, when we analyze the field's co-authorship network evolution below.

Note that an increase in the recruitment rate Λ over time is not able to explain the same effect as it is not directly related to the growth in the numbers of authors; its role is to facilitate a larger pool of susceptible individuals, but this effect eventually saturates. Thus, as we know in hindsight, the years that followed the publication of *Our common future* [1], were the foundational period over which many individuals first became interested in the issue of a science of sustainability and when contacts between them and early practitioners in the field intensified.

2.2. **Geographic distribution.** An interesting and unusual feature of the literature of sustainability science is the broad spatial distribution of its contributions. In a very specific sense this is a necessary condition for a successful field that spans theory and practice as many developing nations are at center stage of the direst challenges of sustainable growth. In fact while research in more specialized fields, particularly in the natural sciences, tends to be concentrated in a few cities and in the most developed world [19], the field of sustainability science has a very different geographic footprint. Figure 2A, and B show the national counts for numbers of publications and citations, respectively, across the globe. (Much more detailed interactive world maps of cities and their collaboration networks are available online at http://www.santafe.edu/∼bettencourt/sustainability/). The first clear signal from these maps is that the field is widely distributed internationally and has a strong presence not only in nations with traditional strength in science, e.g. the United States, Western Europe and Japan, but also elsewhere. Especially noteworthy at the magnitude of contributions from Australia, the Netherlands, the United Kingdom, Brazil, China and India and most especially South Africa, Nigeria, Kenya and Turkey. These nations show not only a large presence in terms of numbers of publications but also in terms of their quality as expressed in terms of citations.

A finer geographic picture can be gleaned by observing productivity and quality in the field at the local level of cities and by mapping their collaboration networks. It is perhaps surprising that the world's leading city in terms of publications in the field is Washington DC, outpacing the productivity of Boston or the Bay Area, which in other fields are several fold greater than that of the US capital. A similar picture is on display in the UK where London (with almost 4000 publications in the field, just a few shy of DC's tally) easily outpaces any other british or european city. Other important cities in the field are Stockholm, Wageningen (Netherlands), Seattle, Madison WI, and, in their regional contexts, Nairobi, Cape Town, Beijing, Melbourne and Tokyo, The networks of collaborations between cities also shed some light on the roots of greater regional productivity. For example Nairobi is well connected to research centers in the US and Western Europe, as are most large Australian cities and Cape Town. The reach of cities like Washington DC, London, Beijing, and to a slightly lesser extent Canberra and Cape Town is truly global, connecting with different scientific centers around the world, and contrasts with the less internationalized (and less productive) cities of Brazil and India, for example.

Another interesting dimension of publications in sustainability science is that not only principal national research centers contribute but many smaller universities and laboratories have a presence in the field. This is especially true in Australia, the Netherlands, the UK and the US, but is also at play in other nations. Thus the geographic distribution of publications in sustainability science paints a picture of a regionally very diverse field with many different contributors, in developed and developing nations and in terms of different institutional types and forms. This network of collaboration has strong roots in national capitals, which are atypically among the most productive research centers in the field, and spans the world in terms of co-authorship links.

2.3. **Discipline footprint and its evolution.** A different perspective into a new scientific field is its footprint in terms of traditional scientific disciplines. Over the last few years this type of endeavor has lead to the creation of a set of diverse maps of science [20, 21, 22, 23, 24], where different traditional disciplines, organized in terms of speciality journals, are inter-related in terms of their journal level citations, clickstreams of readers or any other relationship. Here we use a similar procedure to determine the disciplinary make-up of sustainability science and analyze its temporal evolution (see Materials for more details).

Figure 3A shows the relative composition of the literature of sustainability science in terms of ISI defined disciplines. Figure 3B shows the change in their percent composition over time. The most notable feature of Figure 3A is the fact that the field is dominated by contributions from the social sciences, biology and chemical, mechanical and civil engineering. As a broad area the social sciences are the greatest single contributor to the field with almost 34% of the total output in terms of total number of publications. Its relative importance has decreased somewhat over time reaching a maximum of 42% in 1995 and being down to 32% in 2009. We can go further to quantify the sub-disciplines that contribute the most within the social sciences. We find that environmental policy (20.2% of the social sciences total), environmental management (15.4%), regional studies (5.4%), human resource management (4.9%), political geography (4.5%), rural studies (4.1%), urban studies (3.7%) and econometrics (3.4%) lead the list.

Similarly the field of biology with 23.3% of total publications (achieving its maximum contribution of 30.6% in 1997 and down to 23% in 2009) has as its main subfields a mixture of contributions that is unique to sustainability studies spanning much of ecology and resource management. These include as its main contributions weed management (16.8% of the biology total), biological conservation (15.9%), ecological modeling (11.6%), forest science (6.4%), fish research (4.0%), soil analysis (3.9%), molecular ecology (3.7%) and fish biology (3.5%).

Finally, the large field of chemical, mechanical and civil engineering which is responsible for 21.6 % of all publications in sustainability science is made up of very diverse subfields. Its leading contributors to the literature of sustainability science are soil science (23.6% of the discipline total), solar & wind power (16.9%), water waste (9.4%), ocean coastal management (5.5%), soil quality (4.8%), filtration membranes (2.5%), water policy (2.4%) and environmental pollution (2.3%).

From these lists we clearly see that although a superficial reading of the different main disciples that contribute to sustainability science may suggest non-overlapping research themes this is not the case at all. In fact the main themes that define the field, the concept of management of human, social and ecological systems and of the engineering and policy studies that support and enable them, are the true cross-cutting subjects that unify the field as we know from Ref. [28, 29], which established that these themes are well connected by mutual citation

2.4. **Collaboration network structure and evolution.** The characterization of sustainability science given above provides us with a clear picture of the growth of the field, of where it is based geographically and what it is in terms of its research theme distribution. What our analysis so far does not provide is direct evidence that sustainability science has created a new community of practice and a new synthesis in terms of concepts and methods. We have argued [25] that such unification is the hallmark of a true field of science, and showed that scientific endeavors that have had their bursts of enthusiasm (e.g. cold fusion) but that failed to create unifying methods or concepts never emerged as widespread collaboration networks. On the contrary true fields of research tend to start from a few mutually isolated efforts (which appear as small separate networks of collaboration) that later, after the moment of invention alluded to in the Introduction, grow and congeal into a giant cluster of collaboration that includes the vast majority of authors in the field [25].

In this light it is critical to ask if and when widespread collaboration - between most authors, and spanning geography and disciplines - has become a feature of the literature of sustainability science. There are two properties of research communities in their way to becoming true fields. First the number of co-authorship links tend to grow faster than the number of authors, usually following a power law scaling relation (with an exponent $\beta > 1$). Fig. 4A shows how the number of co-authorship links have increased with numbers of authors, where every point corresponds to a different year. Interestingly there is evidence for two distinct regimes: before 1989 the number of collaborative links per author actually *decreased* with the number of new authors showing that the field did not get denser in terms of its collaboration structure and that different themes in the field, pursued by different communities, did not unify; in fact they became more and more separate. This is sometimes typical of fields founded on an idea that has not yet proven workable. An example is the field of quantum computing, which existed for decades as a fascinating proposal but that only gained tangible algorithms, experiments and new theory in 1994-5, see Ref. [25]. After about 1989, a period that as we have seen above was also marked by an acceleration in the growth of new authors and an inferred increase in contact rate, the field started to become denser with the number of co-authorsip connections per author now increasing with an exponent $\beta = 1.23 > 1$). As a result of growing density the field eventually became dominated by a giant cluster of collaboration to which most authors now belong. This unification happened only around the year 2000, see Fig. 4B. Because the formation of a giant cluster of collaboration is analogous to a topological phase transition in physical systems it can be characterized by a measure of the relative size of the largest collaboration cluster P, and a measure of the relative sizes of disconnected collaboration efforts, which are larger in the beginning of the field, increase towards the onset of the formation of a giant cluster and then fall to almost zero once the field unifies (see Materials for details). These quantities are shown in Fig. 4B, their change characterizes the formation of the field as a giant collaboration cluster emerges. We see that P starts to increase away from (almost) zero and that S drops precipitously around the year 2000.

In addition, although not show here, networks of collaboration between cities or nations, or between disciplines unify somewhat earlier as they are (very) coarse-grained versions of co-authorship networks. As a result we can say that a field of sustainability science has indeed become cohesive over the last decade, sharing large scale collaboration networks to which most authors belong and producing a new conceptual and technical unification that spans the globe.

3. Discussion

The concept of sustainable development has acquired a global cultural and social dimension that vastly transcends the traditional boundaries of a scientific field. For example, in a recent review [17] Kates estimates over that over 8,720,000 web pages existed in January 31, 2005 on the theme of sustainable development alone (a similar search at the time of this writing estimates 21,500,000 documents), as well as being pervasive element in the manifestos of almost every large corporation and government, not to mention the myriad initiatives that derive inspiration from the concept.

This success puts a greater onus on the existence of a scientific practice that we may call the field of sustainability and that can carry the aspirations of so many people and institutions and guarantee the tangible scientific and societal impact of these ideas.

Defining or even circumscribing a field of science is of course not a well defined task as it is somewhat subjective. Over the last few years several methods have been proposed to do this automatically (see e.g. [26, 27]) but many clear difficulties remain. For these reasons identifying fields of science still requires a mixture of automated searches and active domain expertise [11, 25]. Here we have used new concepts and methods from science of science and technology studies to build and analyze the development of the corpus of sustainability science in english, assembled via key term searches, using standard scholarly collections (see Materials and Supplementary Information). A similar collection was assembled and analyzed in terms of network structures in Refs. [28, 29], especially their citation structure and its analysis is complementary to the perspectives given here.

There are several issues of completeness and of the presence of false positives in our corpus that are worth discussing. We have found by manual inspection that some records prior to the 1980s are incorrect and tend to refer to sustainability in terms of the general continuation or maintenance of a process. This is especially troublesome in retrieving patents where almost all records refer to these features of a process and not to themes in sustainability science. For this reason we have not included here an analysis of patent records in the field. A collection of such patents filed in the United States is being developed by Strumsky [30] by other methods. Records found to be erroneous were extracted from the corpus manually; their relative frequency is minute in later years. For these reasons we believe our collections to be mostly free of error.

The issue of completeness is more difficult to establish. Beyond subjective judgement where two human observers may diverge, there are two main issues that plague the construction of comprehensive corpora of interdisciplinary international fields. First the literature available in the world's best search engines is mostly written in english. Second, indexing of many publication in the social sciences and especially related to policy tends to be incomplete in these sources. The incompleteness due to the first issue can be estimated by counting records from the same sources in other languages. Searching the world's largest languages we have found 336 records in german, 225 in spanish, 113 in French, 185 in portuguese and 10 in chinese (mandarin). Recall that this compares with over 20,000 records in english, so we expect that the incompleteness in our corpus is at least of the order of a few percent. However issues remain of whether collections in other languages are equally well sampled and whether a different set of keywords may be necessary in each language to obtain more comprehensive corpora. Other issues that make the analysis difficult have to do with parsing textual records in a variety of languages and their associated different syntax. It will no doubt be desirable to extend corpora in these ways, but we derive some assurance that our collections of scholarly publications in sustainability science constitute, by these estimates, the vast majority of research in the field.

In this light we expect that although the number of total publications and authors can vary somewhat with different search criteria that the form of the temporal trends discussed above should be robust. They make good sense in relation to the general perception of the events that stimulated the growth of the field [4, 3, 17, 6]. The single most important feature of growth in the field is the steep rise in its growth rate in the late 1980s and early 1990s. This corresponds to the years that followed the publication of the Bruntland commission report [1], a widely acknowledged formative document for the field published in 1987 and around the time of the important publication of Agenda 21 at the Rio Earth summit in 1992 [8]. Our analysis suggests that the main development of this period was an increase in the contact rate between active scientists in the field and a growing population of individuals susceptible and exposed to the new ideas of sustainable development, see Fig. 1. These more intense interactions appear also in a change in the structure of collaboration in the field, Fig. 4A, which only at this time starts becoming denser, in terms of the increase in the average number of collaborative links per each new author entering the field. Interestingly the population dynamics established over this early period (when there only a few hundred authors in the field) is preserved subsequently, even as the field grows by over a factor of thirty.

Another aspect of the sustainability science literature that we expect is not sensitive to how collections are assembled refers to its widespread geographic and institutional distribution as well as its disciplinary composition. It certainly possible that our analysis underestimates somewhat the counts of publications and citations especially for nations where english is not the official language and, as discussed above, in the social sciences and at the interface with policy and society. For example it would be important to understand if the contributions of Brazil, and other latin american countries, India and China are underestimated as these nations are fundamental for societal challenges in sustainable development. In Africa it is curious to note that significant contributions to the literature come from three english speaking nations, South Africa, Kenya and Nigeria, thought these are also large and, in their regional context, scientifically strong countries. Nevertheless it is possible that contributions from other African nations in non-english documents are being excluded from our analysis. It will be important to compile and pursue these sources and their potential contribution in order to have a more complete view of sustainability science's geographic distribution.

Nevertheless, perhaps because it establishes links among different science practices, typical not only of traditional research environments in the natural sciences, we can see that the field has a strong presence in smaller universities and laboratories as well as other policy driven scientific organizations and receives contributions from cities and nations that transcend the list of usual suspects in terms of strength in quantity and quality of scientific production. This large and diverse set of contributions constitute both a challenge in terms of conceptual unification, but also a vast opportunity for developments in the field to acquire interdisciplinary and worldwide impact. It will be interesting to continue to analyze how the field develops geographically and the role of its international and regional links in creating new scientific insights and enabling their societal impact. Tapping literatures in local languages and documents closer to application and policy may be essential to understand these linkages.

The issue of cohesion of the field pervades all these discussions. Cohesion is established and can be measured in principle in a variety of ways such as citations [28, 29] and collaborations as we have shown above. However, if anything these are high bar measures of contact and scientific exchange and exclude weaker links that are often also important for the establishment of common scientific knowledge and practices. Nevertheless, by these measures the field of sustainability science has become unified in terms of most authors belonging to the same large giant cluster of collaboration and citation. These network spans the world geographically and a wide range of disciplines in the social sciences, biology and engineering, all primarily concerned with the integrated management of human, social and biological systems.

We believe that all this evidence taken together establishes the case for the existence of a unified scientific practice of sustainability science and bodes well for its future success at facing some of humanities greatest scientific and societal challenges [6, 31].

4. Appendix: Materials and Methods

4.1. **Corpus of sustainability science publications.** We assembled several corpora of scholarly publications (articles and conference proceedings) on sustainability science through keyword searches using *ISI Web of Science*, the Los Alamos National Laboratory's library databases, and Scopus. The corpus discussed here comes from keyword searches on "sustainability" in title, subject or abstract for all years and databases: Science Citation Index Expanded, Social Sciences Citation Index and Arts & Humanities Citation Index. The data contain 23,211 records (June 2010), with 20,376 until the end of year 2009. Similar searches for "sustainable development" yielded a subset of this corpus, that was correct but substantially more incomplete, with 16,647 records through the end of 2009. The Web of Science records were adopted here as they were found to have more complete records, easy downloadable data, including available addresses for publications from which we extracted (via parsing of text addresses) city and nation of authors' institutions. Years of publication and journals, which we matched to ISI disciplines, were also extracted from each record. A small number of journals in our corpus were not present in the maps of science classification and were excluded from the scientific discipline analysis.

4.2. **Population models and parameter estimates.** The populations models sketched in Fig. 1 are of the explicit form

$$\frac{dS}{dt} = \Lambda N - \beta S \frac{I}{N}, \qquad \frac{dE}{dt} = \beta S \frac{I}{N} - \kappa E \frac{I}{N} - \epsilon E,$$
$$\frac{dI}{dt} = \kappa E \frac{I}{N} + \epsilon E - \gamma I. \tag{1}$$

where S, E, and I are population classes corresponding to susceptible individuals, those already exposed and those who use the idea as authors (infected). It is worth elaborating briefly on the meaning of each of the terms in Eq. 1, c.f Fig. 1B. The first term ΛN is responsible for population growth and adds new individuals that are susceptible to the idea. The second term is responsible for the progression of these individuals to a state of exposure to the idea, thorough interaction (training, teaching, publications) with a community of publishing researchers I. The community of exposed individuals in turn can progress to practitioners via an incubation period (ϵE) or via continued contact ($\kappa E \frac{I}{N}$), which is atypical of population biology but was found important in previous analyses and ethnographic studies of other scientific fields where formal training programs, meetings etc were essential to guarantee that individuals initially exposed could become authors. Active researchers may then leave the field at a rate γ (γI). Terms of this form could be added to other classes to account to possible exit rates in the S, E classes, but these do not change the dynamics qualitatively. Estimates of model parameters from data were obtained using a stochastic ensemble method, see [10, 11] and are given in Supplementary Information.

4.3. **Maps of Authors and Citations.** Author numbers and citations were extracted from *ISI Web of Science* records and assigned to cities and nations. Whenever a publication has several authors it is counted and assigned to each location.

We disregarded the possibility of differential credit assignment by order of authors, as this is a subjective measure that varies from field to field. The maps of Figs 2A, B were created using *google charts* software.

4.4. **Discipline Mapping.** We mapped each publication in our corpus of sustainability science to a traditional discipline and sub-discipline using Thomson-Reuters Journal Citation Reports (JCR) and Web of Science (WoS) commercial products. This scheme is the standard in disciplinary analysis and provides the classification of journals into 554 subdisciplines and 13 major disciplines. This is the same procedure used to generate maps of science, which provide the standard color assignments used in Fig. 3.

4.5. **Collaboration Network and Analysis.** Publications and authors form a bipartite graph. We projected this graph onto the space of authors assigning links between them if they have co-authored at least once. This network was created each year between 1975 and 2010, and analyzed in terms of a variety of metrics, including number of edges, number of nodes, clustering, diameter, the fraction of edges in the largest cluster P, and the cluster susceptibility S. S is defined as $S = \left[\sum_i N_i^2 - [\max_i(N_i)]^2\right] / N^2$, where the sum is over all disconnected clusters, N_i is the size of each cluster (in terms of number of edges) and N is the total size of the system, over all clusters. $\max_i(N_i)$ is the size of the largest cluster. P and S are analogous to percolation cumulants where they suffice to define a second order transition in the infinite system size limit. Network analysis was performed using the python package NetworkX (available online at http://networkx.lanl.gov/)

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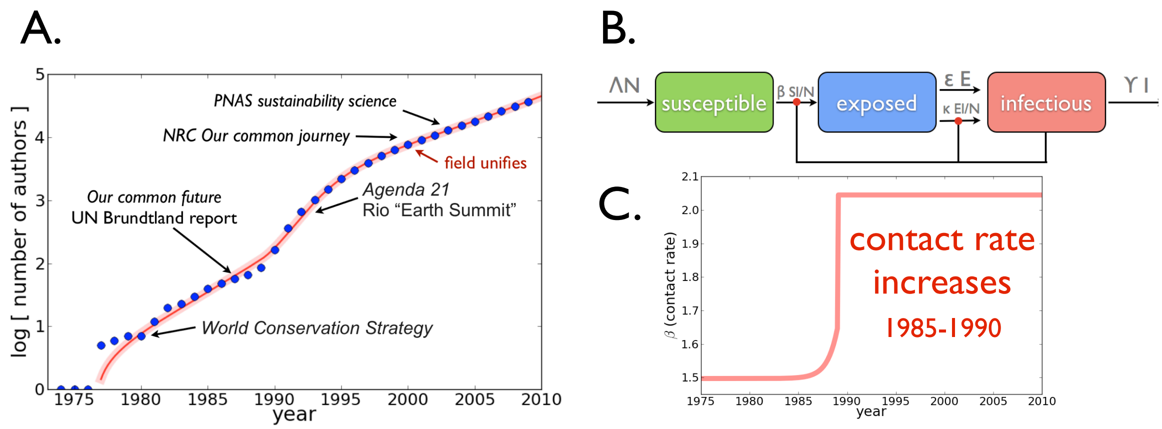

FIGURE 1. The temporal evolution of sustainability science and its population dynamics. A. The number of unique authors vs time and key events in the field (see main text). The field's growth accelerated between the late 1980s and the late 1990s. B. Population model accounting for the recruitment and progression of authors from susceptibility and exposure to the field to publication and exit (see Materials and Methods). C. The acceleration in the field's growth can only be accounted for by an increased contact rate between active individuals and susceptible over the period 1980-1990, where $\beta(t) = \beta + (\beta_0 - \beta)\,[1 - 1.025/\cosh(t - 1991)]$, with $\beta = 2.04$, $\beta_0 = 1.50$. The best account of the growth of the field in terms of its population dynamics is shown in Fig. 1A (solid red line).

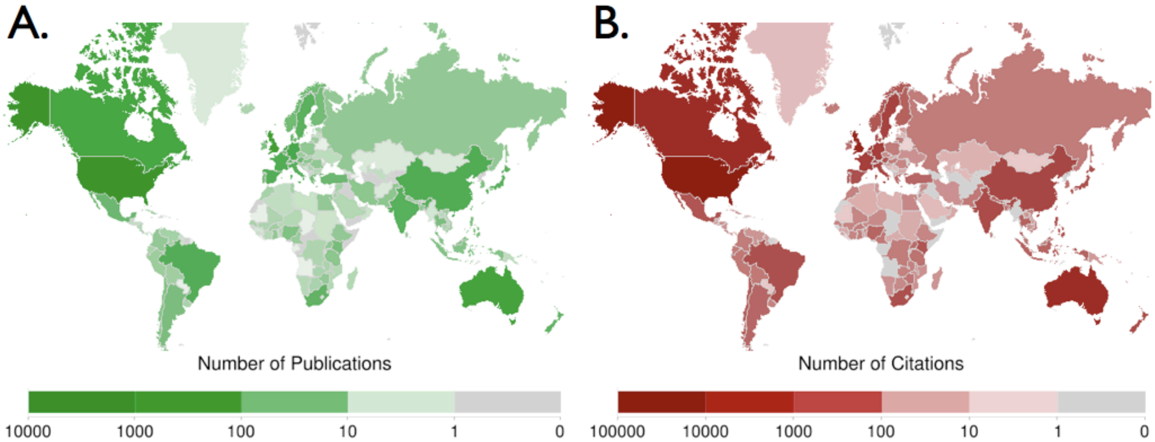

Figure 2. Geographic distribution of Sustainability Science publications. A. National counts of number of publications. B. National counts for number of Citations received. The maps show the wide geographic distribution of the field of sustainability science. This is unusual as compared to typical specialized field in the natural sciences, for example, and notably demonstrates the quality and quantity of contributions from many developing nations. Note the strength of smaller nations such as Australia, the UK, the Netherlands, Sweden, South Africa, Kenya, and of Brazil and China. An interactive world map of cities and their collaboration network is available online and for download at http://www.santafe.edu/∼bettencourt/sustainability/

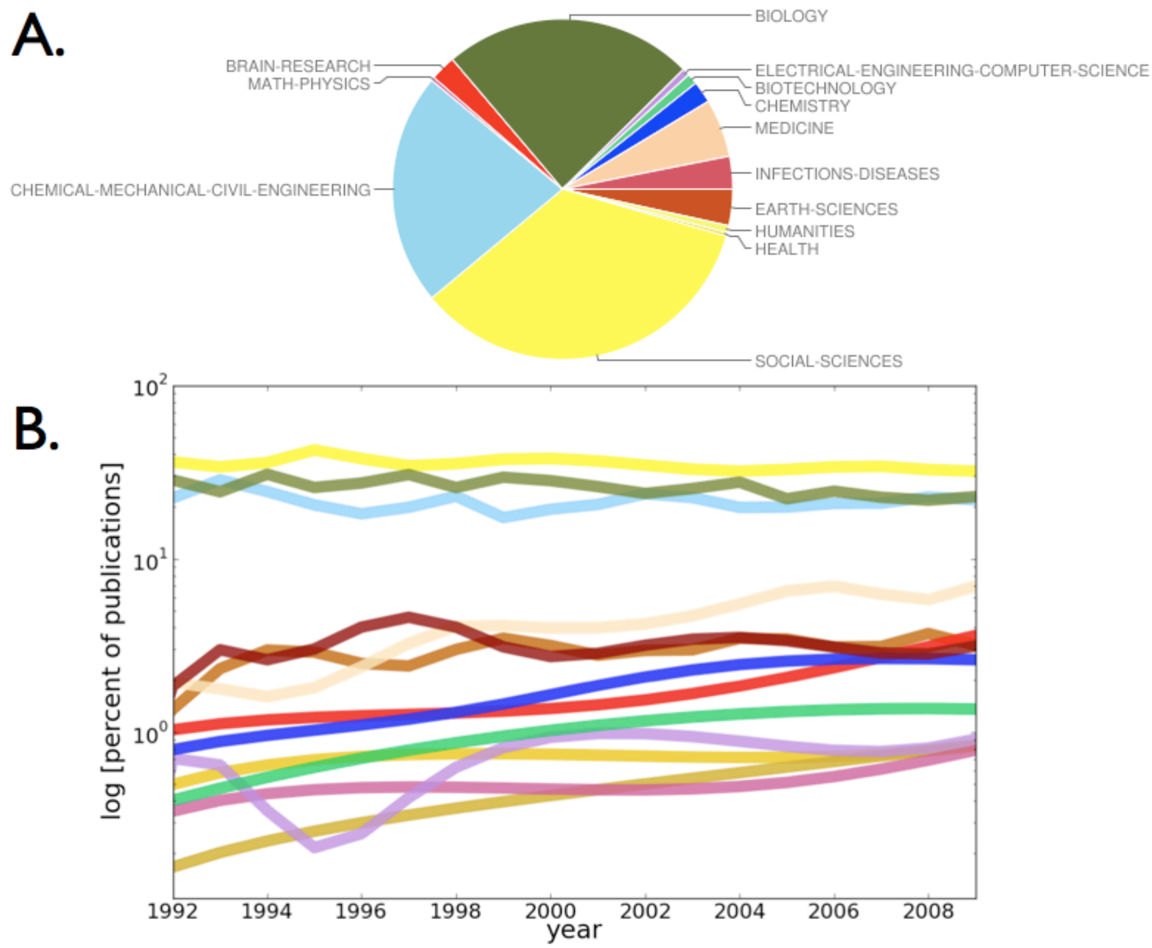

Figure 3. The footprint of sustainability science in terms of traditional scientific disciplines. A. The percent distribution in terms of ISI disciplines determined based on the classification of journals where publications appeared. The field receives its largest contribution (about 34 %) from the social sciences, and other large contributions from Biology and Chemical, Mechanical and Civil Engineering. Other important contributors are from Medicine, Earth Sciences and Infectious Diseases. B. The change in percent contributions of ISI disciplines over time. Even as the field grows exponentially (see Fig 1A) we observe little change in the disciplinary mixture that makes up sustainability science. Nevertheless a small increase in publication in non-core fields (such as Medicine, Earth Sciences, Brain Sciences, Chemistry, and Biotechnology) has developed over the last few years.

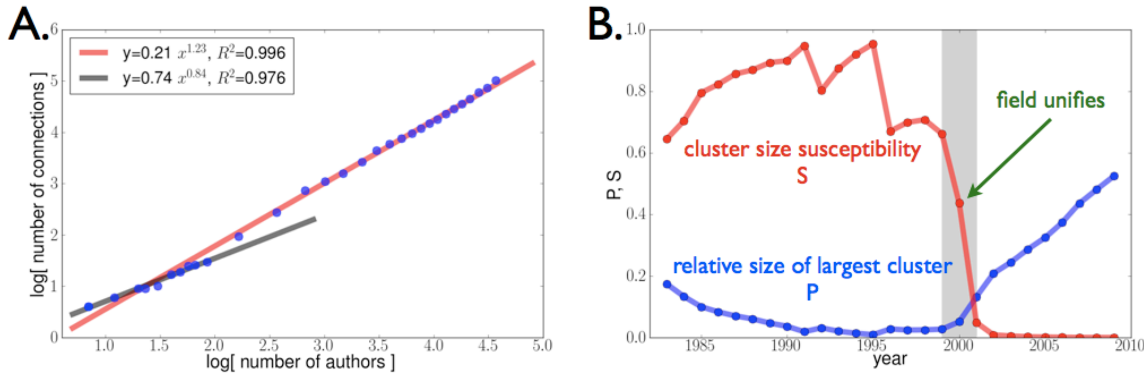

FIGURE 4. The unification of sustainability science as a scientific field. A. The number of collaborations (edges in a co-authorship graph) vs. the number of unique authors. There are two regimes in the development of the field. Early on, before 1989, the number of collaborations per author was decreasing (solid black line, links $l = l_0\ a^{\beta}$, with a the number of authors and $\beta = 0.84 < 1$), due to many publications repeating previous teams or being from a single author. This is typical of fledgeling fields with concepts or techniques that are not yet established. After 1989 the field grows faster (see Fig. 1A) and becomes denser and denser in terms of collaborations ($\beta = 1.23 > 1$). B. As a result of this graph densification most authors eventually belong to a giant collaboration network cluster that defines the field and spans the world in terms of geography (Fig. 2) and groups of traditional disciplines (Fig. 3). This is measured in terms of the fraction of authors in the largest collaboration cluster (P, blue line) and the network cluster susceptibility (S, red line), which is large while there are independent collaboration groups (typical of early fields and technologies) and becomes infinitesimally as most authors become connected. By these measures the field of sustainability science became unified around the year 2000 (grey shaded area).