

Evolution and structure of sustainability science

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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. 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 on 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.

science of science | population dynamics | geography | topological transition | networks

The concept of sustainable development has experienced an extraordinary rise over the past two decades and now pervades the agendas of governments and corporations as well as the mission of educational and research programs worldwide. Although there are some earlier antecedents, these ideas had their formal beginning in the 1980s with several important policy documents, primarily the *World Conservation Strategy* (1) and the now famous Brundtland report *Our Common Future* (2), issuing a call to arms for new policy and, with the publication in 1999 of the National Research Council's *Our Common Journey* report, for the advent of a novel 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 (3–6). 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 socioeconomic impact. Therefore, 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 dis-

ciplines 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, typically 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 1773–1774) 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 was understood 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 (2, 8, 9) on the need for sustainable development, most notably the 1987 United Nations Brundtland report *Our Common Future* (2), provided the first articulated concepts of economic and social development that could occur without irreversible damage to the Earth's natural environment or the depletion of nonrenewable 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 (9, 10).

To characterize sustainability science, we develop here an extensive analysis of the field's 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 quantifying the development of other scientific fields (11, 12), from physics to the medical sciences and from computer science to materials and nanotechnology. This reveals the founding events in the field that triggered the first flurry of publications.

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In particular, we show that a change in the intensity of 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 coauthorship only around the year 2000.

Results

We assembled a large corpus of publications in sustainability science via key word searches, including journal articles and conference proceedings written in English over the period of 1974–2010. Details are given in *Materials and Methods* and *SI Text*. The corpus analyzed below consists of about 37,000 distinct authors of over 20,000 papers, from 174 countries and territories and 2,206 cities worldwide. A first impression of the themes covered by the corpus is given in *Figs. S1–S3*.

Temporal Evolution. Fig. 1*A* shows the temporal evolution of the field in terms of the cumulative number of distinct authors. Two main facts are immediately apparent. First, the field is currently growing exponentially (linearly on the semilog plot), with a doubling period of 8.3 y. Second, 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 on new authors and their collaborative interaction rates. In past publications (11, 12), we have found it useful to infer quantitative characteristics of different scientific fields from data analogous to that of Fig. 1*A* 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. 1*B* and *Materials and Methods*. Perhaps most importantly, these models were motivated by very general considerations for the dynamics of science (13–16), in analogy to population dynamics in ecology and epidemiology, and were developed and tested for fields for which we have detailed ethnographic information (11, 17), such as several subfields of high-energy physics and cosmology, quantum computing, and string theory.

The most critical parameters, shown in Fig. 1*B*, 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 mod-

eled 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 (18).

The other fundamental parameter is the ratio $R_0 = \beta/\gamma$, often known in ecology as the basic reproductive number (19). 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 individuals, over his or her time in the field. $R_0 > 1$ means that the field will grow. The magnitude of R_0 is a measure of the initial growth rate and is 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. 1*C*. 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. 1*A*.

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 coauthorship network evolution below. Note that an increase in the recruitment rate Λ over time is not able to explain the same effect because it is not directly related to the growth in the number 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* (2) were the foundational period over which many individuals first became interested in the issue of sustainable development and when contacts between them and early practitioners in the field intensified to current levels.

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, although research in more specialized fields, particularly in the natural sciences, tends to be concentrated in a few cities in the most developed parts of the world (20), the field of sustainability science has a very different geographic footprint. Fig. 2*A* 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

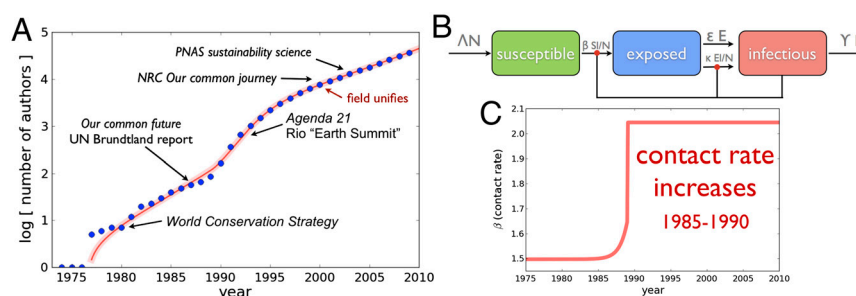


Fig. 1. The temporal evolution of sustainability science and its population dynamics. (A) The number of unique authors vs. time and key events in the field (see main text). By around 2000, many more key publications, such as ref. 3, appear and other key meetings take place (for example, the World Academies Conference Transition to Sustainability in 21st Century in Tokyo in 2000 and the Johannesburg World Summit on Sustainable Development in 2002), not shown. 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 individuals 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. 1*A* (solid red line).

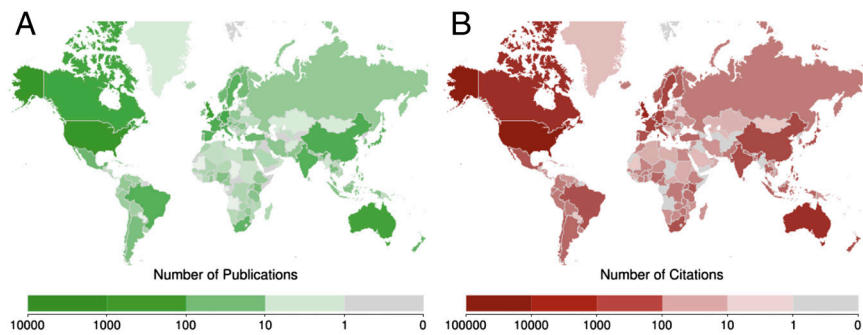


Fig. 2. Geographic distribution of sustainability science publications. (A) National counts of number of publications. (B) National counts for number of citations received. Fig. S4 shows the analogous map for number of citations per paper. The maps show the wide geographic distribution of the field of sustainability science. This is unusual as compared to typical specialized fields 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 United Kingdom, the Netherlands, Sweden, South Africa, Kenya, and of Brazil and China; see Figs. S5–S7. An interactive world map of cities and their collaboration network is available online and for download at <http://www.santafe.edu/~bettencourt/sustainability/>.

their collaboration networks are available in *SI Text* and 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 are the magnitude of contributions from Australia, the Netherlands, the United Kingdom, Brazil, China, and India, and most especially from 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 San Francisco Bay Area, which in other fields (see ref. 20) are several fold greater than that of the US capital. A similar picture is on display in the United Kingdom, where London (with almost 4,000 publications in the field, just a few shy of the tally of Washington, DC) easily outpaces any other British or European city. Other important cities in the field are Stockholm; Wageningen, the Netherlands; Seattle; Madison, WI; and, in their regional contexts, Nairobi; Cape Town, South Africa; Beijing; Melbourne; and Tokyo. The presence of political and economic capitals, rather than traditionally more academic places, is a common trend throughout the world. 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 United States and Western Europe, as are most large Australian cities and Cape Town, South Africa. The reach of cities like Washington, DC; London; Beijing; and, to a slightly lesser extent, Canberra, Australia; and Cape Town, South Africa is truly global, connecting with different scientific centers around the world, and contrasts with the less internationalized (and relatively 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 difficult to show in its full expression, but it is clearly visible through visual inspection of author affiliations. This is especially true in Australia, the Netherlands, the United Kingdom, and the United States, 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 coauthorship links.

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 led to the creation of a set of diverse maps of science (21–25), where different traditional disciplines, organized in terms of speciality journals, are interrelated in terms of their journal level citations, reader's clickstreams, or other relationships. Here, we use a similar procedure to determine the disciplinary makeup of sustainability science and analyze its temporal evolution (see *SI Text* for more details).

Fig. 3A shows the relative composition of the literature of sustainability science in terms of Institute for Scientific Information (ISI)-defined disciplines. Fig. 3B shows the change in their percent composition over time. The most notable feature of Fig. 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

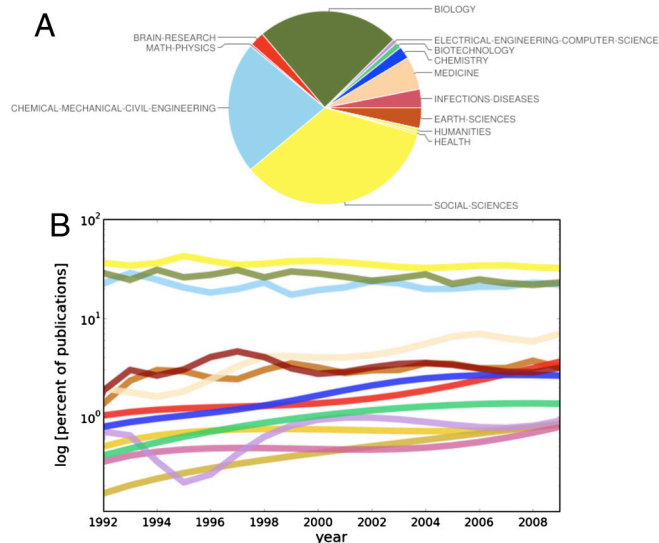


Fig. 3. The footprint of sustainability science in terms of traditional scientific disciplines. (A) The percent distribution in terms of ISI disciplines determined based on the classification of journals where publications appeared. The field receives its largest contribution (about 34%) from the social sciences, and other large contributions from biology and chemical, mechanical and civil engineering. Other important contributors are from medicine, Earth sciences, and infectious diseases. A similar analysis for sustainable development shows the same patterns with only a small 5% increase in the relative contribution of the social sciences vs. biology; see Fig. S8. (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.

terms of total number of publications. The social sciences' 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 subdisciplines 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 that 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's total), solar and 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 disciplines that contribute to sustainability science may suggest nonoverlapping research themes, this is not the case at all. In fact, the main themes that define the field, the concept of integrated management of human, social, and ecological systems and of the engineering and policy studies that support and enable them, are the true crosscutting subjects that unify the field, as we know from refs. 26 and 27, which established that these themes are well connected by mutual citation.

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 (28) 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 such

as cosmological inflation, prion diseases, quantum computing, or string theory, 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 (28).

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 coauthorship links tends to grow faster than the number of authors, usually following a power law scaling relation (with an exponent $b > 1$) (28). Fig. 4A shows how the number of coauthorship 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, 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 at least a couple of decades as a fascinating proposal but that only gained tangible algorithms, experiments, and new theory in 1994–1995; see ref. 28. 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 coauthorship connections per author now increasing with an exponent $b = 1.23 > 1$. As a result of growing link density, the field eventually became dominated by a giant cluster of collaboration to which most authors now belong. This unification in terms of collaboration 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 toward the onset of the formation of a giant cluster, and then fall to almost zero once the field unifies (see *SI Text* 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 shown here, networks of collaboration between cities or nations, or between disciplines, unify earlier as

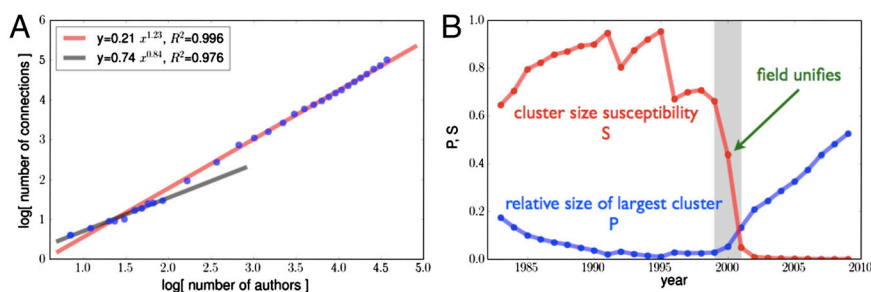


Fig. 4. The unification of sustainability science as a scientific field. (A) The number of collaborations (edges in a coauthorship graph) vs. the number of unique authors. There are two regimes in the development of the field. Early on, before 1989, the number of collaborations per author was decreasing (solid black line, links $l = l_0 a^b$, with a the number of authors and $b = 0.84 < 1$), due to many publications repeating previous teams or being from a single author. This is typical of fledgling 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 ($b = 1.23 > 1$). (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 very small as most authors become connected. By these measures, the field of sustainability science became unified around the year 2000 (gray shaded area).

they are (very) coarse-grained versions of coauthorship networks. As a result, we can say that a field of sustainability science has indeed become cohesive over the last decade, constituting of large-scale collaboration networks to which most authors now belong and producing a new conceptual and technical unification that spans the globe.

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 (18) Kates estimates 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 a 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 because it is somewhat subjective. Over the last few years, several methods have been proposed to do this automatically (see, e.g., refs 29 and 30), but many clear difficulties remain. For these reasons, identifying fields of science still requires a mixture of automated searches and active domain expertise (12, 28). 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 *SI Text*). A similar collection was assembled and analyzed in terms of network structures in refs. 26 and 27, especially their citation networks, 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 (not analyzed here), 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. Records found to be erroneous were extracted from the corpus manually. We also checked visually, by inspection of all titles, that the relative frequency of false positives 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 analysts 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) in the ISI Web of Science database. Recall that this compares with over 20,000 records in English, so we expect that the incompleteness in our corpus is of the order of a few percent. However, issues remain of whether collections in other languages are equally well sampled and if a different set of key words 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 in the future 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, 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 (3, 4, 6, 18). 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 Brundtland report (2), 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 were 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 is 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, because 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, though 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.

Regarding disciplinary composition, we checked that the corpus obtained from a query for "sustainable development" essentially coincides with those obtained in our main corpus. The only tangible change of adopting sustainable development as the field

identifier is a small bias in favor of social sciences and policy (which account for 39.5%, up from 34%) vs. biological sciences (which are reduced from 23% to 19.8%). The relative contribution of chemical, mechanical, and civil engineering is essentially unchanged. (at 23% vs. previously 21.6%). Subdisciplines also have similar relative contributions within these fields showing that the disciplinary makeup of the field is robust to plausible changes in terms of bibliographic queries.

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 (26, 27) and collaborations, as we have shown above, and between different entities from authors to nations and disciplines. If anything, collaboration and citation are high bar measures of contact and scientific exchange at the most disaggregated level possible and exclude weaker links that are often also important for the establishment of common scientific knowledge and practices. As such, we expect that measuring the unification of the field from collaboration links is conservative and any resulting error would not be in whether the field is mostly connected but in delaying such signal somewhat. We also verified that the advent of a giant component of collaboration is not the result of a few authors with large degree connecting the graph, because the top ten most connected authors are highly clustered with each other and account only for a few percent of the edges in the largest component and, moreover, are unambiguously identifiable as single legitimate individuals. It remains difficult to assign disciplinary labels objectively to authors or links, as these identifiers are currently based on the subjects covered by each journal as a whole, and as such it is difficult to see to what extent discipline integration is obtained at the finest level. Improvements in consistent affiliation data may make this type of analysis possible in the near future, but for now we note that the definition of a topological transition requiring more than half of all authors and the citation analysis of refs 26 and 27 supply ample evidence for the large-scale disciplinary integration

of the field. Thus, 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 networks span 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 young and fast-growing 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).

Materials and Methods

The population models sketched in Fig. 1 are of the explicit form

$$\begin{aligned}\frac{dS}{dt} &= \Lambda N - \beta S \frac{I}{N}, \\ \frac{dE}{dt} &= \beta S \frac{I}{N} - \kappa E \frac{I}{N} - \epsilon E, \\ \frac{dI}{dt} &= \kappa E \frac{I}{N} + \epsilon E - \gamma I,\end{aligned}\quad [1]$$

where S , E , and I are population classes corresponding to susceptible individuals, those already exposed, and those who use the idea as authors (infected), respectively.

Descriptions of the corpus of sustainability science publications, population models and parameter estimates, maps of authors and citations, discipline mapping, and collaboration network construction and analysis can be found in *SI Text*.

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1. International Union for Conservation of Nature and Natural Resources, et al. (1980) *World Conservation Strategy: Living Resource Conservation for Sustainable Development* (International Union for the Conservation of Nature and Natural Resources, Gland, Switzerland).
2. World Commission on Environment and Development (1987) *Our Common Future* (Oxford Univ Press, Oxford), pp 8–9.
3. Kates RW, et al. (2001) Sustainable science. *Science* 292:641–642.
4. Clark WC, Dickson NM Sustainability science: The emerging research program. *Proc Natl Acad Sci USA* 100:8059–8061.
5. Parris TM, Kates RW (2003) Characterizing and measuring sustainable development. *Annu Rev Environ Resour* 28:559–586.
6. Levin S, Clark WC, eds. (2009) *Report from Toward a Science of Sustainability Conference* (Harvard Univ Press, Cambridge, MA).
7. Kuhn TS (1970) *The Structure of Scientific Revolutions* (Univ. of Chicago Press, Chicago), 2nd Ed.
8. *Agenda 21 Report of the United Nations Conference on Environment and Development* (United Nations, Rio de Janeiro), Available at <http://www.un.org/esa/dsd/agenda21/>.
9. National Research Council, Policy Division, Board on Sustainable Development (1999) *Our Common Journey: A Transition Toward Sustainability* (National Academy Press, Washington, DC).
10. Kates RW (2011) *From the Unity of Nature to Sustainability Science: Ideas and Practice* (Harvard University, Cambridge, MA), Center for International Development Working Paper No. 218.
11. Bettencourt LMA, Cintron-Arias A, Kaiser DI, Castillo-Chávez C (2006) The power of a good idea: Quantitative modeling of the spread of ideas from epidemiological models. *Physica A* 364:513–536.
12. Bettencourt LMA, Kaiser DI, Kaur J, Castillo-Chávez C, Wojick DE (2008) Population modeling of the emergence and development of scientific fields. *Scientometrics* 75:495–518.
13. Goffman W, Newill VA (1964) Generalization of epidemic theory: An application to the transmission of ideas. *Nature* 204:225–228.
14. Goffman W (1966) Mathematical approach to the spread of scientific ideas: The history of mast cell research. *Nature* 212:449–452.
15. Goffman W, Harmon G (1971) Mathematical approach to the prediction of scientific discovery. *Nature* 229:103–104.
16. Garfield E (1980) The epidemiology of knowledge and the spread of scientific information. *Current Contents* 35:5–10.
17. Kaiser D (2005) *Drawing Theories Apart: The Dispersion of Feynman Diagrams in Post-war Physics* (Univ. of Chicago Press, Chicago).
18. Kates RW (2005) What is sustainable development? Goals, indicators, values and practice. *Environment* 47:8–21.
19. Anderson RM, May RM (1995) *Infectious Diseases of Humans* (Oxford Univ Press, Oxford).
20. The century of the city. *Nature* 467:900–901.
21. Boyack KW, Klavans R, Börner K (2005) Mapping the backbone of science. *Scientometrics* 64:351–374.
22. Börner K, Dall’Ásta L, Ke W, Vespignani A (2005) Studying the emerging global brain: Analyzing and visualizing the impact of co-authorship teams. *Complexity* 10:57–67.
23. Boyack KW, Klavans R (2006) Quantitative evaluation of larhe maps of science. *Scientometrics* 68:475–499.
24. Klavans R, Boyack KW (2007) Is there a convergent structure to science? *Proceedings of the 11th International Conference of the International Society for Scientometrics and Informetrics*, eds D Torres-Salinas and H Moed (Conference of the International Society for Scientometrics and Informetrics, Madrid), pp 437–448.
25. Bollen J, et al. (2009) Clickstream data yields high-resolution maps of science. *PLoS One* 4:e4803.
26. Kajikawa Y, Ohno J, Takeda Y, Matsushima K, Komiyama H (2007) Creating an academic landscape of sustainability science: An analysis of the citation network. *Sustainability Sci* 2:221–231.
27. Kajikawa Y (2008) Research core and framework of sustainability science. *Sustainability Sci* 3:215–239.
28. Bettencourt LMA, Kaiser DI, Kaur J (2009) Scientific discovery and topological transitions in collaboration networks. *J Informetr* 3:210–221.
29. Shiffrin RM, Börner K (2001) Mapping knowledge domains. *Proc Natl Acad Sci USA* 98:5183–5185.
30. Chen C (2004) Searching for intellectual turning points: Progressive knowledge domain visualization. *Proc Natl Acad Sci USA* 101(Suppl):5303–5310.
31. Schellnhuber HJ, Molina M, Stern N, Huber V, Kadner S, eds. (2010) *Global Sustainability: A Nobel Cause* (Cambridge Univ. Press, Cambridge).