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"What Kind of a Science is Sustainability Science?" An Evidence-Based Reexamination

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Abstract: Sustainability science (SS), rooted in multiple disciplines, has been developing rapidly during the last two decades and become a well-recognized new field of study. However, the "identity" of SS remains unclear. Therefore, this study was intended to help synthesize the key characteristics of SS by revisiting the question raised by the leading sustainability scientist, Robert Kates (2011): "What kind of a science is sustainability science?" Specifically, we reviewed the literature in SS, and developed a synthesis of definitions and core research questions of SS, using multiple methods including change-point detection, word cloud visualization, and content and thematic analyses. Our study has produced several main findings: (1) the development of SS exhibited an S-shaped growth pattern, with an exponential growth phase through to 2012, and a asymptotic development phase afterwards; (2) ten key elements from the existing definitions of SS were identified, of which understanding "human–environment interactions" and "use-inspired" were most prominent; and (3) sixteen core questions in SS were derived from the literature. We further proposed an eight-theme framework of SS to help understand how the sixteen questions are related to each other. We argue that SS is coming of age, but more integrative and concerted efforts are still needed to further consolidate its identity by developing a coherent and rigorous scientific core.

Keywords: sustainability science; sustainable development; definition; core questions; thematic framework; sustainability education; landscape sustainability

1. Introduction

A grand challenge of our time is to meet the increasing needs of a growing population while protecting the environment, which is now widely known as the sustainability challenge [1–3]. During the last half century, efforts from various disciplines to help achieve sustainability have evolved into a new field of research: sustainability science (SS) [4]. In particular, during the past two decades, SS has gained remarkable development [5], with associations created (e.g., Association for the Advancement of Sustainability in Higher Education, International Society for Sustainability Science), journals launched (e.g., Sustainability Science, Sustainability), schools and programs established (e.g., School of Sustainability at Arizona State University), and young SS scholars produced [6].

Yet, despite the rapid development of SS, doubts remain on the potential of SS to fulfill its great ambition of fostering sustainability transitions. In classrooms, graduate students often ask how SS differs from and relates to other fields of study [6]; at conferences and in publications, sustainability scholars explore how to better integrate SS with other disciplines which each employ different jargons and assumptions [7]; in industries and governmental agencies, decision makers and resource managers are eager to know how SS can guide sustainability practice and actions. Some even question whether SS is a science or fiction [8]. Before tackling the sustainability challenge of our time, SS must first address a challenge of its own—communicating what kind of a science it is.

When the term "sustainability science" was coined by the National Research Council (NRC) in 1999, it was introduced as "the science of sustainable development" [2]. In a seminal paper, Kates et al. [4] further pointed out that SS focuses on understanding "the fundamental character of interactions between nature and society", with seven distinct but related core questions [4]. Since then, scholars have been trying to communicate various distinctive characteristics of SS. The SS knowledge systems emphasizing boundary management issues were discussed [9]; the metadisciplinary nature of the SS knowledge structure was illustrated [10]; use-inspired basic research characteristics, like agricultural science and health science, was identified [11]; and along this line of effort, the skills and key competencies needed in SS were also elaborated [12–15]. Scholars have also used review methods, especially bibliometric reviews, to map the landscape of SS. For example, Kajikawa et al. [16] identified 15 research domains of SS through citation and text analysis, and subsequently, the domain list was updated twice [17,18]. Similarly, the research cores and topics were also bibliometrically identified [19,20]; the collaborative networks in SS were mapped [20,21]; and the knowledge base and contributing disciplines of SS were unveiled [22]. In addition, the methodological aspect of SS was also reviewed [23–25]. As a new field, SS is now widely recognized within and beyond academia [5], with its unique knowledge and discipline bases, research topics, methods, and approaches. However, the ontological, epistemological, and methodological characteristics of SS still need further clarification.

Robert Kates, the pathfinder in SS [26], offered a concise commentary on the identity of this rapidly developing field [27]. He cited the SS definition from the website of Proceedings of the National Academy of Sciences of the United States of America (PNAS), revised the seven core research questions of SS, and concluded that, "Sustainability science is a different kind of science that is primarily use-inspired, as are agricultural and health sciences, with significant fundamental and applied knowledge components, and commitment to moving such knowledge into societal action." This is a straightforward approach, yet it is a profound description because it captures well the nature, scope, and ultimate goal of SS. Clear definition is a prerequisite of a good science [28], and identifying core research questions or topics facilitates developing the scientific core of an emerging science [29]. Thus, it is worthwhile to reexamine Kates' [26] question—"What kind of a science is sustainability science?"—by systematically analyzing the existing definitions and core questions of SS.

In this paper, we enriched Kates' depiction of SS [27] by addressing three specific questions: (1) How has SS been defined in the literature and what are the key elements that comprise these definitions? (2) What are the proposed core questions and key themes for SS? (3) What are the implications of this literature analysis for advancing SS? We compiled datasets of SS definitions and core questions by systematically searching the existing literature, and subsequently used word cloud analysis, content analysis, and thematic analysis for examining the compiled text datasets. In particular, a thematic framework was proposed for mapping and structuring SS research. The remainder of the paper is organized as follows: Section 2 describes the methods; Section 3 examines the growth of the SS field, and then reports the findings for answering Questions 1 and 2; Section 4 addresses Question 3 based on our results and related literature; and Section 5 concludes with our take-home messages.

2. Materials and Methods

2.1. Literature Sampling and Data Collection

To identify the existing definitions and proposed questions of sustainability science (SS) for this analysis, we followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach [30] to sample the literature (Figure 1). During the first stage, a literature search was conducted on January 10, 2018 using the Web of Science Core Collection database. In total, 832 papers were selected as the 1st database by searching the titles, abstracts, and keywords for the terms "sustainability science", "science of sustainability", and "science for sustainability". We used the three terms because the literature suggests that both "science of sustainability" and "science for sustainability" are parts of SS [23]. Specifically, the 832 items included 16 papers with "science for sustainability", 43 papers with "science of sustainability", and 789 papers with "sustainability science" (with 16 duplicates). Additionally, using the Online Public Access Catalog (OPAC), we searched for journals with "sustainability" in their titles, resulting in 27 journals. Another two sources, *PNAS Sustainability Science* and *Nature Sustainability*, were added, although they were not included in the OPAC database. The number of publications, total cites, and sources of the 832 papers in the 1st database, together with the accumulative number of SS journals (Table S1), were illustrated to show how the SS field has grown. To determine the temporal trends and probable change points of SS, the number of publications, total cites, and sources of the 832 papers in the 1st database, together with the accumulative number of SS journals (Table S1), were statistically examined using the Mann–Kendall test [31] and Pettitt's test [32], respectively.

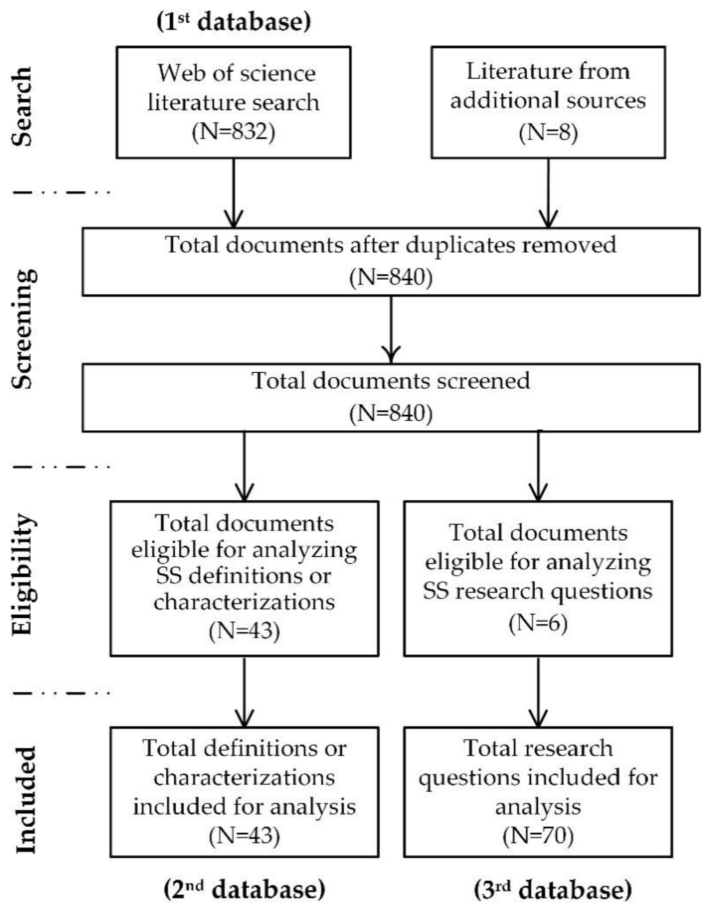

Figure 1. Flow diagram of the selection of publications for databases 1, 2, and 3, based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) rules and templates. SS refers to Sustainability Science.

At the second stage, the full-text of the 832 papers were screened to remove those that did not explicitly define or describe what SS is, resulting in 37 papers. By full-text screening those papers' references, we added another six, relevant "gray literature" publications that were cited by Kajikawa [19], Kates et al. [4], Jerneck et al. [33], Miller [24], Spangenberg [23], and Wu [34]. In total, we identified 43 definitions or characterizations of SS as the 2nd database for further analysis (Table S2), three of which used "science of sustainability" and one of which used "science for sustainability". Additionally, in screening the 832 papers and relevant grey literature, we found four sets of SS core research questions [4,27,35,36]. Two gray sources were from the Sustainability Science Distributed Graduates Seminar (DGS) participants [7] and Clark [37]. Considering that Swart et al. [36] added only one question to the question set of Kates et al. [4], which was already captured in the two other gray literature sources, we excluded Swart et al. [36] from further analysis. To enhance comparability and consistency, the questions compiled from Levin and Clark [35], Sustainability Science DGS [7], and Clark [37] were second-level questions. In total, 70 proposed questions from five sources were compiled into the 3rd database (Table S4) for analysis.

2.2. Procedure and Methods for Analyzing the Definitions and Characterizations of Sustainability Science

To get an intuitive impression of how scholars have defined SS, we used word cloud analysis [38] to visualize the keywords covered in the 43 definitions and characterizations. The keywords were identified as phrases, using two-word, three-word, four-word, and five-word phrase-frequency analysis [39]. The identified phrases were cleaned by removing stop words and grouping word variations. The resulting keywords were further used to inform our content analysis of the definitions for determining the key points made by SS scholars. Content analysis is widely used in social sciences for rigorous interpretation of the content of text data through the systematic process of coding and identifying themes or patterns [40,41]. It has two major approaches: the inductive approach versus the deductive approach [42]. In this study, the inductive approach was adopted with the following steps: (1) a preliminary codebook drafted based on the word cloud was tested by two independent coders, (i.e., the first and third authors); (2) the codebook was refined during the test coding process, and then finalized (Table S3); (3) a second round of coding was conducted again by the two coders in which their discrepancies were solved by discussion with the corresponding authors; and (4) the resulting key points from the coding were grouped into higher-level categories by discussion between all the authors for constructing meaningful interpretation.

2.3. Procedure and Methods for Analyzing the Core Research Questions of Sustainability Science

The compiled questions were analyzed by the authors following the inductive thematic analysis procedure [43,44]. First, the coders read the 70 questions repeatedly and carefully to get familiar with the corpus data. Second, word cloud analysis was used to identify the keywords of the questions, which were then used to facilitate the initial coding of all the questions. Third, discrepancies among the coders in their initial coding were solved by heated discussion and recursive feedback from other authors, which resulted in 16 final synthesized core questions. Fourth, using techniques described by Bernard et al. [45] (e.g., investigating similarities and differences, checking repetitions, sorting questions), the coders together identified potential research themes from the synthesized questions. Fifth, the initially identified themes were decomposed, merged, or kept based on feedback from other authors, resulting in a thematic map of eight finalized themes. Sixth, the results of the thematic analysis were presented to both insiders and outsiders of SS, which helped refine the theme names and finalize the thematic map.

3. Results

3.1. Growth of the Field of Sustainability Science

During the past 20 years, sustainability science (SS) has grown rapidly from an emerging field of research with fewer than five articles per year in the late 1990s to an inclusive and fast developing scientific field with more than 100 articles produced per year since 2015 (Figure 2A). The number of articles explicitly mentioning SS per year increased from 1 in 1997 to 13 in 2002, 50 in 2010, and 121 in 2017. With the substantial growth in size, the influence of SS has also expanded quickly. Annual citations on SS were below 100 prior to 2004, but rose to 533 in 2008, and came close to 2000 by 2012.

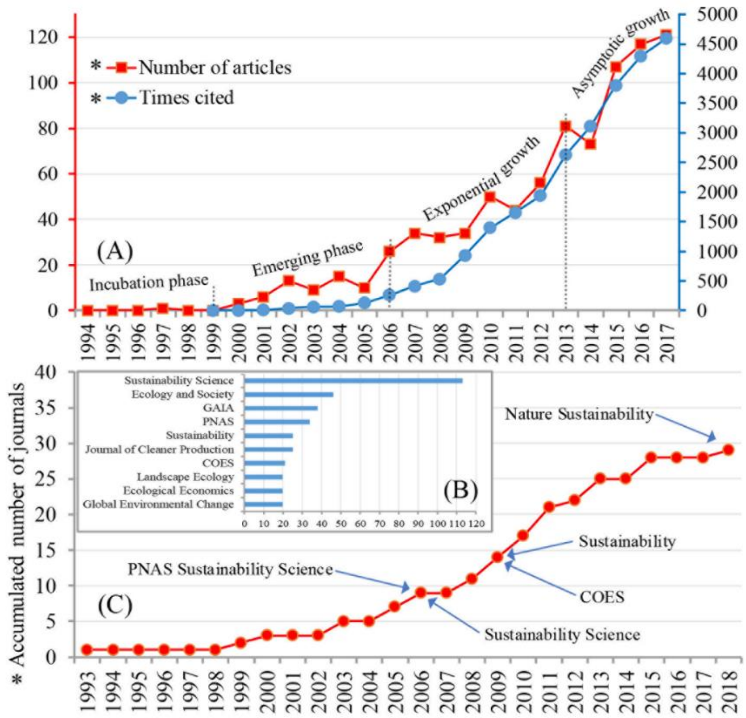

Figure 2. The growth trends and interdisciplinary impacts of sustainability science. (**A**) The number of articles on sustainability science and their citations by year; (**B**) the top ten journals ranked by the total number of publications on sustainability science; and (**C**) the accumulative number of journals including "sustainability" in their titles. Note: asterisks indicate significant growth trends ($p < 0.05$) identified by Mann–Kendall test; the years with dashed line represent change points detected by Pettitt's test ($p < 0.05$); GAIA refers to *Ecological Perspectives for Science and Society*; PNAS refers to *Proceedings of the National Academy of Sciences of the United States of America*; COES refers to *Current Opinion in Environmental Sustainability*.

Sustainability science has become an increasingly interdisciplinary and integrative field which spans natural and social sciences over the past two decades (Figure 2B). The top ten journals that have published the most SS papers to date suggest that the field is dominated by contributions from ecological studies, environmental management, econometrics, and other sub-disciplines related to human, social, and ecological systems. Among the ten journals, *Sustainability Science*, launched in 2006, has published 113 articles, which provides the largest outlet for articles in this field, followed by *Ecology and Society* (46 articles), *Ecological Perspectives for Science and Society (GAIA)* (38 articles), and *Proceedings of the National Academy of Sciences of the United States of America (PNAS)* (34 articles) (Figure 2B). Moreover, the accumulative number of journals with "sustainability" in their titles also increased from 1 in 1993 to 29 in 2018. The first journal—*Journal of Environmental and Sustainability Law*—was launched in 1993, and other journals involving agricultural, urban, textiles, and engineering sustainability and policy were subsequently launched (Figure 2C; Table S1), which shows SS' roots in and influences on multiple disciplines.

Interestingly, all the curves of the numbers of articles, citations, and specialized journals of SS (Figure 2A,C) show an S-shaped growth pattern characterized by an exponential growth phase and an asymptotic (or steady) growth phase. To quantify this pattern, we ran two-stage trend and change-point detection for the three curves, using the Mann–Kendall test and Pettitt's test. During the first stage, the tests were run for each curve over its time span; the results all showed statistically significant ($p < 0.05$) increasing trends, and identified the same change point at 2006 when a temporal shift probably occurred. At the second stage, the tests were run again using data before 2006 and data after 2006, respectively. The results of the former showed statistically significant ($p < 0.05$) increasing trends and another change point at 1998 (suggested in the trends of citations and journals) or 1999 (suggested in the trend of article number). The results of the latter also showed statistically significant ($p < 0.05$) increasing trends and the third change point at 2012. The tests together suggest four specific development phases of SS: (1) the incubation phase prior to 1999, with statistically negligible growth; (2) the emerging phase from 2000 to 2006, with a steady growth; (3) the exponential growth phase from 2007 to 2012, with rapid expansion; and (4) the asymptotic (or steady) growth phase since 2013, with less quantitative growth, yet maybe more qualitative change.

3.2. How Has Sustainability Science Been Defined or Described in the Literature

Several phrases are noticeable in the word cloud of existing definitions and characterizations of SS (Figure 3). The phrase with the highest frequency is "between nature and society", indicating human–environment systems or social-ecological systems perspective. "Life supporting systems", a main object to be sustained in sustainable development (SD), is of the second largest size. The third most mentioned phrase is "solution oriented", which is a distinctive characteristic of SS. In addition, "future generations", "social sciences", "sustainable trajectories", and "decision making" are also frequently mentioned phrases.

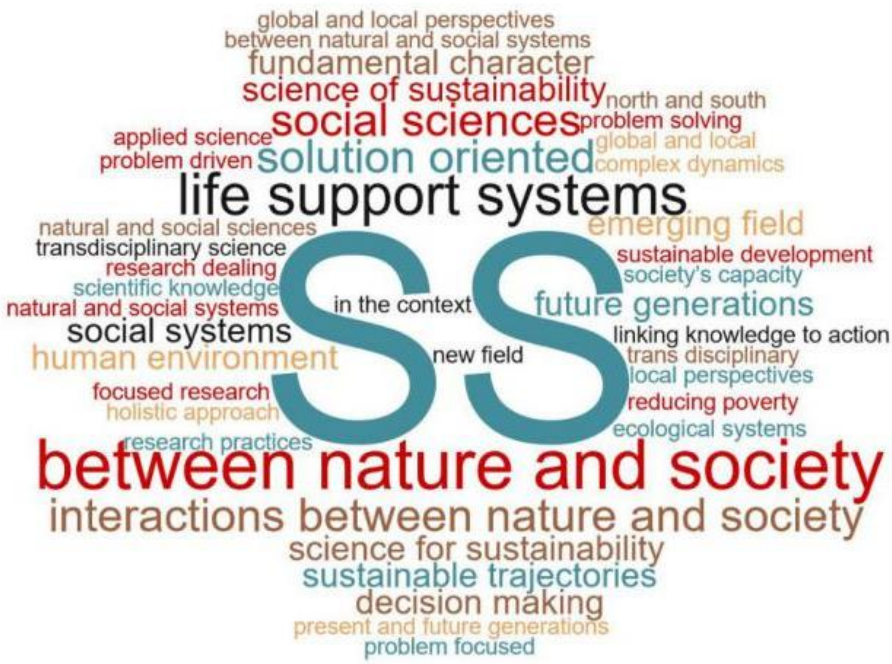

Figure 3. Word cloud of the phrases contained in the 43 identified definitions or characterizations of sustainability science. SS refers to sustainability science; the size of letters is proportionate to each phrase's relative frequency; and color is used for visibility. For a list of the definitions, please refer to the online Supplementary Materials Table S2.

Ten key elements, grouped in three broad categories, were identified from the existing SS definitions and characterizations (Table 1). Regarding SS research objectives, there are four key elements: what is to be sustained, what is to be developed, sustainable for how long, and strong or weak sustainability. These four key elements are also the four questions that define SD. The keywords generating them provided the answers: life support systems should be sustained; human well-being should be developed; future generations should be considered; and the strong sustainability perspective should be emphasized regarding the relationship between what to be sustained and what to be developed. Regarding SS research contents, there are two key elements identified: understanding human–environment interactions and linking knowledge to action. Regarding SS research characteristics, use-inspired, cross-disciplinarity, place-based, and scale-multiplicity are the four key elements describing SS features. Among them, use-inspired, which is indicated by keywords use-inspired, problem-driven, and solution-oriented, is the most highlighted key element. The next high-frequency key element is cross-disciplinarity, which is denoted by the keywords of interdisciplinary and transdisciplinary, followed by place-based and scale-multiplicity.

Table 1. Content analysis of the existing SS definitions and characterizations. For a list of the original definitions and characterizations, please refer to the online Supplementary Materials Table S2. For the codebook used for analyzing the definitions and characterizations, please refer to the online Supplementary Materials Table S3.

Key Points in SS Definitions	Frequency (%)	Key Elements of SS	Categories
1. Life support systems	9	1. What is to be sustained?	Research Objectives
2. Human well-being	14	2. What is to be developed?	
3. Future generations	9	3. Sustainable for how long?	
4. Strong sustainability	14	4. Strong or weak sustainability	
5. Human–environment interactions	49	5. Understanding human–environment interactions	Research contents
6. Emergent properties	3		
7. Linking knowledge to action	30	6. Linking knowledge to action	
8. Interdisciplinary	40	7. Cross-disciplinarity	Research Characteristics
9. Transdisciplinary	42		
10. Use-inspired	9	8. Use-inspired	
11. Problem-driven	47		
12. Solution-oriented	35		
13. Place-based	9	9. Place-based	
14. Scale-multiplicity	21	10. Scale-multiplicity	

To investigate how the ten key elements of SS have been perceived by leading SS scholars, we further compared the definitions or characterizations from the five most cited sources (Table 2). Unsurprisingly, scholars from different disciplines have different emphases when talking about SS. The definitions by Kates et al. [4] and Turner II et al. [46] emphasize understanding the interactions between human and environment, while those by Clark and Dickson [47] and Ostrom et al. [48] pay more attention to linking knowledge to action and the cross-disciplinarity of SS. Despite the difference, these two opinions can both trace back to the three priority tasks for constructing SS proposed by the NRC [2] (Table 2). In addition, place-based and scale-multiplicity were highlighted by the NRC [2] and Kates et al. [4], but were not reflected in the other three. Combining the key elements and their frequencies in all 43 definitions (Table 1), Table 2 suggests that the NRC [2] provided the most widely accepted characterization of SS.

The ten key elements in defining SS (Table 1) also help distinguish science of sustainability (SOS) and science for sustainability (SFS) (Table S2). The earliest SOS definition emerged in 1997: "the study of human agency and well-being in the context of enmeshed economic, social, and biophysical systems" [49]. Later, Levin and Clark delineated SOS as "focuses on the narrower but essential task of SS: characterizing the needs for fundamental work on the core concepts, methods, models, and measurements that, if successful, would support work across all of those sectoral applications" [35]. This definition distinguished SOS as the research core of SS. Spangenberg [23] followed this understanding of SOS, and further, defined SFS as "an attempt to strengthen the dialogue between society and science, and thus a service provided by science to society". In relation to the analyzed SS definitions, SOS and SFS together compose the research contents of SS (Table 1), with SOS focusing on understanding human–environment interactions and SFS focusing on linking knowledge to action.

Table 2. Definitions or characterizations of sustainability science that are provided in the five most cited publications among the 43 identified sources. GS refers to Google Scholar; WoS refers to Web of Science.

Source	Definition or Characterization	Times Cited	
		GS	WoS
NRC 1999 [2]	"Three priority tasks for advancing the research agenda of what might be called 'sustainability science': (1) Develop a research framework for the science of sustainable development that integrates global and local perspectives to shape a place-based understanding of the interactions between environment and society; (2) Initiate focused research programs on a small set of understudied questions that are central to a deeper understanding of those interactions; (3) Promote better utilization of existing tools and processes for linking knowledge to action in pursuit of a sustainability transition."	625	-
Kates et al. 2001 [4]	"A new field of sustainability science is emerging that seeks to understand the fundamental character of interactions between nature and society. Such an understanding must encompass the interaction of global processes with the ecological and social characteristics of particular places and sectors."	2622	957
Turner II et al. 2003 [46]	"The emergence of sustainability science builds toward an understanding of the human–environment condition with the dual objectives of meeting the needs of society while sustaining the life support systems of the planet."	2753	1150
Clark and Dickson 2003 [47]	"Sustainability science is not yet an autonomous field or discipline, but rather a vibrant arena that is bringing together scholarship and practice, global and local perspectives from north and south, and disciplines across the natural and social sciences, engineering, and medicine."	1020	411
Ostrom, Janssen, and Anderies 2007 [48]	"If sustainability science is to grow into a mature applied science, we must use the scientific knowledge acquired in the separate disciplines of anthropology, biology, ecology, economics, environmental sciences, geography, history, law, political science, psychology, and sociology to build diagnostic and analytical capabilities."	749	318

3.3. What Are the Proposed Core Research Questions of Sustainability Science

As shown in the word cloud of the proposed questions (Figure 4), five aspects of SS research are highlighted. The top two most frequent keywords, "SD (sustainable development)" and "human well-being", pertain to objectives of SS research. While "decision making", "decision support" and the like (e.g., "decision choices", "decision makers") emphasize the use-inspired and solution-oriented characteristics of SS. The coupled human–environment system perspective for SS research is relatively prominent. The fourth aspect, characterized by "long term" and the like (e.g., "long term trends", "long term trends and transitions"), refers to the time dimension of SS research. Lastly, the diversity of SS research topics, is illustrated by the "fragmented landscape" of the remaining phrases such as "early warnings", "ecosystem services", "consumption pattern", "governance systems", and "development outcomes".

Figure 4. Word cloud of the phrases contained in the 70 proposed questions of sustainability science. SD refers to sustainable development; the size of phrases is proportionate to each phrase's relative frequency; color is used for visibility. For a list of the 70 original questions, please refer to the online Supplementary Materials Table S4.

Informed by the keywords emerged in the above word cloud, we synthesized the original 70 proposed questions into 16 core questions (Table 3), about which three features are worth noting. First, two were proposed in all five of the original question sets, (i.e., Questions 3 and 16). Question 3 asks how to measure and monitor sustainability dynamics. Question 16 asks how to design the governance systems that can address the collective action dilemma in fostering sustainability transition. The answers to Questions 3 and 16 are urgently needed for achieving the sustainable development goals. Second, another two were proposed in four of the five original question sets, (i.e., Questions 13 and 14). Question 13 addresses the emerging properties of human–environment systems like adaptability, vulnerability, and resilience. Question 14 asks whether system boundaries can be defined for early warnings of an unsustainable future. Questions 13 and 14 both deal with when to intervene for sustainability transition. The four shared core questions represent SS scholars' common concerns: how can we know if we are on an unsustainable trajectory, how can we transition to a sustainable future, and when should we take actions to change. Last but not the least, the remaining twelve questions were not proposed in the majority of the original five question sets. This suggests that the five sets are complementary to each other and that the sixteen core questions together contribute to developing the scientific core of SS.

Table 3. Core questions and research themes of sustainability science according to: A, Kates et al. [4]; B, Levin and Clark [35]; C, Sustainability Science DGS [7]; D, Clark [37]; and E, Kates [27]. For a list of the 70 original questions, please refer to the online Supplementary Materials Table S4.

Core Questions	Sources	Research Themes
1. How to integrate the diversity of views on well-being into a unified, comparable, and legitimate definition of sustainability?	C	① Sustainability
2. How to make sustainability science more easily understood?	C, D	
3. How to create, maintain, and use long-term, place-based observations to measure and monitor progress toward or movement away from sustainability	A, B, C, D, E	② Knowledge systems (data, metrics, models, methods, and theories)
4. How can theory and models be formulated that better characterize complex human–environment systems for contributing to decision-making toward sustainability?	B, D, E	
5. How to better integrate today's relatively independent activities of research planning, monitoring, assessment, and decision support into systems for adaptive management and societal learning?	A, B, D	
6. How to address grand sustainability challenges such as ecosystem restoration, agro-ecological systems management, and transitions in consumption, industry, and technology?	B, C, D	③ Sustainability challenges
7. What are the long-term trends in environment and development, including consumption and population, in various human–environment systems?	A	④ Long-term trends, social-ecological feedback loops, and non-intervention future scenarios
8. How are the driving factors and feedback loops that underlie the long-term trends reshaping human–environment interactions in ways relevant to sustainability?	B, D, E	
9. What are the principal tradeoffs and co-benefits between human well-being and the natural environment?	B, C, E	⑤ Human–environment tradeoffs and synergies
10. How to incorporate equity into human–environment system analysis?	C	
11. How to develop alternative science-based scenarios of the moving target of sustainability?	B	⑥ Human values and sustainability visions
12. How to integrate the diversity of values in envisioning sustainable future scenarios?	D	
13. What determines the adaptability, vulnerability, and resilience of human–environment systems?	A, C, D, E	⑦ Leverage point for interventions
14. Can scientifically meaningful "limits" or "boundaries" be defined that would provide effective warning for human–environment systems?	A, B, C, E	
15. How do belief, value, and emotion affect individual behavior, judgment, and decision-making?	C	⑧ Sustainability transition
16. How to design adaptive governance systems by incentive structures–including markets, institutions, rules, norms, and scientific information–that can address collective action dilemma in achieving sustainability?	A, B, C, D, E	

For easier communication of the 16 core questions, we synthesized them into eight research themes using thematic analysis. The themes and their relations are depicted in Figure 5. The first three themes seem to focus on the foundational research that can be interpreted as SOS: theme 1 (i.e., sustainability) operationalizes sustainability; theme 2 (i.e., knowledge systems) builds the basis of SS by providing data, metrics, models, methods, and theories; and theme 3 (i.e., sustainability challenges) identifies the most urgent sustainability problems for SS to tackle. Themes 4–8 tend to emphasize more problem-solving and place-based research that can be interpreted as SFS: theme 4 (i.e., long-term trends, social-ecological feedback loops, and non-intervention future scenarios) analyzes the current problem constellation; theme 5 (i.e., human–environment tradeoffs and synergies) and theme 6 (i.e., human values and sustainability visions) create future scenarios and sustainability visions; and theme 7 (i.e., emergent properties and intervention point) and theme 8 (i.e., sustainability transition) intervene with adaptive transition strategies toward sustainability visions. Corresponding to the four shared core questions (i.e., questions 3, 13, 14, and 16), themes 2, 7, and 8 are the priorities of SS research.

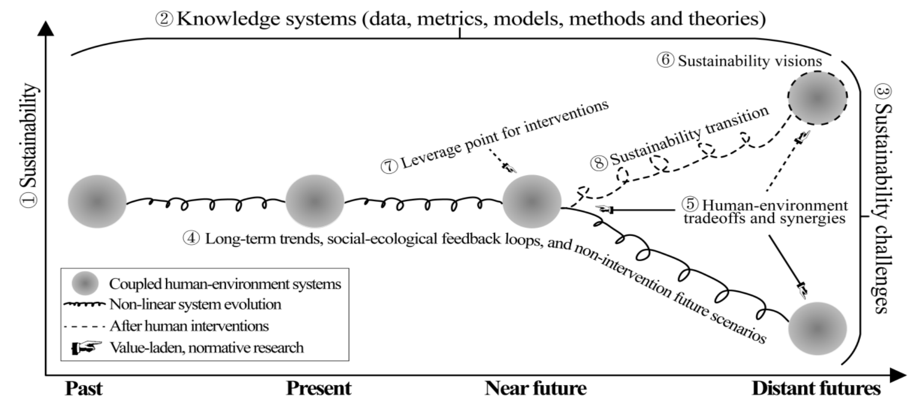

Figure 5. The eight-theme framework of sustainability science. The numbering of the research themes is the same as in Table 3. See text for more explanation.

4. Discussion

4.1. What is Sustainability Science, Really

Our analysis of SS definitions supports that (1) SS is use-inspired basic science [11,27]; (2) SS focuses on understanding human–environment interactions, as well as linking knowledge to action [4,27]; and (3) SS adopts inter- and transdisciplinary approaches [16,20,50]. These three features are the most emphasized by SS scholars (Table 1) that give SS a unique academic niche. First, being use-inspired basic science, SS differs from other traditional sciences that are mostly use-inspired (e.g., landscape architecture) or mainly basic research (e.g., bio-ecology), and this characteristic of SS also reflects the current scientific paradigm shift from the mode-1 science to mode-2 science, or from normal science to post-normal science [8]. Second, the two research contents of understanding human–environment interactions and linking knowledge to action distinguish SS from other use-inspired basic sciences, such as agricultural science and health science. Last but not least, inter- and trans- disciplinarity are distinctive methodological characteristics of SS determined by its special research contents: it should not only bring together natural sciences and social sciences to understand human–environment interactions, but also bring together scientists and practitioners to link that understanding to solve real word problems. Analogous to health science, SS can be understood as offering "health services" (i.e., sustainability) to human–environment systems that are facing or might face "health problems" (i.e., sustainability challenges).

Also, a multi-scale and place-based research approach has become increasingly prominent in SS research, as indicated in Table 1. In this regard, the analogy of SS to health science also applies. Treating an "unhealthy" human–environment system needs first a prudent diagnosis of the focal system's unsustainability “syndrome” and its “pathology”, which often requires not only multi-scale [34,51] but also multi-dimensional [52,53] and multi-method [54,55] approaches. It is also unsurprising that SS is expected to be place-based, because the prescriptions to treating any unsustainability “syndrome” must all be based tightly on the focal system’s specific social-ecological setting [2,4]. To our surprise, however, only a small group of SS scholars have explicitly addressed the four basic research questions of SS: (1) what is to be sustained; (2) What is to be developed; (3) sustainable for how long; and (4) strong or weak sustainability. While “sustainability of what” has been debated in the literature [56,57], clarifying these four basic questions is important for specifying the two broad research contents of SS: understanding human–environment interactions and linking that knowledge to action.

Our analysis of the SS core research questions helps better understand the identity of SS in two ways. First, the congruence of the five versions of proposed SS core questions suggests that SS is expected to provide three key services for making human–environment systems sustainable: (1) informatics services—assessing and monitoring the “health status” of a focal system, which is actually a subfield in its infancy, yet with great potential in this era of big data [58]; (2) diagnostic services—identifying and understanding the emergent properties and system boundaries for diagnosing unsustainability syndromes, on which substantial work has already been done [59,60]; and (3) therapeutic services—prescribing transition solutions to transform an unsustainable system to a sustainable one, which also receives much research interest [61,62]. Second, the incongruence of the five sets of proposed core questions implies that there are other “sustainability services” SS should provide, some of which are captured in Kates’ [27] latest update, while others are not. More attention should be placed on those value-laden services, for example, (1) construct a sustainability index that reflects not only “physical health” but also “mental health”; (2) help societies develop science-based and value-laden sustainability visions; and (3) incorporate human values into achieving sustainability transitions. The essential role of human values in SS is deeply rooted in the ultimate goal of sustainability—to improve and sustain human well-being [34]. Acknowledging the critical role of human values opens another door to achieve sustainability, for instance, via changing people’s unsustainable consumption preferences or living styles through education and social learning.

So, what is SS, really? Sustainability science is a use-inspired, basic science of sustainable development, which focuses on understanding human–environment interactions and linking the understanding to actions by promoting a place-based, multi-scale, and transdisciplinary approach. In short, SS is the science that trains “doctors” of human–environment systems who provide informatics services, diagnostic services, therapeutic services, and other “sustainability services”. There are dermatologists, psychiatrists, physicians, surgeons, pediatricians, and many other types of doctors in health science; likewise there are SS scholars specializing in water sustainability, food sustainability, energy sustainability, corporate sustainability, landscape sustainability, and the sustainability of other subsystems or dimensions of human–environment systems. However, like that dermatologists alone cannot make a patient healthy and that skin disease can be a symptom of more complex health problems, studies on one or more sectoral sustainability challenges should also consider the deeper social-ecological roots and provide social-ecological solutions.

4.2. Implications for Advancing Sustainability Science

Where is SS now in terms of its development stage, and where is it going? Our analysis suggests that SS has been in a steady development phase since 2013 (Figure 1), suggesting a transition from a quantitative proliferation of publications to a qualitative consolidation and coalescence of ideas. This may indicate that SS is maturing. But it may also be a sign of the emerging science losing its momentum or perishing. Our analysis indicates that ten key elements regarding the ontology, epistemology, and methodology of SS are identifiable (Table 1). Eight research themes seem to make up the scientific core of SS (Table 3). Thus, our study suggests that SS is coming of age, yet in a critical transition from quantitative growth to qualitative development.

More integrative and concerted efforts from SS communities will help the transition. The previous two developmental bursts of SS (Section 3.1) were likely driven by the group efforts of pioneering SS scholars. The detection that the field of SS started to emerge around 2000 is in line with the insider story by Kates [27]. The NRC proposed SS during 1999 in its report that resulted from a 5-year effort of a working group [2], followed by the Friibergh Workshop on SS in late 2000, and finally, the publication of the seminal paper on SS in 2001 [4]. Bettencourt and Kaur [5] also found that studies on sustainability unified around 2000. Around 2006, the field of SS also saw noticeable institutional efforts. For example, *PNAS Sustainability Science* and the Springer journal, *Sustainability Science*, were launched subsequently; the experimental Sustainability Science Fellowship Program was initiated at Harvard University, and concurrently, Arizona State University's School of Sustainability was established.

Although discussing where SS should go next is outside the scope of this paper, our study has some implications for sustainability education. Haider et al. [6] reported that the younger generation of SS scholars face the challenges of "developing a strong and specific methodological skill-set while at the same time gaining the ability to understand and communicate between different epistemologies", and thus, called for enhancing epistemological agility and methodological groundedness as capable sustainability scientists. Given the broad scope of SS, future SS scholars may specialize in one or more areas, such as water sustainability, food sustainability, landscape sustainability, and so on, while also understanding the big picture of how human–environment systems function and how specialized research fits into system-level sustainability. Towards this end, several versions of the big picture of SS may help, including the integrated sustainability research and problem-solving framework that highlights the competencies of SS scholars [13], the three-dimensional matrix that structures the knowledge of SS [33], and the "undisciplinary" framework that guides development of the competencies of early-career SS scholars [6].

5. Conclusions

Based on a comprehensive literature analysis, we conclude that understanding human–environment interactions, use-inspired, inter- and trans- disciplinarity, and linking knowledge to action are the most emphasized features that give SS a unique academic niche. The 16 synthesized core questions further specify the two broad research contents of SS, of which the questions how to gauge (un)sustainability, how to transition to a sustainable future, and when to take actions to change are the top concerns of scholars. The perspectives on SS and its core questions are pluralistic and largely complementary to each other. Only by taking diverse perspectives together can we depict the ontological, epistemological, and methodological characteristics of SS comprehensively.

The field of SS is entering a critical stage, transitioning from quantitative growth to qualitative development, indicating the beginning of its maturing process. Given the plurality of disciplinary roots, research goals, and methodologies, more cross-disciplinary collaborations from the different SS communities are urgently needed for advancing a more cohesive and rigorous SS. Concerted efforts in sustainability education are needed to make SS itself "sustainable". We suggest that the younger generation of SS scholars may specialize in one or a few areas, but must understand the big picture of how human–environment systems function and how their specialized research fits into the system-level sustainability. The ten key elements and eight-theme framework of SS presented in this paper can help build the big picture of SS. Following Einstein's dictum that "a problem cannot be solved by the same mindset that helped create it", SS is poised to play an increasingly important role in solving real-world sustainability challenges.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/10/5/1478/s1. Table S1: A list of academic journals that include "sustainability" in their titles or subtitles (data obtained using the Online Public Access Catalog). Table S2: A list of 43 definitions and characterizations of sustainability science, GS refers to Google Scholar, WoS refers to Web of Science. Table S3: Codebook for coding the definitions and characterizations of sustainability science. Table S4: A list of 70 proposed questions of sustainability science compiled from Kates et al. 2001, Levin and Clark 2010, Sustainability Science DGS 2010, Clark 2010, and Kates 2011.

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