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**From Basic Research to Applied Solutions: Are Two Approaches to Sustainability Science Emerging?**

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**Abstract:**

Despite its widespread emergence and adoption, sustainability science continues to suffer from definitional ambiguity within the academe. A review of efforts to provide direction and structure to the science reveal a continuum of approaches anchored at either end by differing visions of how the science interfaces with practice (solutions). At one end, basic science of societally defined problems informs decisions about possible solutions and their application. At the other end, applied research directly affects the options available to decision makers. While clear from the literature, we also point to survey data that suggests the dichotomy does not appear to be as apparent in the minds of practitioners.

**Introduction**

Despite the widespread emergence of sustainability science, complete with associated journals [1-4] and programs of study [5-8], sustainability per se remains surrounded by conceptual ambiguity, even within the research academy at large [9]. In recent years, several efforts to characterize sustainability research using bibliographic analysis have been undertaken [10-17]. These studies reveal that the core concerns of sustainability science are rooted in consideration of the function of the Earth system and ecosystems that enable resource provisioning and other environmental services [12,17,18], and, in the socioeconomic development and well-being of humankind [17,19], including questions of equity [20] and justice [21].

Within this context, various formal and informal assessments and frameworks have emerged worldwide that seek to provide structure and direction to the theory and application of sustainability science. These efforts, we propose, have formed a continuum of characteristics anchored at either end by differing visions of how this science interfaces with practice (solutions), consistent with typology of science (Fig. 1). At one end, proposed implicitly and explicitly in various publications [1,3,4,22], basic science of societally defined problems informs decisions about possible solutions and applications, akin to the Pasteur quadrant of science in Stokes 1997 formulation[[3]](#footnote-3) [23]. The other end of the spectrum coincides with Edison’s quadrant engaged in applied research seeking solutions, often technological in kind, that directly affect the options available for decision makers [24]. This approach has no formal literature proclamation but, we suggest, has emerged in the practice of certain research communities (e.g. [2,24-30]).

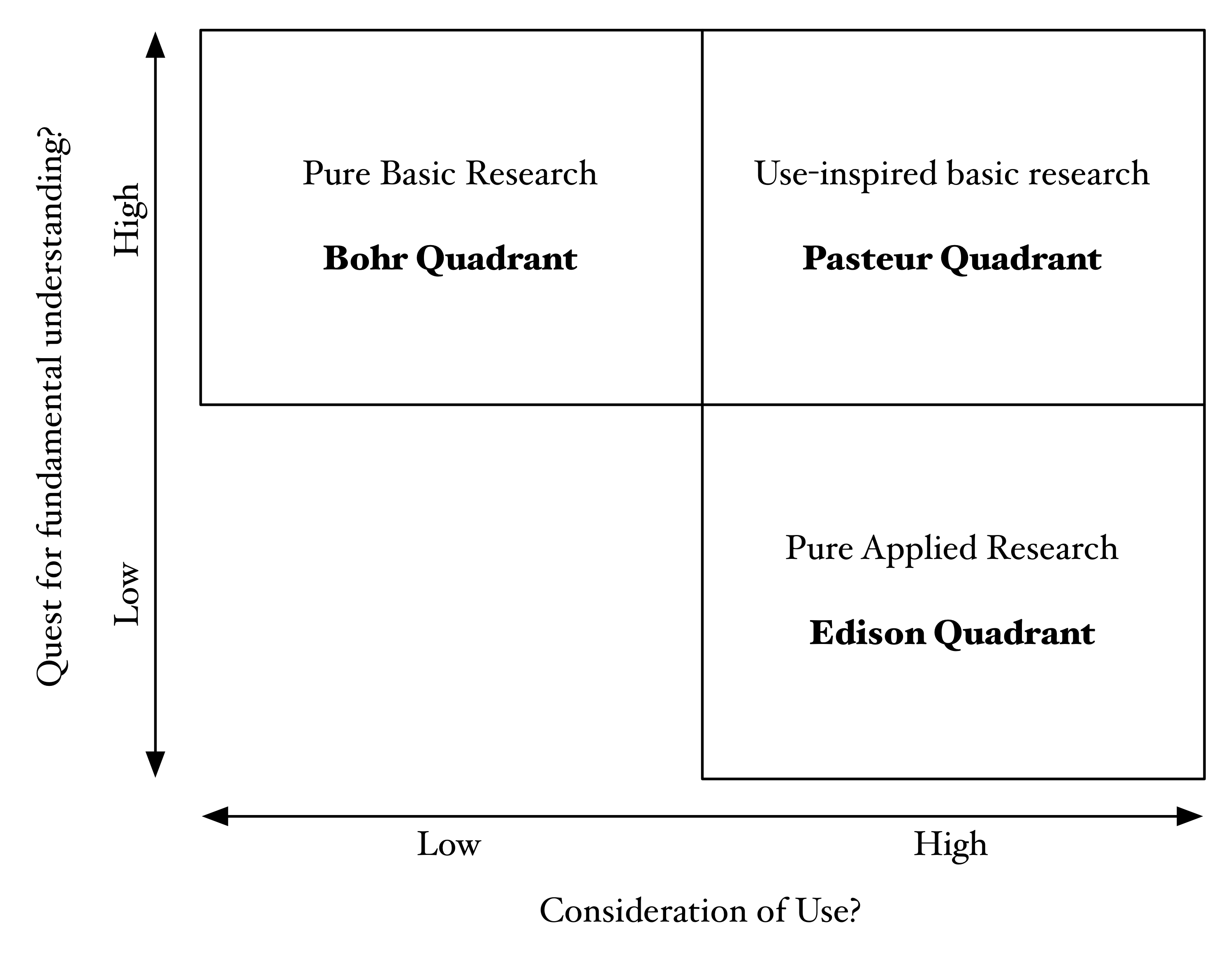


Figure 1. Stokes Quadrant for classification of research inspiration (modified from Stokes, 1997)

Is this view of the range of engagement in sustainability/sustainability science, foremost the Pasteur-Edison anchors, accurate? Does it help to capture the state-of-the-art of this emerging field or fields of study and research? We explore these questions through two initial, if incomplete, data sources—a subjective assessment of publications and use of a small-sample practitioner survey.

**Assessment of Publications**

We drew 200 publications from more than 60 journals and books from across a wide range of disciplines contributing to “the science of sustainability” identified by Bettencourt and Kaur [10: Fig. 3]. This sample is by no means exhaustive, but captures several broad themes and some of the more highly cited works within the primary sustainability outlets and related journals [14].

**<Table 1 here>**

This literature reveals to us a set of shared research questions consistent with the sustainability challenge of meeting the needs of humanity while preserving the life support systems of Earth [31]. This framing, in turn, leads to a shared phenomenon of study, social-environmental systems (SES; a.k.a. coupled human-environment systems, coupled human-natural systems, social-ecological systems), although individual research efforts tend to examine only a subset of the components or processes in these systems by way of analyses that vary in their scale dynamics. Conceptually, this literature tends to address such common themes as tradeoffs between subsystems or among components within one subsystem (e.g., [32]); complexity, non-linearity and uncertainty (e.g., [33]); resilience and vulnerability (e.g., [34,35]); equity and intergenerational wealth in which natural capital is included [36,37]; and, adaptive management (e.g., [38]).

A substantial cohort of the reviewed research focused on basic research of societally defined sustainability problems (Pasteur’s quadrant), somewhat akin to the agricultural sciences [20]. These problems are treated as the outcome of interacting processes operating between and within the two subsystems at multiple scalar dimensions (spatio-temporal and hierarchical). Employing mixed methods [39,40] within scientific modes of understanding, the goal is to understand these interactions, or parts of them, sufficiently to project the states of SESs and their consequences into the future [41], thus providing science-based insights for decision-making (e.g., [40,42,43]). It is recognized, however, that complexity of SESs are such that few, if any, sustainability panaceas exist [44,45], reflecting the inherent interdependencies in human-environmental relationships in the Anthropocene [46]. We recognize at least two subgroups among this cohort. The first is an outgrowth of interest in global environmental change but refocused on sustainable development [20,47-49]; the second includes the longstanding efforts addressing environment-development, resource management, and related topics such as the equity in human wellbeing (e.g. [50-53]).

A second substantial cohort emerged from practitioners trained and working largely in the applied sciences, including engineering and business management, and focused on the implementation of technical and managerial solutions to particular sets of sustainability challenges [2]. Many of these efforts are tied to long-standing efforts originating in industry to assess the impact of products and services across multiple dimensions, like the life cycle assessment methodology, which has become a sub-discipline onto itself [54,55], or the application oriented parts of industrial ecology [27]. Research approaches in this cohort tend to separate the techno-economic and social dimensions of SESs consistent with the sustainability triangle concept (i.e., nature, society, and economy: [56-62]), and attempts to identify a solution that balances the three legs of the triangle. Analyses might treat each leg separately before joining them [58] or employ integrated, context specific models [59]. Regardless, the objective is not to project the state of the SES into the future per se, although the work recognizes that, for example, consequential LCA [63,64] is at times an approach to project consequences of actions into the future. Rather, the focus of triparte methods is to design solutions based on integrative understanding. While the appropriate application of techno-managerial solutions to augment sustainability is debated in many applied fields [60,28,29], we find the methods are used to address an array of challenges, including nexus interactions between energy, water, food and health [65-67], the availability and security of the supply chains as well as production-consumption systems [2,30,68,69], and the built environment [70,71].

**Practitioner Survey**

In addition, we employed an online survey instrument and invited researchers worldwide to provide insights on our views taken from the literature (Table 1). The survey was active from October 3-17, 2014. Individual candidates for survey participation were identified: [1] from the corresponding author information provided in the published literature reviewed (N = 82); [2] via affiliation with a selection of academic or research programs advertising connections to sustainability science (N = 1,392), including 16 in the U.S. and 11 external to the U.S.; and [3] from national and international government agencies and other organizations noted for sustainability activities (N = 32). The survey instrument included 23 questions and was open for 14 days. Of the total population contacted (N = 1,506), 537 (36%) opened the survey and 97 (7%) responded, ten of which were incomplete, resulting in 87 responses used in this analysis. The survey data were addressed by way of Chi-square tests for correlation with a tolerance threshold of 95 percent; and, using analysis of variation (ANOVA) tests to assess variance in mean values between multiple groups, again assuming a 95 percent confidence threshold [72-74]. Owing to selection methods and sample size, the results must be considered exploratory in kind.

**<Table 2 here>**

The survey results (Table 2) point to certain distinctions in our Pasteur-Edison spectrum as valid, others more equivocal, specifically, the following two findings.

(1) The distinctive Pasteur and Edison quadrant categories described by Stokes [23] and the audiences each addressed, as we identified in the literature, are apparent but much more blurred than we anticipated. This suggests that practitioners array their research and the field in multiple gradations of the dichotomy we supposed.

Specifically, asked to identify their research directly with Stokes classification scheme (Question #1), the distinctions between the Pasteur and Edison clusters revealed a strong relationship between disciplinary affiliation and research approach (χ2 = 39.31, df = 15, p < 0.05), but with an unexpected twist. In contrast to their solution interests (above), applied researchers identified their approach rather evenly: as Edison’s quadrant (34%), Pasteur’s quadrant (28%), and a mix of Edison’s with Pasteur’s (31%). Natural science and social science researchers in contrast were biased toward reporting their research as a mix of Edison’s and Pasteur’s (50% and 40% respectively), while another cluster identified with Pasteur’s approach (25% and 16% respectively). Combined, these two approaches constituted 63% of the responses for natural and social scientists. While statistically differentiated, these results suggest a bit more blurring of the two approaches, at least in regard to how those registering “implementing alternative solutions” and “complex human-environment interactions” interpreted their aims within Stokes classification scheme.

When asked to identify sustainability science at large within Stokes classification scheme (Question #2), the disciplinary communities remain strong (χ2 = 21.99, df = 12, p < 0.05), but appear to coalesce towards an Edison-Pasteur mix identification. A majority of 55% of those answering survey Question #2 (N = 82) identified sustainability science at large as either “use inspired basic research” (Pasteur’s quadrant) (17%) or a “mix” of this with application research (Edison’s quadrant) (38%). Of applied researchers, 74% identified the field as either residing in Pasteur’s quadrant or an Edison-Pasteur mix (35% and 39% respectively). Natural scientists, in contrast, strongly characterize the field as an Edison-Pasteur mix (60%), while social scientists were more divided: Pasteur’s quadrant (32%), Edison-Pasteur mix (21%). Again, this last result may reflect the number of social scientists that did not classify themselves as sustainability scientists (below).

(2) Despite the Pasteur-Edison orientation of the researchers surveyed, an overwhelming response to Question 3 (N = 76) indicates that the primary research audience for all respondents was “other scientists” (55%). Applied science researchers, however and as expected, were more likely to collaborate with industry partners “very often” (43%) compared to the natural and social science researchers reporting to “never” collaborate with industry partners (43%) (Question #4; χ2 = 15.76, df = 8, p < 0.05).

**Summary – Findings and Needed Research**

Our exploration into the questions posed about sustainability science reveals that distinctions we observed in the literature about the field may be far less apparent in the minds of practitioners and that the Stokes dichotomy is a useful heuristic but may belie the variance that exists. These observations, however, should be viewed cautiously. Our survey results imply, perhaps strongly so, the existence of an emerging dichotomy of approaches within the maturing field of sustainability science, however they may reflect the biases in our survey sample. In particular, our respondents were overwhelmingly English speaking, based in the United States (80%), holding or having held tenured positions within universities and research institutions (61%), and were not evenly distributed across the many fields of study from which sustainability researchers are drawn. While our findings are consistent with previous undertakings of this kind [10,13,15], a more inclusive survey by world region, base language, and profession is required to determine the validity of our base claims and survey results. Such inclusiveness should increase the sample size of sustainability researchers housed or trained within the humanities (N = 3 in our survey) in our review, and might further aim to distinguish results between researchers identifying as sustainability scientists versus those affiliated with sustainability programs but not identifying as sustainability scientists. Finally, while we understand from this study that there is a bias in knowledge production oriented inward toward the scientific community and that Edison practitioners exhibit a propensity to collaborate with industry partners, we did not fully explore the dimensions of involvement stakeholders take in knowledge production and translation to practice [75,76]. Therefore, additional attention should also be given to the distinctions between the knowledge emanating from those researchers identified as Pasteur and Edison practitioners and the role that knowledge plays in pathways of decision-making.

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**References**

\* of special interest

\*\* of outstanding interest

1. Kates RW, Clark WC, Corell R, Hall JM, Jaeger CC, Lowe I, McCarthy JJ, Schellnhuber HJ, Bolin B, Dickson NM, et al.: **Sustainability Science**. *Science* 2001, **292**:641-642.

2. Komiyama H, Takeuchi K: **Sustainability science: building a new discipline**. *Sustainability Science* 2006, **1**:1-6.

3. Lubchenco J: **Entering the Century of the Environment: A New Social Contract for Science**. *Science* 1998, **279**:491-497.

4. Clark WC: **Sustainability Science: A room of its own**. *Proceedings of the National Academy of Sciences* 2007, **104**:1737-1738.

5. Sherren K: **Balancing the disciplines: A multidisciplinary perspective on sustainability curriculum content**. *Australian Journal of Environmental Education* 2005, **21**:97-106.

6. Figueiro PS, Raufflet E: **Sustainability in higher education: a systematic review with focus on management education**. *Journal of Cleaner Production* 2015, **106**:22-33.

7. Dentoni D, Bitzer V: **The role(s) of universities in dealing with global wicked problems through multi-stakeholder initiatives**. *Journal of Cleaner Production* 2015, **106**:68-78.

8. Hume T, Barry J: **Environmental Education and Education for Sustainable Development**. In *International Encyclopedia of the Social & Behavioral Sciences*, edn 2. Edited by; 2015. vol 7.]

9. White MA: **Sustainability: I know it when I see it**. *Ecological Economics* 2013, **86**:213-217.

\*\*10. Bettencourt LMA, Kaur J: **Evolution and structure of sustainability science**. *Proceedings of the National Academy of Sciences* 2011, **108**:19540-19545.

**The explosive growth of sustainability science is documented through an extensive cross-discipinary and international assessment of the literature.**

\*11. Kajikawa Y, Saito O, Takeuchi K: **Academic landscape of 10 years of sustainability science**. *Sustainability Science* 2017, **12**:869-873.

**The evolving topical landscape of sustainability science research is documented using an annualized citation network analysis of published literature from both the Science Citation Index and the Social Sciences Citation Index. The researchers find that in 2016, “Environmental and Social Systems” is the largest citation cluster, with secondary clusters belonging to “Economy and Business Systems,” “Energy Systems,” “Fishery and Forestry Systems,” “Health,” “Industry,” and “Urban and Transport Systems.”**

12. Kajikawa Y: **Research core and framework of sustainability science**. *Sustainability Science* 2008, **3**:215-239.

13. Kajikawa Y, Ohno J, Takeda Y, Matsushima K, Komiyama H: **Creating an academic landscape of sustainability science: an analysis of the citation network**. *Sustainability Science* 2007, **2**:221-231.13. Buter RK, Van Raan AFJ: **Identification and analysis of the highly cited knowledge base of sustainability science**. *Sustainability Science* 2013, **8**:253-267.

14. Buter RK, Van Raan AFJ: **Identification and analysis of the highly cited knowledge base of sustainability science**. *Sustainability Science* 2013, **8**:253-267.

15. Kajikawa Y, Tacoa F, Yamaguchi K: **Sustainability Science: the changing landscape of sustainability research**. *Sustainability Science* 2014, **9**:431-438.

16. Aisati Mh, Chi Y, Fowler N, von Hindenburg H, Ruth D, Terheggen P, Perkins N, Bos C, Pan L, Agnew K, et al.: **Sustainability Science in a Global Landscape**. In *Research Initiatives*. Edited by Bos C. http://www.elsevier.com: Elsevier & SciDev.Net; 2015:92.

\*17. Bolis I, Morioka SN, Sznelwar LI: **When sustainable development risks losing its meaning. Delimiting the concept with a comprehensive literature review and a conceptual model**. *Journal of Cleaner Production* 2014, **83**:7-20.

**The authors provide a comprehensive review of sustainable development based on a bibliographic literature review and hermeneutic analysis. This analysis and discussion is unique compared to other bibliographically based reviews of the fields. The authors also propose a conceputal model for sustainable development with consideration for natural resources, satisfaction of human needs and decision making.**

18. Miller TR: **Constructing sustainability science: emerging perspectives and research trajectories**. *Sustainability Science* 2013, **8**:279-293.

\*\*19. Heinrichs H, Martins P, Michelsen G, Wiek A (Ed): *Sustainability Science: An Introduction* Dordrecht, Heidelberg, New York, London: Springer; 2016.

**This volume presents a cross-section of the multiple dimensions of sustianability with twenty eight chapters ranging from ethics to art to climate change and consumption. Through this approach, the editors seek to provide the building blocks of a comprehensive perspective on sustainability science written by experts in the fields. The volume is geared as an introduction to the field for students specifically.**

20. Clark WC, Dickson NM: **Sustainability Science: The Emerging Research Program**. *Proceedings of the National Academy of Sciences* 2003, **100**:8059-8061.

21. Boone CG, Fragkias M (Ed): *Urbanization and Sustainability: Linking Urban Ecology, Environmental Justice and Global Environmental Change* Dordecht, Heidelberg, New York, London: Springer; 2013.

\*\*22. Matson P, Clark WC, Andersson K: *Pursuing Sustainability: A Guide to the Science and Practice*: Princeton University Press; 2016.

**A framework for understanding and linking knowledge to action for sustainable development is proposed. The authors use four case studies thoughout to illustrate key concepts including the link between sustainability goals and underlying determinants of dynamic social-environmental systems. Additional chapters address governance and links between knowledge and action. The book is geared toward practioners and students at all levels.**

23. Stokes DE: *Pasteur's Quadrant: Basic Science and Technological Innovation*: Brookings Institution Press; 1997.

24. Dodds R, Venables R: **Engineering for Sustainable Development: Guiding Principles**. Edited by Dodds R, Venables R: The Royal Academy of Engineering; 2005.

25. Graedel TE, Allenby BR: *Industrial ecology*. Englewood Cliffs, N.J.: Prentice Hall; 1995.

26. Anastas PT, Zimmerman JB: **Peer Reviewed: Design Through the 12 Principles of Green Engineering**. *Environ. Sci. Technol.* 2003, **37**:94A-101A.

27. Weisz H, Suh S, Graedel TE: **Industrial Ecology: The role of manufactured capital in sustainability**. *Proceedings of the National Academy of Sciences* 2015, **112**:6260-6264.

28. Matlin S A, Mehta G, Hopf H, Krief A: **The role of chemistry in inventing a sustainable future**. *Nature Chemistry* 2015, **7**:941-943.

\*29. Matlin S A, Mehta G, Hopf H, Krief A: **One-world chemistry and systems thinking**. *Nature Chemistry* 2016, **8**:393-398.

**Argues for the role of chemistry as a central “sustainability science” that leverages the foundational nature of chemistry knowledge and couples that with systems thinking and integration with other disciplines to address such challenges as the persistent presence of chloroflourocarbons in the atmosphere and plastic waste in the oceans.**

30. Vergragt P, Akenji L, Dewick P: **Sustainable production, consumption, and livelihoods: global and regional research perspectives**. *Journal of Cleaner Production* 2014, **63**:1-12.

31. WCED: **Report of the World Commission on Environment and Development: Our Common Future - A/42/427 Annex - UN Documents: Gathering a body of global agreements**. Edited by Brundtland GH: United Nations World Commission on Environment and Development; 1987.

32. Bateman IJ, Harwood AR, Mace GM, Watson RT, Abson DJ, Andrews B, Binner A, Crowe A, Day BH, Dugdale S, et al.: **Bringing Ecosystem Services into Economic Decision-Making: Land Use in the United Kingdom**. *Science* 2013, **341**:45-50.

33. Lenton TM, Held H, Kriegler E, Hall JW, Lucht W, Rahmstorf S, Schellnhuber HJ: **Tipping elements in the Earth's climate system**. *Proceedings of the National Academy of Sciences* 2008, **105**:1786-1793.

34. Turner II BL: **Vulnerability and resilience: Coalescing or paralleling approaches for sustainability science?** *Global Environmental Change* 2010, **20**:570-576.

\*\*35. Becker P: *Sustainability Science: Managing risk and resilience for sustainable development* edn 1. Oxford, UK: Elsevier; 2014.

**In this three part volume, the author provides historical context and emergence of sustinable development and risk; offers a conceptual framework combining risk and resilience for understanding today's sustainability challenges including drought, disesases, land degredation and social conflict; and, discusses the role of a changing science in developing knowledge and solving problems. This book is geared toward practioners and graduate level students in the discipline.**

36. Dasgupta P: **Nature in Economics**. *Environmental and Resource Economics* 2008, **39**:1-7.

37. Duraiappah AK, Muñoz P: **Inclusive wealth: a tool for the United Nations**. *Environment and Development Economics* 2012, **17**:362-367.

38. Tompkins EL, Adger WN: **Does Adaptive Management of Natural Resources Enhance Resilience to Climate Change?** *Ecology and Society* 2004, **9**:10.

39. Rindfuss RR, Walsh SJ, Turner BL, Fox J, Mishra V: **Developing a science of land change: Challenges and methodological issues**. *Proceedings of the National Academy of Sciences of the United States of America* 2004, **101**:13976-13981.

40. Turner II BL, Janetos AC, Verburg PH, Murray AT: **Land system architecture: Using land systems to adapt and mitigate global environmental change**. *Global Environmental Change* 2013, **23**:395-397.

41. Kishita Y, Hara K, Uwasu M, Umeda Y: **Research needs and challenges faced in supporting scenario design in sustainability science: a literature review**. *Sustainability Science* 2016, **11**:331-347.

42. Schellnhuber HJ: **'Earth system' analysis and the second Copernican revolution**. *Nature* 1999, **402**:C19-C23.

43. Hoffmann M, Lubell M, Hillis V: **Linking knowledge and action through mental models of sustainable agriculture**. *Proceedings of the National Academy of Sciences* 2014, **111**:13016-13021.

44. Ostrom E: **A diagnostic approach for going beyond panaceas**. *Proceedings of the National Academy of Sciences* 2007, **104**:15181-15187.

45. Ostrom E, Janssen MA, Anderies JM: **Going beyond panaceas**. *Proceedings of the National Academy of Sciences* 2007, **104**:15176-15178.

46. Crutzen PJ: **Anthropocene man**. *Nature* 2010, **467**.

47. Turner BL, Kasperson RE, Matson PA, McCarthy JJ, Corell RW, Christensen L, Eckley N, Kasperson JX, Luers A, Martello ML, et al.: **A framework for vulnerability analysis in sustainability science**. *Proceedings of the National Academy of Sciences* 2003, **100**:8074-8079.

48. Cash DW, Clark WC, Alcock F, Dickson NM, Eckley N, Guston DH, Jäger J, Mitchell RB: **Knowledge systems for sustainable development**. *Proceedings of the National Academy of Sciences* 2003, **100**:8086-8091.

\*49. Leemans R: **The lessons learned from shifting from global-change research programmes to transdisciplinary sustainability science**. *Current Opinion in Environmental Sustainability* 2016, **19**:103-110.

**Personal insight and perspective from the front lines of the transition from the international research program ESSP to Future Earth is provided. The author’s experience highlights the challenge of reaching consensus among multi-stakeholder groups as was the case with the development of the Future Earth conceptual framework for research, and the challenge of implimenting effective transdisciplineary research structures and governance.**

50. Ostrom E: **A General Framework for Analyzing Sustainability of Social-Ecological Systems**. *Science* 2009, **325**:419-422.

51. Anderies JM, Rodriguez AA, Janssen MA, Cifdaloz O: **Panaceas, uncertainty, and the robust control framework in sustainability science**. *Proceedings of the National Academy of Sciences* 2007, **104**:15194-15199.

52. Graedel TE, Klee RJ: **Getting Serious about Sustainability**. *Environmental Science & Technology* 2002, **36**:523-529.

53. Adrianto L, Matsuda Y, Sakuma Y: **Assessing local sustainability of fisheries system: a multi-criteria participatory approach with the case of Yoron Island, Kagoshima prefecture, Japan**. *Marine Policy* 2005, **29**:9-23.

54. Curran M: **Life Cycle Assessment: a review of the methodology and its application to sustainability**. *Current Opinion in Chemical Engineering* 2013, **2**:273-277.

\*55. Onat N C, Kucukvar M, Halog A, Cloutier S: **Systems Thinking for Life Cycle Sustainability Assessment: A Review of Recent Developments, Applications, and Future Perspectives**. *Sustainability* 2017 **9**:706.

**This review provides an overview of recent research to extend traditional LCA techniques to include sustainability dimensions with additional indicators to capture social, environmental and economic system dimensions and in the context of expanded system scope.**

56. Hecht AD, Fiksel J, Folton SC, Yosie TF, Hawkins NC, Leueberger H, Golden JS, Lovejoy TE: **Creating the future we want**. *Sustainability: Science, Practice and Policy* 2012, **8**.

57. Kloepffer W: **Life cycle sustainability assessment of products**. *The International Journal of Life Cycle Assessment* 2008, **13**:89-95.

58. Elkington J: *Cannibals with forks : the triple bottom line of 21st century business*. Gabriola Island, BC ; Stony Creek, CT: New Society Publishers; 1998.

59. Fiksel J: **A systems view of sustainability: The triple value model**. *Environmental Development* 2012, **2**:138-141.

60. Iles A, Mulvihill MJ: **Collaboration Across Disciplines for Sustainability: Green Chemistry as an Emerging Multistakeholder Community**. *Environ. Sci. Technol.* 2012, **46**:5643-5649.57. von Hauff M, Wilderer PA: **Industrial ecology: engineered representation of sustainability**. *Sustainability Science* 2008, **3**:103-115.

61. von Hauff M, Wilderer PA: **Industrial ecology: engineered representation of sustainability**. *Sustainability Science* 2008, **3**:103-115.

62. Mihelcic JR, Crittenden JC, Small MJ, Shonnard DR, Hokanson DR, Zhang Q, Chen H, Sorby SA, James VU, Sutherland JW, et al.: **Sustainability Science and Engineering:  The Emergence of a New Metadiscipline**. *Environmental Science & Technology* 2003, **37**:5314-5324.

63. Marsiglia A, Benetto E, Rege S, Jury C: **Modeling approaches for consequential life-cycle assessment (C-LCA) of bioenergy: Critical review and proposed framework for biogas production**. *Renewable and Sustainable Energy Reviews* 2013, **25**:768-781.

64. Zamagni A, Guinee J, Heijungs R, Masoni P, Raggi A: **Lights and shadows in consequential LCA**. *The International Journal of Life Cycle Assessment* 2012, **17**:904-918.

65. Marshall JD, Toffel MW: **Framing the Elusive Concept of Sustainability:  A Sustainability Hierarchy**. *Environ. Sci. Technol.* 2004, **39**:673-682.

66. Bazilian M, Rogner H, Howells M, Hermann S, Arent D, Gielen D, Steduto P, Mueller A, Komor P, Tol RSJ, et al.: **Considering the energy, water and food nexus: Towards an integrated modelling approach**. *Energy Policy* 2011, **39**:7896-7906.

67. Elliott SJ: **The transdisciplinary knowledge journey: a suggested framework for research at the water-health nexus**. *Current Opinion in Environmental Sustainability* 2011, **3**:527-530.

68. Lebel L, Lorek S: **Enabling Sustainable Production-Consumption Systems**. *Annual Review of Environment and Resources* 2008, **33**:241-275.

69. Jaeger-Erben M, Ruckert-John J, Schafer M: **Sustainable consumption through social innovation: a typology of innovations for sustainable consumption practices**. *Journal of Cleaner Production* 2015, **108**:784-798.

70. Golden JS, Brazel A, Salmond J, Laws D: **Energy and Water Sustainability: The Role of Urban Climate Change from Metropolitan Infrastructure**. *Journal of Green Building* 2006, **1**:124-138.

71. Seto KC, Golden JS, Alberti M, Turner, BLII: **Sustainability in an urbanizing planet.** *Proceedings of the National Academy of Sciences* 2017, **114**:8935-8938

72. Pallant J: *SPSS survival manual : a step by step guide to data analysis using IBM SPSS* edn 5. Maidenhead, Berkshire, England: McGraw Hill; 2013.

73. Field AP: *Discovering statistics using IBM SPSS statistics : and sex and drugs and rock 'n' roll* edn 4. Los Angeles: Sage; 2013.

74. Wilcox RR: **Understanding the Practical Advantages of Modern ANOVA Methods**. *Journal of Clinical Child & Adolescent Psychology* 2002, **31**:399-412.

75. Ravetz J: **Post-normal science and the complexity of transitions toward sustainability**. *Ecological Complexity* 2006, **3**:275-284.

76. Mielke J, Vermaben H, Ellenbeck S, Milan B F: **Stakeholder invovlement in sustainability science—A critical view**. *Energy Research & Social Science* 2016, **17**:71-81.

Table 1. Journals included in literature review

|  |  |
| --- | --- |
| Ambio | Harvard Business Review |
| Annual Review of Ecology, Evolution & Systematics | International Journal of Life Cycle Assessment |
| Annual Review of Environment and Resources | Integrative Zoology |
| Annual Review of Ecology and Systematics | International Journal of Animal Science |
| Annual Reviews in Control | Journal of Agricultural and Environmental Ethics |
| Asian Development Review | Journal of Cleaner Production |
| Biodiversity and Conservation | Journal of Experimental Botany |
| Biological Reviews | Journal of Industrial Ecology |
| Bioscience | Management Science |
| BioSystems | Mathematics and Computers in Simulations |
| Business Strategy and the Environment | Nature |
|  | Nature Physics |
| Chemical Engineering Science | Nonlinearity |
| Ecological Complexity | PANS |
| Ecological Economics | Philosophical Transactions of The Royal Society B |
| Ecological Modeling | PNAS |
| Ecology and Society | Policy and Society |
| Ecosystems | Policy Sciences |
| Energy Policy | Research on the Scientific Basis for Sustainability (RSBS) Secretariat |
| Environmental Resource Economics | Science |
| Environment | Sustainable Development |
| Environment and Planning B: Planning and Design | Sustainability Science |
| Environmental Development | Sustainability |
| Environmental Engineering Science | Sustainability: Science, Practice, & Policy |
| Environmental Impact Assessment Review | Sustainable Development Law & Policy |
| Environmental Management | System Dynamics Review |
| Environmental Modelling & Software | Systems Practice |
| Environmental Science & Technology | The Academy of Management Journal |
| Fluid Phase Equilibria | UNEP |
| FORUM: Science and Innovation for Sustainable Development | Urban Ecosystems |
| Geomorphology | Whole Earth |

Table 2. Sustainability Science Survey Results Summary

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Question 1. Classify your research (Stokes):** | | | | | | |
|  | **Discipline** | | | | **All Respondents** | |
| **Answer Categories** | **Applied Science** | **Natural Science** | **Social Science** | **Humanities** | **Response Count** | **Response Percent** |
| Bohr's Quadrant | 0 | 0 | 0 | 0 | 0 | 0% |
| Edison's Quadrant | 11 | 0 | 4 | 0 | 15 | 17.2% |
| Pasteur's Quadrant | 9 | 5 | 5 | 2 | 21 | 24.1% |
| Mix of Edison's and Bohr's | 0 | 2 | 0 | 0 | 2 | 2.3% |
| Mix of Edison's and Pasteur's | 10 | 10 | 13 | 0 | 33 | 37.9% |
| Mix of Pasteur's and Bohr's | 0 | 3 | 5 | 0 | 8 | 9.2% |
| None of the Above | 2 | 0 | 5 | 1 | 8 | 9.2% |
| *Answered Question* | ***32*** | ***20*** | ***32*** | ***3*** | ***87*** | ***100%*** |
| *Skipped Question* | 0 | 0 | 0 | 0 | 0 | 0% |
| **Question 2. Classify Sustainability Science in general (Stokes):** | | | | | | |
|  | **Discipline** | | | | **All Respondents** | |
| **Answer Categories** | **Applied Science** | **Natural Science** | **Social Science** | **Humanities** | **Response Count** | **Response Percent** |
| Pasteur's Quadrant | 11 | 4 | 9 | 0 | 14 | 17% |
| Mix of Edison's and Pasteur's | 12 | 12 | 6 | 1 | 31 | 37.8% |
| None of the Above | 1 | 0 | 4 | 2 | 7 | 8.5% |
| Mix of all three | 1 | 1 | 4 | 0 | 6 | 7.3% |
| Other | 6 | 3 | 5 | 0 | 14 | 17.1% |
| *Answered Question* | ***31*** | ***20*** | ***28*** | ***3*** | ***82*** | ***94%*** |
| *Skipped Question* | 1 | 0 | 4 | 0 | 5 | 6% |
| **Question 3. Primary research audience?** | | | | | | |
|  | **Discipline** | | | | **All Respondents** | |
| **Answer Categories** | **Applied Science** | **Natural Science** | **Social Science** | **Humanities** | **Response Count** | **Response Percent** |
| Policy Makers | 4 | 5 | 6 | 0 | 15 | 19.7% |
| Industry or commercial enterprises | 9 | 0 | 3 | 0 | 12 | 15.8% |
| Other Scientists | 12 | 14 | 14 | 2 | 42 | 55% |
| Combination | 2 | 1 | 2 | 0 | **5** | 7% |
| Other | 1 | 0 | 1 | 0 | 2 | 2.6% |
| *Answered Question* | ***28*** | ***20*** | ***26*** | ***2*** | ***76*** | ***87%*** |
| *Skipped Question* | 4 | 0 | 6 | 1 | **11** | 13% |
| **Question 4. I collaborate with Industry…** | | | | | | |
|  | **Discipline** | | | | **All Respondents** | |
| **Answer Categories** | **Applied Science** | **Natural Science** | **Social Science** | **Humanities** | **Response Count** | **Response Percent** |
| Very Often | 12 | 1 | 5 | 0 | 18 | 23.4% |
| Somewhat Often | 4 | 1 | 3 | 0 | 8 | 10.4% |
| Regularly | 2 | 1 | 1 | 0 | 4 | 5.2% |
| Somewhat Regularly | 6 | 6 | 8 | 1 | 21 | 27.3% |
| Never | 4 | 10 | 10 | 2 | 26 | 33.8% |
| *Answered Question* | ***28*** | ***19*** | ***27*** | ***3*** | ***77*** | ***89%*** |
| *Skipped Question* | 4 | 1 | 5 | 0 | 10 | 11% |

1. Present address: VT EPSCoR BREE and Gund Institute for Environment, University of Vermont, 23 Mansfield Ave, Burlington, VT 05401 [↑](#footnote-ref-1)
2. Present address: Vice Chancellor and Department of Engineering, 2200 S Charles Blvd Ste 1500, Mail Stop 157, East Carolina University, Greenville, NC 27858-4353 [↑](#footnote-ref-2)
3. At the end of World War II, Vannevar Bush, the Director of Scientific Research and Development during the war, proposed a peace time role for science that was anchored by “basic research” on the one hand and “applied research” on the other. Basic research was defined as research performed “without thought of practical ends.” Applied research, in contrast, was then intended to convert discoveries from basic science into technological innovations to meet “the full range of society’s economic, defense, health, and other needs” (Stokes, 1997). In his 1997 critique, Donald Stokes extended the dichotomy into a two-dimensional spatial grid oriented along two axis, the first: consideration of use, the second: quest for fundamental understanding. Stokes placed Bush’s basic research in the low use/high understanding quadrant and labeled it Bohr’s Quadrant in honor of Niels Bohr, the Nobel Prize winning physicist. He further placed Bush’s applied research in the high use/low understanding quadrant and labeled it Edison’s Quadrant honoring Thomas Edison, the prolific American inventor. Finally, Stokes proposed a third role for science, naming the high use/high understanding quadrant Pasteur’s quadrant, in honor of Louis Pasteur, a French biologist, microbiologist and chemist whose work was revolutionary for vaccines, microbial fermentation and pasteurization. [↑](#footnote-ref-3)