Research core and framework of sustainability science

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Abstract This paper reviews recent achievements in sustainability science and discusses the research core and framework of sustainability science. We analyze and organize papers published in three selected core journals of sustainability science: *Sustainability Science*, *Proceedings of the National Academy of Sciences of the United States of America*, and *Sustainability: Science, Practice, & Policy*. Papers are organized into three categories: sustainability and its definition, domain-oriented research, and a research framework for sustainability science. First, we provide a short history and define the basic characteristics of sustainability; then we review current efforts in the following research domains: climate, biodiversity, agriculture, fishery, forestry, energy and resources, water, economic development, health, and lifestyle. Finally, we propose a research framework for sustainability science that includes the following components: goal setting, indicator setting, indicator measurement, causal chain analysis, forecasting, backcasting, and problem–solution chain analysis. We emphasize the importance of this last component for improving situations and attaining goals.

Keywords Sustainability science · Research framework · Research core · Structuring knowledge

Introduction

Emerging concerns about sustainability are apparent in a number of societal sectors, including the political and

economic sectors, universities, and the public at large. This growing interest is driven partly by widespread dissemination of the fact that a growing world population and the depletion of natural resources are threatening our sustainability, and by such visible phenomena as increasing oil and grain prices. Reflecting this interest and concern, sustainability science is becoming a distinctive research field (Kates et al. 2001; Clark and Dickson 2003; Komiyama and Takeuchi 2006; Clark 2007).

This does not mean, however, that the perception of sustainability as an important issue has gained popularity only recently; in fact, it has been a focus of attention for a long time. Over 30 years ago, Meadows et al. (1972) warned that our future development is constrained by the growing world population and the depletion of natural resources, and their well-known book *The Limits to Growth* stimulated public concern. As cited by Bozuwa (2006), two decades ago William Ruckelshaus (1989), the United States Environmental Protection Agency's first administrator, had already asked:

Can we move nations and people in the direction of sustainability? Such a move would be a modification of society comparable in scale to only two other changes: the Agricultural Revolution of the late Neolithic and the Industrial Revolution of the past two centuries. These revolutions were gradual, spontaneous, and largely unconscious. This one will have to be a fully conscious operation, guided by the best foresight that science can provide. If we actually do it, the undertaking will be absolutely unique in humanity's stay on Earth.

We cannot judge whether sustainability science will be comparable in impact to the previous two changes, but it is required, and urgently so. Such a belief drives our

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perception of sustainability science and related research as a top priority mission for science and technology (Raven 2002; Holdren 2008).

There is an ongoing discourse on the characteristics of sustainability science. Ostrom et al. (2007) characterized sustainability science as an applied science, and stated that 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 science, geography, history, law, political science, psychology, and sociology to build diagnostic and analytical capabilities. But it is also claimed that sustainability science is neither “basic” nor “applied” research, but rather an enterprise centered on “use-inspired basic research”, where both the quest for fundamental understanding and considerations of use are important (Clark 2007). As pointed out by Clark and Dickson (2003), 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, and various disciplines.

The multidisciplinary, interdisciplinary, and transdisciplinary characteristics (Palmer et al. 2007) of sustainability science have been emphasized repeatedly (National Research Council 1999; Komiyama and Takeuchi 2006; Martens 2006; Rapport 2007; Draggan 2007; Kates and Dasgupta 2007; Perrings 2007; Loorbach 2007). For example, Martens (2006) mentioned that the central elements of sustainability science are inter- and intra-disciplinary research, co-production of knowledge, co-evolution of a complex system and its environment, learning through doing and doing through learning, and system innovation instead of system optimization. Loorbach (2007) cited such contributing scientific disciplines as ecology, biology, complexity science, sociology, psychology, demography, science and technology studies, and history. It is argued that while the development of discipline-based science has been the source of almost all the scientific advances of the last century, it has also limited the capacity of science to address problems that span multiple disciplines (Perrings

2007). Rapport (2007) noted that sustainability science is not a “science” by any usual definition—that is, it is not yet a set of principles by which knowledge of sustainability may be systematically built. Rather, it consists of a plethora of ideas and perspectives, sometimes conflicting, by which one might hope to achieve a viable future for humankind. Although the importance of sustainability is well recognized, the interdisciplinary character of the research hampers us in grasping the entire structure of sustainability science.

Figure 1 is a schematic illustration of the relationship between sustainability science and related scientific fields. One interpretation of sustainability science is that it is a multidisciplinary research field consisting of related research fields including agriculture, fishery, forestry, water, energy, economics, sociology, and all other sciences (Fig. 1a). In this view, the role of sustainability science is to promote research focusing on sustainability-related issues in each field and to gather the outcomes. Sustainability can work as a symbolic concept to focus attention on an issue. Another interpretation is that sustainability science conducts interdisciplinary research that is not performed sufficiently in each discipline-based science (Fig. 1b). In this case, sustainability science has an important role in educating and promoting people who have multiple skills and perspectives. The last interpretation is that sustainability science is a distinct discipline engaged in a transdisciplinary effort arching over existing disciplines (Fig. 1c). In this view, sustainability science will have its own specific body of knowledge and framework with which to address sustainability issues, even while retaining relationships with other disciplines. This paper’s stance is based on the latter interpretation.

The aim of this paper is to review current research efforts in sustainability science and to discuss the research core and framework that constitute sustainability science. Sustainability science is, in fact, currently a work in progress, and therefore one may argue that it is still too early to discuss what sustainability science is. But we consider it worthwhile to review current efforts in sustainability

Fig. 1 Relationship between sustainability science and related scientific fields: **a** multidisciplinary, **b** interdisciplinary, and **c** transdisciplinary interpretations of sustainability science

science and to discuss its research core and framework even at this nascent stage of development in order to answer the following questions, or at least to offer an intellectual basis for answering them. The questions are: “Sustainability Science” is becoming a commonly used term, but what does it mean? At the very least, it clearly refers to science that is used to sustain, but to sustain what (Reitan 2005)? And which model(s) will cover the essence of sustainability science satisfactorily (Wilderer 2007)?

Scope

Reviewing the current status of sustainability science is no easy task; it requires that we carefully select a range of literature that covers all relevant papers in a field that has a growing number of publications and is multidisciplinary in nature. Currently, it is estimated that over 3,000 papers are published in the field annually (Kajikawa et al. 2007).

In this paper, we limit our analysis to publications in three selected core journals of sustainability science. These are *Sustainability Science* (SS), *Proceedings of the National Academy of Sciences of the United States of America* (PNAS), and *Sustainability: Science, Practice, & Policy* (SSPP). It is worth noting that although there are a dozen journals with “sustainability” or “sustainable” in their titles and bibliographic headings (Kajikawa et al. 2007), most of them focus on a specific traditional discipline such as sustainable agriculture, sustainable forestry, and so on. Therefore, to limit our analysis to the core field of sustainability science we have selected the aforementioned three journals, which seem to have little bias toward any particular discipline. These journals contain a variety of publication categories, including original papers, editorials, reviews, reports, and book reviews. However, we have treated these papers without distinguishing between categories, book reviews being the sole exception. Some editorials and commentaries are included because, since sustainability science is still at the nascent stage of research, such articles also contain useful information, especially for our purpose of considering what sustainability science is and what it aims for.

By limiting our corpus to the selected journals, some relevant papers will inevitably be missed. Due to the interdisciplinary nature of sustainability science, even the most popular journals carrying sustainability science articles may capture no more than 5% of all of the important papers published (Clark 2007). Despite this, we should be able to derive the principal components of sustainability science by reviewing and analyzing these three core journals. The aim of this paper is not to offer a complete overview of sustainability science but to extract a cross-section of current efforts in the field by focusing on these

journals. The characteristics of the three journals are briefly described here, and the number of papers published in these three journals is shown in Table 1.

SS was launched in 2006 on the initiative of the Integrated Research System for Sustainability Science (IR3S). IR3S is a research network founded to serve as a global research and educational platform for sustainability scientists. The journal has declared its intent to provide “a platform for building sustainability science as a new academic discipline that can point the way to a sustainable global society by facing challenges that existing disciplines have not addressed.” There were 35 papers published in SS in 2006 and 2007.

PNAS was established by the National Academy of Sciences (NAS) in 1914, with its first issue published in 1915. A section for sustainability science in PNAS, launched in 2005, aims to “capture more of the new research being carried out on fundamental properties of the complex, adaptive human–environment systems that are the heart of sustainability science.” The online collection of sustainability science papers in PNAS includes 108 papers published from 2003 to 2007. The collection includes both papers published in the section for sustainability science and related papers published in the other sections of PNAS before launching the sustainability science section.

SSPP started in 2005 as an “open-access journal that provides a platform for the dissemination of new practices and for dialog emerging out of the field of sustainability. This e-journal fills a gap in the literature by establishing a forum for cross-disciplinary discussion of empirical and social sciences, practices, and policies related to sustainability. *Sustainability* will facilitate communication among scientists, practitioners, and policy makers who are investigating and shaping nature–society interactions and working towards sustainable solutions.” SSPP published 57 papers from 2005 to 2007.

For the purposes of our overview, these papers have been organized into the following categories: sustainability and its definition, domain-oriented research, and a research framework for sustainability science. After summarizing the papers in the above journals in these categories, we will discuss the current status of sustainability science research.

Table 1 Number of papers in three core journals on sustainability science: *Sustainability Science* (SS), *Proceedings of the National Academy of Sciences of the United States of America* (PNAS), and *Sustainability: Science, Practice, & Policy* (SSPP)

	2003	2004	2005	2006	2007	Total
PNAS	8	10	6	27	57	108
SSPP			13	13	21	47
SS				11	24	35
Total	8	8	19	53	103	191

First, we shall provide a short history and overview of previous discussions of sustainability and propose a definition.

Sustainability and its definition

Sustainability literally means the ability to sustain, or a state that can be maintained at a certain level. The term has been used to express the state in which levels of harvest in agriculture, fishery, and forestry are maintained within the capacity of the ecosystem, which is therefore recoverable. In that sense, sustainability means environmental sustainability—in other words, sustainability of the ecosystem's function to provide us with food, fish, and other products and services. It is not the same as conservation, where the intention is to preserve the ecosystem regardless of human purposes. Although the term sustainability has such roots, sustainability science also has origins in other fields such as industrial ecology, climate change science, policy science, and activism. A meaningful shift from conservation to sustainability came after the Brundtland Report by the World Commission on Environment and Development (WCED), in which the concept of sustainable development or sustainability represents an attempt to link the environment with development. The report carefully defined sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” The report, *Our Common Future* (WCED 1987), also stated that global environmental problems resulted from both the South's enormous poverty and the North's unsustainable consumption and production.

The Brundtland Report has made several contributions; one is to broaden the definition of sustainability to encompass the entire range of human values (Ascher 2007). This expanding definition is also seen in the so-called WEHAB targets for water, energy, health, agriculture, and biodiversity declared at the Johannesburg Summit of the United Nations World Summit on Sustainable Development (UNWSSD 2002). In recent years, it has become common to represent sustainability by a set of triangular concepts. A well-known example is the three-pillar model, where the pillars represent the economy, the environment, and society, respectively (Kastenhofer and Rammel 2005). Similarly, the triple-bottom-line (People, Planet, Profit) or P3 (People, Prosperity, and the Planet) model (Zimmerman 2005) has gained popularity. According to panelists at a recent EPA-sponsored forum, sustainability requires the simultaneous promotion of equitable economic growth, environmental protection, and social well-being (Koehler and Hecht 2006). Here the economy, the environment, and society

are again emphasized, and are interlinked in the biosphere in a manner in which natural capital sustains the economy, which in turn supports quality of life—for example, health, security, and the pursuit of happiness. It is also argued that healthy ecosystems are an essential condition for healthy people, healthy communities, and sustainable livelihoods (Rapport 2007). In short, sustainability is achieved only when there is full reconciliation between (1) economic development; (2) meeting, on an equitable basis, growing and changing human needs and aspirations; and (3) conserving limited natural resources and the capacity of the environment to absorb the multiple stresses that are a consequence of human activities (Hay and Mimura 2006).

Another contribution to the definition of sustainability is the introduction of a spatial and temporal perspective to sustainability. The temporal perspective raises public awareness of intergenerational phenomena, for example, a tradeoff between short-term gains and long-term concerns. The spatial perspective in turn brings an emphasis to intragenerational equity, including economic disparity, particularly among nations.

Martens (2006) concisely summarized these latter characteristics of sustainable development as being an intergenerational phenomenon, including levels of scale, and consisting of multiple domains. In other words, sustainability can be characterized by the target to be sustained, and the time and space in which sustainability is threatened and recognized as an issue. According to Martens, if we wish to say anything meaningful about sustainable development, we have to take into account a time span of at least two generations. We must also keep in mind that concepts of the future may depend upon ethnicity, linguistic background, lifestyle, and life expectancy (Crabbe 2006).

Such a definitional expansion raises two issues. One is a diffusion of focus. The target of sustainability diffuses into environmental conservation, economic development, human well-being, and other goals. Martens (2006) calls this characteristic of sustainability “multiple interpretations,” by which he means the involvement of multiple interests, lack of structure, structural uncertainty, and apparent uncontrollability. But uncertainty in the target of sustainability and diffusion of focus are not always a problem; they reflect an effort to expand the set of goals so that all aspects of human (and perhaps non-human) benefits and costs are taken into account. Different ideas exist regarding sustainable development for actors in various sectors (for example, energy, transportation, agriculture, food systems, waste management). But we must keep in mind that existing solutions tend to be sustainable within these sectors rather than across the whole of society (Kemp and Martens 2007).

Another issue is the vagueness of the direction of sustainability. Although sustainability means a state that can be maintained at a certain level and does not have a directional bias, sustainable development has the connotation of sustainable economic growth, not its saturation. Therefore, if we say that sustainable development is the target to sustain, it is not clear what sustainability means (Koehler and Hecht 2006). Does a sustainable economy mean sustaining a certain level of economic activity, or sustaining a given rate of growth, or a sustainable depression? Marcuse (1998) gives the following example: a problem such as the world's poor is not that their condition cannot be sustained but that it should not be sustained. It is clear that what needs to be sustained is not poverty but the reduction of poverty.

This argument reveals the normative characteristic of sustainability. Besides objective interactions among natural, social, and human systems, the subjective aspects of human beings must also be taken into account (Sumi 2007). Defining sustainability is ultimately a social choice about what to develop, what to sustain, and for how long (Parris and Kates 2003), and is thus a deeply normative process (Kemp and Martens 2007). We have to design a future society that maximizes the happiness of both present and future generations. The meaning of happiness and the factors that degrade and threaten it may differ for each individual and culture (Sumi 2007). Therefore, an issue-driven approach is crucial. As cited by Brewer (2007), “Problems are not given. They are constructed by human beings in their attempts to make sense of complex and

troubling situations” (Schon 1979). Problem definition is a matter of representation based on human experience and expectations. An issue being faced differs among different people and cultures and in different timeframes. Sustainability is a term with multiple meanings because it encompasses a variety of objectives, including environmental, social, and human sustainability, as well as a variety of trend goals—equilibrium, growth, or reduction. Sustainability may focus on multiple goals because different people have different aspirations in different time periods, over different time scales, and in different contexts.

Domain-oriented research

In this paper, we identify ten domains of sustainability-related research: climate, biodiversity, agriculture, fishery, forestry, energy and resources, water, economic development, health, and lifestyle. This categorization was developed inductively by examining the contents and self-descriptions of the selected set of articles. We have organized papers published in the three selected journals according to these domains. Table 2 shows the number of papers assigned to each domain. Economic development includes the largest number of papers (23), and water has the smallest number of papers (8).

In Table 2, the categorization and the number of papers in each category derived from our previous paper (Kajikawa et al. 2007) are also shown. In that paper, a citation network consisting of 9,973 papers relating to sustainability was

Table 2 Number of papers categorized in each domain in this study, #ref, and number of papers included in each cluster extracted by the citation network approach, #node (Kajikawa et al. 2007)

Rank	Domain name (this study)	#ref	Cluster name (Kajikawa et al. 2007)	#node	Sum	#ref/sum ($\times 100$)
1	Economic development	23	Ecological economics	1,135	2,556	0.90
			Business	450		
			Tourism	423		
			Urban planning	277		
			Rural sociology	271		
2	Forestry	21	Forestry (agroforestry)	614	1,064	2.0
			Forestry (tropical rain forest)	450		
3	Climate	20	—	—	—	—
4	Agriculture	17	Agriculture	1,584	1,792	0.95
			Soil	208		
5	Energy and resources	12	Energy	229	229	5.2
6	Health	11	Health	211	211	5.2
7	Fishery	9	Fisheries	1,419	1,419	0.63
8	Biodiversity	9	Forestry (biodiversity)	353	514	1.75
			Wildlife	161		
9	Lifestyle	9	—	—	—	—
10	Water	8	Water	361	361	2.2

clustered, and the cluster names of the 15 main clusters were identified. Because both the corpora and analyzing procedure differ between this paper and the previous one, some of the results differ but some are shared in common. For example, two domains identified in this paper, climate and lifestyle, do not appear in the previous paper. This is because these topics are common topics among these clusters and thinly distributed in each citation cluster (Kajikawa et al. 2007). We have compared the number of papers in these two categories. Due to the lack of one-to-one correspondence, some clusters obtained by citation network analysis have been merged into one related domain. We find that the number of papers in the fishery domain is much lower in this study, and therefore the number of papers determined in the previous paper seems to be overestimated. On the other hand, the numbers of papers in the energy and resources domain and health domain are much larger. This might reflect increasing interest in these domains.

In the following sections we shall review the current discourse in each domain. Because the corpus of this overview is not all relevant papers on sustainability science but a selected portion thereof, readers may feel that the discussion is fragmented. If so, this is due to the limited corpus, not to actual fragmentation in sustainability science research. Some domains overlap and some articles must be categorized as belonging to more than one domain. Despite these drawbacks, some facets of the current status of sustainability science research will, we believe, become apparent.

Climate

First, let us look at the climate domain. Papers in this domain focus on the sustainability of the climate and factors affecting it. Global warming by greenhouse gases (GHGs) is of primary concern, but global vapor flow, including evaporation and precipitation, is also studied. Increases in CO₂ emissions are the main cause of the increasing anthropogenic greenhouse effect, so efforts to mitigate global warming must focus on CO₂ and the carbon cycle in global and social systems. The annual flux of CO₂ emissions from fossil fuel combustion, land use change, and other emission sources is greater than absorption by sinks, including land and ocean, and CO₂ has consequently accumulated in the atmosphere (Canadell et al. 2007).

One direction of research is to estimate the amount of carbon emissions and sinks. For example, Haberl et al. (2007) focused on biomass, and measured the recent net primary production of carbon as over 8 Pg C/year. Gardi and Sconosciuto (2007) measured carbon stock variation in soils in Italy over the last 70 years. In addition to

recognizing historical and current emission patterns, predicting future patterns is also important. For example, future GHG emissions in the energy sector of China (Zhou 2006) and in a region of Japan (Gomi et al. 2007) have been estimated. However, it would be a mistake to infer that non-CO₂ emissions are unimportant relative to CO₂. Moreover, the reversal and feedback effect of global warming, where temperature increases result in increased “natural” emissions of CO₂, N₂O, and CH₄, must also be dealt with. According to the results of time series analysis of Antarctic ice core records, an increase in temperature is associated with a subsequent increase in the concentration of CO₂ and CH₄ over several hundreds of years (Hansen and Sato 2004).

Both anthropogenic and natural factors can alter climate, and therefore understanding and predicting both are important research topics. While it is a minor component, Keith et al. (2004) analyzed the climatic impacts induced by the extraction of wind power using a global circulation model. Physical objects can alter climatic conditions and can mitigate global warming. For example, atmospheric brown clouds can account for decreases in surface solar radiation, changes in surface and atmospheric temperatures over land and sea, and decreases in monsoon rainfall in South Asia (Ramanathan et al. 2005). Gill et al. (2006) discussed the effect of cooling by aerosol on coral bleaching driven by the El Niño–Southern Oscillation (ENSO). When aerosol levels are low, bleaching is determined largely by El Niño strength, but high aerosol levels mitigate the effects of a severe El Niño. High aerosol levels, resulting principally from recent volcanic activity, have thus protected Caribbean reefs from more frequent widespread bleaching events but cannot be relied on to provide similar protection in the future. Brack et al. (2006) developed a comprehensive model for estimating GHG emissions from land systems in Australia. The model includes the effects of climate, land cover change, crop yield, and forest growth. Models that include past trends as well as the current situation can contribute to predictions with improved accuracy.

Other studies focus on global water circulation. Gordon et al. (2005) showed that deforestation has a comparable impact on global water vapor flows to that of irrigation. Deforestation decreases global vapor flow from land by 4% (3,000 km³/year), a decrease that is quantitatively as large as the increased vapor flow caused by irrigation (2,600 km³/year). Although the net change in global vapor flows is close to zero, the spatial distributions of deforestation and irrigation are different, leading to major regional transformations of vapor flow patterns. For example, increasing food needs in the Asian monsoon region lead to irrigation in that region, while in sub-Saharan Africa, such needs lead to deforestation. Such vapor flow patterns can

affect the global climate. Related to water flow, Poff et al. (2007) measured river flows in terms of magnitude, frequency, duration, and timing of extreme high flows and low flows, and discussed the effect of dams on those parameters and the homogenization of river flows.

There are two societal response options for reducing these risks: mitigation of climate change and adaptation to climate change. In the context of climate change, mitigation usually means reducing emissions of GHGs or enhancing their sinks. For example, Stephens (2006) reviewed carbon capture and storage technologies from an institutional perspective. There are a variety of other mitigation options, but these are not discussed further here because climate is affected and can be controlled by a variety of factors such as GHG emissions and land cover, which are, in turn, affected by a number of economic activities. Mitigation also has multiple effects. For example, reducing the amount of fossil fuel combustion contributes to mitigating not only global warming but also to energy resource depletion, while carbon capture and storage mitigates only climate change. Therefore, these aspects are discussed in later sections covering other domains.

Adaptation means actions responding to actual or expected climate change with the objective of moderating harm or exploiting opportunity. Mitigation and adaptation are complementary rather than mutually exclusive (Füssel 2007). Reducing the causes, reducing the impact of the result, and redistributing, avoiding, and accepting risk are five adaptation options (Hay and Mimura 2006). Adaptation has been a traditional strategy of human beings. Dillehay and Kolata (2004) provided a historical perspective on adaptive behavior in the Andes under conditions of environmental uncertainty and vulnerability. In northern coastal Peru, adaptation has taken the form of relocation or periodic abandonment of agricultural lands.

There are three types of adaptation strategy: institutional, behavioral, and technological. Institutions, and their associated policies, are one of the three key dimensions of adaptation to climate change. International protocols such as the Kyoto Protocol and economic schemes such as insurance are major institutional options. International protocols are a powerful option when they work. In fact, the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer is a landmark agreement that has successfully reduced the global production, consumption, and emission of ozone-depleting substances (Velders et al. 2007). Organization for information sharing is another form of adaptation that might have only an indirect effect of adaptation to climate change. For example, Miles et al. (2006) argued the necessity of integrating the climate services of nations into an international climate service. This is because current United States observational capacity,

which is primarily national and administered by federal agencies, is highly fragmented, with different systems established at different times by different organizations for different reasons, all without cross-calibration. Regarding social and behavioral strategy, reputation can work positively as a factor, at least in situations of economic experiment (Milinski et al. 2006). Technological methods of adaptation include reducing consequences by, for example, ensuring healthy reef and mangrove systems that act as buffers during storm surges (Hay and Mimura 2006). Another technological option is cooling the Earth with a cloud of small spacecraft shading solar flux, the feasibility of which was evaluated by Angel (2006). Sustainability of climate is one aspect of global and environmental sustainability; another—biodiversity sustainability—is discussed in the next section.

Biodiversity

Biodiversity is disturbed directly by human activities and also indirectly by various paths resulting from human activities, as is the case with climate as illustrated above. Pimm et al. (2006) estimated the recent bird extinction rate to be 100 extinctions per million species per year (E/MSY), and predicted $\sim 1,000$ E/MSY in the twenty-first century due to invasive species, expanding human technologies, and global climate change. Biodiversity provides a variety of functions and values (Díaz et al. 2007) in agriculture, pharmaceuticals, and tourism. In addition to such practical reasons, ethical motivations to conserve biodiversity arise from cultural values. Consequently, biodiversity has been a major target of conservation policy.

One cause of disturbed biodiversity is the change and expansion of human settlement patterns, which impact biodiversity directly by invading habitats, and indirectly by affecting land prices and other costs of achieving conservation. Human settlements are expanding in species-rich regions and pose a serious threat to biodiversity conservation. Luck et al. (2004) showed that there is a positive relationship between human population density and the percentage of threatened species. Human settlement not only degrades the biodiversity of a local area, but also invades and disturbs the ecosystem. Taylor and Irwin (2004) analyzed the relationship between the number of exotic plant species and economic activity in the United States. They used real-estate gross state product (GSP) as a measure of the intensity of economic activities and observed a positive relationship between the number of exotic plant species and real-estate GSP, which implies that economic activities in construction and urban development have the potential to disturb natural landscapes. This results in an increase in the import, dispersal, and establishment of

exotic species. Another route of disturbance is the agricultural path. Cattaneo et al. (2006) evaluated the impact of transgenic cotton and pesticide use on biodiversity and yield, showing that transgenic cotton reduced insecticide use but did not affect herbicide use. Transgenic cotton had a higher yield than non-transgenic cotton for any given number of insecticide applications. They suggested that broad-spectrum insecticides be replaced by narrow-spectrum insecticides because the use of the former reduces the diversity of non-target insects. The other disturbance factor is climate change. Thuiller et al. (2005) simulated the future distributions of 1,350 European plants species under different climate change scenarios. They showed that more than one-half of the species could be vulnerable or threatened by 2080, affected by changes in temperature and moisture conditions. Meyer et al. (2007) modeled the effect of climate change on the metabolic composition and pathways of plants.

One solution for biodiversity conservation is to purchase land to protect species and ecosystems. But conservation purchases alter the supply of, and demand for, land. Armsworth et al. (2006) discussed how conservation purchases affect land prices and generate feedback that can undermine conservation goals. When conservation groups invest significant sums in local land markets, land prices rise, which increases the overall attractiveness of an area to developers seeking to capitalize. Another solution is community-based conservation. According to Berkes (2007), the key point here is partnerships and deliberative processes among different stakeholders, because the latter differ in power, agendas, and objectives. He mentioned that there is little common language or concepts between conservation practitioners and development practitioners. We have to seek routes to bridge and reconcile them and to balance biological conservation, rural development, and livelihoods.

So far we have reviewed papers in the climate and biodiversity domains. These directly target global and environmental sustainability, in other words, the sustainability of the ecosystem itself. Next, we will examine research in agriculture, fishery, forestry, energy and resources, and water. In these domains the focus is, relatively speaking, on social and economic activities. However, the sustainability of these activities is supported by sustainability of the ecosystem's function to provide us with food, fish, and other products and services; hence they are closely interlinked as will be seen below.

Agriculture

Agriculture seeks to increase crop yields to feed and sustain the burgeoning world population. But agricultural

activities have disturbed natural conditions, which in turn affect agricultural productivity and threaten the sustainability of agriculture. This is not a new problem. For example, Hartshorn et al. (2006) measured the amount of soil nutrients in Hawai'i and analyzed the difference between those of cultivated and undisturbed dry lands. They concluded that soil nutrients such as phosphorus and calcium were lost after agricultural activities beginning 500 years ago. Such interactions within and between the human system and environmental system are a primary concern for sustainable agriculture (Smith et al. 2007).

A major part of research is dedicated to the issue of climate change. For example, Tubiello et al. (2007) reviewed the impacts of climate change and air pollutants on plant growth, diseases, and soil carbon pools. Schmidhuber and Tubiello (2007) reviewed the potential impact of climate change on food security. The four main elements of food security are availability, stability, utilization, and access. Modeling the effect of climate change on food production is an essential target. For example, Naylor et al. (2007) simulated future precipitation in Indonesia using a global climate model. Their results predicted an increase in precipitation later in the crop year (April–June) of around 10% but a substantial decrease (up to 75% at the tail) in precipitation later in the dry season (July–September). These results indicate a need for adaptation strategies in Indonesian rice agriculture, including increased investments in water storage, drought-tolerant crops, crop diversification, and early warning systems. By analyzing longitudinal data on rainfall, temperature, and rice harvest, Auffhammer et al. (2006) concluded that joint reductions in atmospheric brown clouds and GHGs have already affected the reduction in rice harvest in India. These studies clearly show the impact of climate change on agriculture. On the other hand, agricultural activity itself contributes to global environmental change. Nitrate leaching and N₂O emission as a GHG from agricultural soils are recognized as significant environmental threats. The primary source of N pollution is N-based agricultural fertilizers. Kramer et al. (2006) demonstrated that organically farmed soils exhibit higher potential denitrification rates, greater denitrification efficiency, higher organic matter, and greater microbial activity than conventionally farmed soils.

Howden et al. (2007) discussed adaptation in agriculture to climate change, proposing the following steps: keep policy relevant, notify mitigation targets, announce investments, reward early adopters, and focus on climate risk management. First, because climate change adaptation policies are a subset of policies on sustainable development and natural resource management, they must be kept relevant to other policies. Second, notifying mitigation targets leads to a mix of both mitigation and adaptation and

will maximize societal welfare under future climate risk. Third, announcing investments enables stakeholders to make investment or disinvestment decisions. Fourth, rewarding early adopters is effective in enhancing transitions. Finally, we should focus on climate risk management, which includes the identification of drivers of risk, assessment of impacts on systems under alternative management, and translating adaptation options into adaptation actions.

To this we should add that the effects of climate change may be particularly apparent in smallholder and subsistence agriculture. Morton (2007) reviewed the impact of climate change on smallholder and subsistence agriculture, while Patt et al. (2005) focused on the learning process of farmers in developing countries. The latter organized workshops to learn about seasonal climate forecasts, and reported that farmers who had attended a workshop were significantly more likely to use forecasts than farmers who learned of forecasts through non-participatory channels. They also reported that attending farmers responded by altering the time of planting and by planting a different variety of crops. These informative activities will be increasingly necessary for such farmers.

Climate change is not the sole factor degrading agricultural sustainability. Other factors include changes in biodiversity and soil quality. Greenleaf and Kremen (2006) investigated the pollination of sunflowers by bees. Honey bees are commonly used for pollination, but it was found that behavioral interactions between wild and honey bees increase the pollination efficiency of honey bees on hybrid sunflower up to five-fold. To preserve biodiversity, farmland preservation is necessary; consequently the participation of various stakeholders is an important element of land use policy (Koontz 2006). Christensen (2007) introduced an urban agriculture movement called SPIN-Farming in Philadelphia, where SPIN stands for “Small Plot INTensive.” Urban agriculture also constitutes a form of regional biodiversity.

Soil quality is also a subject of debate. Although grain production has doubled in the past four decades, largely because of the widespread use of synthetic nitrogenous fertilizers, pesticides, and irrigation, this rate of increased agricultural output has become stagnant and is unsustainable. Fox et al. (2007) showed that some organochlorine pesticides, agrichemicals, and environmental contaminants inhibited both rhizobia bacteria in host plant roots and nitrogenase activity, thus reducing overall plant yield at time of harvest. The environmental consequences of synthetic chemicals compromising symbiotic nitrogen fixation are increased dependence on synthetic nitrogenous fertilizer, reduced soil fertility, and unsustainable long-term crop yields.

A common strategy to reduce dependence on nitrogenous fertilizers is the production of leguminous crops,

which fix atmospheric nitrogen via symbiosis with nitrogen-fixing rhizobia bacteria, in rotation with non-leguminous crops. Another strategy is the improvement of pesticides and fertilizers to increase food productivity while reducing economic and environmental costs. Komatsuzaki and Ohta (2007) reviewed issues relating to soil management. Liu et al. (2007) investigated grass weed resistance to herbicides, and detected amino acid substitutions as a molecular basis of resistance. Economic and regulatory factors are also effective routes to controlling fertilizer use. Zhang et al. (2006) focused on nitrogen runoff in China as a primary source of pollution in fresh water bodies and evaluated nitrogen runoff control policies such as taxes, bans, mandatory substitution of fertilizer, and subsidies for using compost. By maximizing farmers’ net income under these policies, they showed that all four policies would effectively reduce nitrogen runoff, and subsidies for recycling domestic animal manure and utilizing compost had the most significant effect on the reduction of nitrogen runoff without reducing household income.

Fishery

Fishery as a discipline has for a long time discussed sustainability in terms of maximum sustainable yield. Brander (2007) reviewed the global fish production system as consisting of fish stocks in the marine ecosystem, fishing activity, climate, and their interactions. Current global fishery production is about 160 million tons, of which 76% was used for direct human consumption in 2002, and the remaining 24% for fishmeal and oil.

The effect of climate change on the marine ecosystem is a current focal point of arguments for the sustainability of fisheries. Battin et al. (2007) and Thresher et al. (2007) investigated the effect of climate change on marine fish. Battin et al. showed a large negative impact of climate change on freshwater salmon habitats. Thresher et al. found that the effect depends on sea depth. Rising temperatures near the ocean surface correlate with increasing growth rates by species found in depths of less than 250 m, whereas growth rates of deep-water (more than 1,000 m) species have declined substantially during the last century, a finding that correlates with evidence of long-term cooling at these depths. Zeidberg and Robison (2007) monitored the habitat distribution of the squid by video survey, revealing that it has substantially expanded its perennial geographic range in the eastern North Pacific. They pointed out that this range expansion coincides with changes in climate-linked oceanographic conditions.

Temperature is not the sole factor affecting the marine ecosystem. For example, Doney et al. (2007) modeled

ocean acidification by anthropogenic atmospheric nitrogen and sulfur deposition. Other studies have attempted to model complex interactions between the marine ecosystem and the human system. Although research is typically conducted on a single-species target, we must also note effects on the multi-species level. Hilborn et al. (2003) investigated sockeye salmon and emphasized the importance of the biocomplexity of fish stocks. Hjermann et al. (2004) modeled an interactive and dynamic perspective of the capelin population in the marine ecosystem. Both overexploitation and predation by herring can cause the population to collapse, whereas predation by cod is demonstrated to delay a stock's recovery after a collapse. Wilson et al. (2007) modeled the behavior of fishers by multi-agent simulation to understand the self-organized process of forming small groups through collective action.

Increasing the fraction of farmed fish is one solution for sustainable fisheries. Global fish production in aquaculture has grown by 10% annually over the last decade (Brander 2007). But Krkošek et al. (2006) warned of the spread of infectious diseases by farm-origin lice, which threatens aquaculture. Under natural conditions, sea lice are common on adult Pacific salmon but rare on juvenile ones. The life cycles of most temperate marine fish involve a period of spatial segregation between juveniles and adults, which may protect juveniles from the parasites associated with adults. But in areas containing salmon farms, the farms provide parasites with novel access to these juvenile hosts, resulting in measurable and sometimes severe impacts on salmon survival.

Forestry

Forests cover 4 billion hectares of the Earth's land surface, of which 36% is primary and 53% is modified natural forests. However, the primary forest area has been slowly decreasing at a rate of about 6 million hectares annually since the 1990s, an amount that corresponds to about 0.4% of existing primary forest (Kirilenko and Sedjo 2007). However, this does not mean that forest is uniformly lost; forest can be lost somewhere but recovered elsewhere. Kauppi et al. (2006) proposed the "forest identity" formula to measure forest transition from deforestation to reforestation, accumulating data on the area and density of the forests and the weight of the biomass of each country. They investigated forest identity and showed that deforestation is severe in Indonesia and Brazil while other countries, including India, China, the United States, Japan, and France are undergoing reforestation. Asner et al. (2006) monitored forest coverage in the Brazilian Amazon using longitudinal satellite data. They showed that at least 76% of all harvest practices across the region resulted in high

levels of canopy damage sufficient to leave forests susceptible to drought and fire. They found that about 16% of selectively logged areas were deforested within 1 year of logging, with a subsequent annual deforestation rate of 5.4% for 4 years after timber harvest. Laurance et al. (2006) showed that forest fragmentation during deforestation provoked surprisingly rapid and profound alterations in Amazonian tree-community composition. Morton et al. (2006) combined deforestation maps, field surveys, and satellite-based information on the Brazilian Amazon, and showed that deforestation was accompanied by cropland expansion that might be driven by increasing global soybean prices.

Forests provide value directly as timber and fuel and indirectly by increasing the productivity of other human activities and providing ecosystem services to the human social system (Easterling 2007; Kirilenko and Sedjo 2007; Alger 2006). Concerning the former, Kirilenko and Sedjo (2007) reviewed recent trends in increasing demand for and production of industrial timber, and also the impact of climate change on timber supply. Goldstein et al. (2006) evaluated the financial value of a forest based on a discount cash flow model with different strategies such as timber production, grazing, and conservation, i.e., a mixture of direct and indirect outcome.

An example of an indirect outcome is the enhancement of coffee bean production. Coffee is cultivated in many of the world's most biodiverse regions; it is able to self-pollinate, and bee visitation can increase yields. Ricketts et al. (2004) observed that forest-based pollinators increased coffee yields by 20% within about 1 km of forest, and improved coffee quality near forests by reducing the frequency of small misshapen seeds by 27%. They estimated that pollination services from forest increase total farm income near forest compared to other areas by an average of 7%. Another example is the cacao agroforestry system in Indonesia, which was investigated by Steffan-Dewenter et al. (2007). In the area studied, the transformation from near-primary forest to agroforestry had little effect on overall species richness, while doubling farmers' net income. Forest not only maintains species richness but also affects the quality of the soil. Lawrence et al. (2007) studied interactive feedback between forestry and soil systems. After three cultivation–fallow cycles, available soil P declines by 44% and one-time P inputs from biomass burning decline by 76% from mature forest levels. Deforestation disrupts the phosphorus cycle by weakening the rate of P deposition. This is because P is input to the system through hydrological and biogeochemical feedback to the cycling of phosphorus. Deforestation is likely to slow forest regeneration, affecting crop yields and farmers' livelihoods in the near future.

Forests may also have an impact on human health. Pattanayak et al. (2006) discussed relationships between deforestation, malaria, and poverty. They noticed that deforestation changes the ecology of the malaria vector; large-scale deforestation increases temperature and moisture in the region, which increases the growth of mosquitoes, their frequency of blood feeding, and infection rates. Malaria then imposes substantial social and economic costs, and impedes economic development by degrading quality of life; decreasing savings, investment and labor productivity; and increasing medical costs and mortality. In turn, the severe economic situation may cause the inappropriate use of drugs and pesticides and thus hinder long-term malaria prevention and treatment. Moreover, poverty drives people to overexploit forest resources. In simplistic terms, malaria could be considered a cause of deforestation because malaria can make people poorer, and poverty can cause deforestation under certain conditions.

Because forests have beneficial effects for us as discussed above, forest management is crucial. In forestry research, societal aspects have been frequently addressed. Chapin et al. (2006) reviewed human–environment interactions affecting Alaskan boreal forests and suggested four broad policy strategies: fostering human adaptability, enhancing resilience, reducing vulnerability, and enhancing transformability. The ownership of forests, including public protected areas, private forests, and community forests, is a critical issue under active discussion. Public ownership of forest, preferably as designated parks, is often regarded as the only way to achieve sustained conservation over time. But it is not a panacea. Ostrom and Nagendra (2006) referred to the importance of community-based conservation. The temptation to overharvest natural resources is always great even in protected areas, where extractive resource use is in fact common (Naughton-Treves et al. 2006).

Community-based conservation is required for the following reasons (Ostrom and Nagendra 2006). If the formal rules limiting access and harvest levels are not known or considered legitimate by local resource users, substantial investment in fences and official guards to patrol boundaries are needed to prevent illegal harvesting. Without these expensive inputs, government-owned, protected forests may not be protected in practice. On the other hand, when the users themselves have a role in making local rules, or at least consider the rules to be legitimate, they are frequently willing to engage in the monitoring and sanctioning of uses considered illegal, even of public property. When users are genuinely engaged in decisions regarding rules that affect their use, the likelihood of users following the rules and monitoring others is much greater than when an authority simply imposes rules on users. These co-management initiatives have succeeded in reducing

park–people conflicts, taking some pressure off national parks and encouraging forest protection and regrowth in the larger landscape within which the park is embedded.

Analyzing the case of reforestation in Nepal, Nagendra (2007) noted the importance of community forests and leasehold forests as tenure regimes, and of the local monitoring of forest regrowth. However, because it involves multiple stakeholders, forest management is not always done well. Manson and Evans (2007) simulated the decision-making process in land use by agent-based modeling. Brueckner and Horwitz (2005) explored policy formulation in the Western Australian Regional Forest Agreement (RFA) and RFA stakeholders' perceptions of the scientific credibility of this process. More than 500 scientists and experts were reported to have been involved in the RFA process. But despite their efforts, it appears that the Western Australian RFA failed to gain public acceptance partly due to a lack of scientific credibility, even though science was said to have underpinned its entire development. There are many critical comments regarding this credibility and conflicts among different groups of participants. One solution to such conflict is interactive learning among different groups. Andersson (2006) evaluated the effect of learning among different stakeholders and observed a positive relationship between learning among participants and their satisfaction.

The remaining papers in this domain study forest fires. Spyrtos et al. (2007) modeled the expansion of fire at the wildland–urban interface by considering the flammability of houses. Thompson et al. (2007) discussed the impact of post-wildfire management on future fire severity and concluded that areas that were salvage-logged and planted after the initial fire burned more severely than comparable unmanaged areas, suggesting that fuel conditions in conifer plantations can increase fire severity despite the removal of large woody fuels.

Energy and resources

This category of papers studies the sustainability of resource extraction from the Earth, including energy and inorganic resources. In the second edition of the *Oxford English Dictionary*, “resource” is defined as “a stock or reserve upon which one can draw when necessary.” The phrase “when necessary” seems to imply that there are times when certain resources are perceived as unnecessary and are thus dismissed (Sato 2007). Sato investigated the process by which the resource concept was formed in Japan, finding that the orientation of resource policy was drastically different before and after World War II. In the pre-war period, the military government used the resource concept to create a comprehensive inventory of the nation's

military forces, and “resource” was thus a convenient term to neutralize the aggressive connotations of top-down military mobilization. After the radical turn to democratic principles in 1945, “resource” suddenly gained the symbolic connotation of a means to serve the people. Particularly after the 1980s, the resource concept expanded to include “soft” dimensions such as the ability to utilize information or influence other countries through cultural–political means.

Any technological cycle that brings either a product or a service to our everyday lives is composed of a sequence of activities from resource extraction, storage, transport, transformation, production, storage and distribution, use, waste formation, partial material recycling and product reuse, to waste disposal into water, air, and ground (Orecchini 2007). According to Orecchini, sustainable development should not consume resources; it should use and reuse them, endlessly, in a closed system. A circular economy, which is a mode of economic development based on the ecological circulation of natural materials, is a concept vital to attaining the sustainability of resources, following the principles of “reducing resource use, reusing, and recycling.” Feng and Yan (2007) suggested that a circular economy should be realized first at the level of enterprises, then of industrial parks, finally expanding to cities and regions.

A circular energy system can be achieved only by exploiting renewable resources using incident solar energy (Orecchini 2007). One direction of research is to estimate current and future energy demands and potential supply to predict the future, set goals, and analyze the gap between goals and trends. Trieb and Müller-Steinhagen (2007) reported on future trends in energy demands and potential renewable energy in Europe, the Middle East and North Africa. Another research direction is to improve energy efficiency and develop a renewable energy source in order to fill the gap and realize energy sustainability.

Hill et al. (2006) estimated the energy input and output and potential supply of biofuels. They showed that ethanol yields 25% more energy than the energy invested in its production, whereas biodiesel yields 93% more. But even dedicating all United States corn and soybean production to biofuels would meet only 12% of gasoline demand and 6% of diesel demand. Thus it is necessary to develop a synthesis route for transportation of biofuels from, for example, cellulosic or waste biomass. Chen and Logan (2007) proposed biohydrogen production via electrohydrogenesis. Hydrogen gas can be produced from cellulose fermentation by adding a small voltage to bacteria, but a slow production rate and low-energy efficiency of around 60% hampers its application. Agrawal et al. (2007) proposed a mixture of biomass and hydrogen for a liquid biofuel feed. By combining biomass with hydrogen, the land area needed to grow the

biomass is reduced to less than 40% of that needed by other routes that solely use biomass.

In addition to the technological point of view, a social and economic perspective is also necessary for energy sustainability. Hess (2007) highlighted the difficulty of implementing a new social system by studying the compressed natural gas (CNG)-versus-diesel controversy in the United States—particularly conflicts among stakeholders around political, environmental, and economic tradeoffs. Based on another case study of the CNG-versus-diesel controversy in Colombia, Valderrama and Beltran (2007) stated that contractual arrangements that fairly distribute financial costs and technological risks are necessary to implement new socio-technical systems because private sector partners are likely to select the least risky and most profitable options and to justify them as environmentally acceptable.

Sustainability of resource use is also becoming an issue in other sectors besides energy. Gordon et al. (2006) reviewed metal sustainability and estimated metal stocks, focusing especially on copper. Müller et al. (2006) investigated the iron cycle and the iron stock of the United States over the period 1900–2004. They reported that the iron reservoir in use (3,200 million tons) has reached approximately the same size as the stock of economically recoverable natural ore, with 2,100 million tons of reserves and a 4,600 million ton domestic reserve base. They also pointed out that the relative significance of iron stocks as a potential iron source is increasing, whereas ores are shrinking in size and grade. Steinfeld (2006) described the sustainability of the chemical industry. This industry depends on the availability of petroleum as a feedstock, but current rising oil prices are threatening its sustainability; therefore it will require not only renewable energy sources but also renewable feedstock, i.e., biomass.

Water

Water has been one of the central issues discussed at international ecology-related conferences (Rahaman and Varis 2005). Marcotullio (2007) reviewed urban water-related issues in Southeast Asia and classified them into the following categories: brown issues such as access to water supply, access to sanitation, and adequate drainage; gray issues such as river pollution, overdrawn groundwater supplies, ground subsidence, coastal area degradation, and flooding; and green issues such as increasing water consumption per capita, water scarcity, and increased vulnerability because of climate change or variability.

In the brown issue category, Bhandari and Grant (2007) surveyed the relationship between user satisfaction and willingness to pay for drinking water in rural communities

of Nepal, while Wing et al. (2007) introduced activities to design and implement an engineering project to provide fresh water to rural communities in El Salvador.

In the gray issue category, salinization of water is also becoming an issue. For many years, salinization of fresh water related to agricultural practices has been recognized as an environmental problem. Chloride concentrations are increasing at a rate that threatens the availability of fresh water in the northeastern United States. Increases in roadways and deicer use are now salinizing fresh waters, degrading the habitats of aquatic organisms and impacting large supplies of drinking water for humans throughout the region. Kaushal et al. (2005) measured the chloride concentration of waters in streams and rivers of the northeastern United States in rural, suburban, and urban areas, and observed chloride concentrations of up to 25%.

In the green issue category, Rockström et al. (2007) reviewed the water–agricultural system. Agricultural productivity is directly related to the availability of water; hence agricultural productivity per unit of water, i.e., water productivity, should be increased. At current water productivity levels, other vapor flows will be needed in the amount of 2,200 km³/year in 2015 and 5,200 km³/year in 2050 (Rockström et al. 2007). Population growth occurs almost exclusively in developing countries, and water sustainability will therefore become an issue in these countries. For this reason, assessment of regional water capacity and capability is important. Sidle et al. (2007) measured the open-water surface area of a lake in Myanmar, finding that 32.4% of the surface area has been lost during the last 65 years. Because the relationship between vapor flow and yield growth is non-linear, particularly in low-yielding savanna agro-ecosystems, there is a high potential for water productivity increase in those areas (Rockström et al. 2007). To solve water-management problems, Meinzen-Dick (2007) mentioned that combinations of institutions, combining government, user groups, and markets, rather than single institutions are essential.

So far we have summarized papers in the climate and biodiversity domains that focus on global and environmental sustainability, as well as papers in the agriculture, fishery, forestry, energy and resources, and water domains, which address the sustainability of ecosystem functions and the resulting sustainability of our social and economic activities in those sectors. Below, we will examine the domains of economic development, health, and lifestyle, which tend to be more directly related to our daily lives.

Economic development

This category of papers addresses the sustainability of economic activities. One focus of study is the sustainability

of economic development; another is the sustainability of poverty reduction. First, let us look at studies on sustainable economic development. These papers can be divided according to the level of geographic scale into global-level studies and local-level studies, with local-level studies usually focusing on sustainable urban development.

At the global level, the increasing consumption of meat, water, and cars brought about by the growing world population and economic development, can cause major environmental damage (Myers and Kent 2003). Nordhaus (2006) discussed the relationship between global warming and economic activities using fine-scale geographical data on economic activities. The results suggested that doubling CO₂ in the atmosphere, which corresponds to a surface mean temperature increase of 3°C, decreases economic activity by around 1%. These conclusions are derived from the fact that high-latitude countries currently show high economic performance. Yasuhara et al. (2007) estimated the effect of global warming on groundwater-level variations and sea-level rises, which affect economic activities as well as daily life in coastal areas.

At the local level in urban areas, researchers have investigated the impact of population growth and urban development on environmental degradation, heat island effects, and land use. Among these, environmental degradation is a primary concern. Savage (2006) reviewed issues relating to sustainable urban development in Southeast Asia. Industrialization in East Asia involves transboundary air pollution, deforestation, destruction of the marine environment, water shortages, and drinking water contamination (Kim 2006). Andersen (2007) wrote an introductory note on environmental economics focusing on the estimation of externalities in economic activities, such as the cost of pollution, and the value of a circular economy. Dudley (2007) modeled resource activities influenced by penalties for environmental damage. Yoshida (2007) described how the environmental restoration of a formerly polluted Japanese city, Minamata, was achieved through environmentally friendly agriculture and fishery, ecotourism, and citizen participation. The urban heat island effect was reported on by Zhou et al. (2004), who estimated the effect to be +0.05°C per decade in southeast China, where rapid urbanization is taking place. Land use pattern change during urbanization is also an issue. Irwin and Bockstael (2007) showed that increasing land fragmentation is accompanying urban sprawl in the United States. However, there are few studies of solutions to these problems. Hecht and Sanders (2007) described policies and research programs concerning urban ecosystems in the United States. Yli-Pelkonen and Kohl (2005) stressed the importance of local ecological knowledge in land use planning. But it cannot be said that urbanization has only negative effects. Bettencourt et al. (2007) analyzed the

correlation between population and economic indicators such as GDP, household consumption, infrastructure, and research and development (R&D) activities. They showed that agglomeration of population has a positive impact on GDP and R&D activities, and requires less infrastructure (e.g., fewer roads, gasoline stations, and gasoline sales).

Another type of study, focusing on poverty reduction, tends to be rural in focus as opposed to the above urban studies. Using purchasing-power-parity exchange rates, Chen and Ravallion (2007) estimated a time series of the number of people in absolute poverty. Their results indicated that people living below the extreme poverty line of US\$1 per day decreased between 1981 and 2004 from 1,470 million to 969 million worldwide. The percentage of extremely poor fell from 40% to 18%. However, in sub-Saharan Africa, the number almost doubled, from 168 million to 298 million, and the percentage stayed almost constant. On average, over the period 1960–2000, Africa's population-weighted per-capita annual growth of gross domestic product (GDP) was a mere 0.1%, while other regions experienced 5% growth between 1980 and 2000 (Collier 2007). Population growth has been an obstacle to sustainable economic development in both South Asia and sub-Saharan Africa (Dasgupta 2007).

Africa's growth failure has been explained by inappropriate economic policies related to the interests of powerful groups (e.g., the taxation of export agriculture), institutions, leadership, and geography (Collier 2007). Auer (2007) discussed the causes of poverty in Equatorial Guinea, where the sudden discovery of oil triggered large inflows of foreign direct investment, which added to inflation pressures, and rural-to-urban labor migration, which led to declining production of export crops such as cocoa and coffee and other non-oil economic activities. Auer argues that good governance is the key to sustainable development, comparing Equatorial Guinea with Botswana, whose GDP grew an average of 7% between 1995 and 2005. Okwi et al. (2007) analyzed geographic determinants of poverty with regression models including slope, soil type, distance/travel time to public resources, elevation, type of land use, and demographic variables. Their results indicated that investments in roads and improvements in soil fertility potentially reduce poverty rates. Collier (2007) proposed different solutions for different countries categorized by geographic differences. Resource-rich countries with high ethnic diversity need strong checks and balances on how governments use their power and distribute funding. International policies on transparency and financial disclosure can help. Such countries are also prone to violent internal conflicts, so expanding international and regional peacekeeping and security guarantees could be of aid. Resource-scarce coastal countries that have missed opportunities to

develop Asian-style export-based manufacturing will require temporary preferential market access. Finally, countries that are both resource-scarce and landlocked have the least opportunity for growth. They will need substantial foreign aid, not for fostering economic growth but for direct provision and consumption of basic necessities.

Despite the knowledge accumulated on the status of poverty and its causal chain, the problem is far from solved. Hyden (2007) commented that for someone studying development in Africa since the early 1960s, it is shocking how little learning there is among agencies funding development in the region. He attributed this failure to the dominance of economists in formulating the international development policy agenda, and the tendency for political scientists to look at how economic variables shape political ones, rather than the other way around. Larson and Ribot (2007) cited the existence of an uneven playing field with double standards of access to both markets and natural resources, where the rural poor are excluded from the natural wealth around them. Nieuwsma (2007) found difficulties in sustainable development projects arising from the conflict among different languages, such as the languages of market economics, technoscience, rural development, and local knowledge, used by different stakeholders in different organizations.

Recently, however, trials to utilize scientific knowledge toward action and participatory field experiments to improve situations and understand them better have been undertaken. Sanchez et al. (2007) described the African Millennium Villages Project, which targets public-sector investments to raise rural productivity and thereby increase private-sector saving and investments. This is carried out by empowering impoverished communities with science-based interventions. The basic assumption of the project is that poverty, hunger and disease, rapid population growth, environmental degradation, and poor governance are all mutually reinforcing. The project has been initiated at 12 sites in ten African countries. They reported that, in its first year, the project contributed to reducing malaria prevalence, meeting caloric requirements, generating crop surpluses, enabling school feeding programs, and providing cash earnings for farm families. Mabogunje (2007) described an experiment in poverty reduction in a city in Nigeria where 90% of the population lived below the poverty line of US \$1 per person per day. With 7 years of experience, the experiment has been successful in many ways. There is increasing evidence that poverty in the city has been reduced significantly through the microfinancing of existing and new productive activities, and that up to 8,000 jobs have been created through these activities. Training and social capital have been critical factors in the establishment of cooperatives and the development of new

enterprises in specialty crops and small animal and fish production. These studies must be continually performed to reduce hunger until they become unnecessary.

Health

Sustainable health is one of the newer dimensions of sustainability science (Bloom 2007). Bloom and Canning (2007) modeled life expectancy in 1963 and 2003 across countries. Their results indicated that countries can be classified into two groups, high-mortality and low-mortality. After 40 years, life expectancy in low-mortality countries has lengthened. On the other hand, countries with high mortality in 1963 had varying fates. Some joined the low-mortality group, while others stayed in the high-mortality group and their life expectancy did not change. Thus sustainable health is closely related to the dispersion of wealth among nations.

Most sustainable health research is based on the schema of vulnerability analysis in which humans suffer from the environment, focusing on elucidation of the process and modeling the risk of disease. For example, Aufderheide et al. (2004) investigated the origin of Chagas' disease in South America. Their results suggested that the infection process of the disease involved a vast reservoir among wild mammals and that it was transmitted by a large number of insect vectors. Eisenberg et al. (2006) analyzed the causal structure of transmission of diarrheal pathogens in rural Ecuador, elucidating the causal path from road proximity, social contact, and infection rates. Raso et al. (2006) modeled the risk of *Schistosoma mansoni* (hookworm) coinfection by age, sex, socioeconomic status, elevation derived using ground maps, and land cover derived using satellite images, and mapped the risk profiling and spatial prediction of coinfection in Côte d'Ivoire. Tatem et al. (2006) evaluated the risk of spread of insect disease vectors among international seaports and airports through traffic movements, using data on traffic volume, world distribution of insects, and climate conditions. West et al. (2006) analyzed the impact of CH₄ emissions on health through the generation of ozone. Tropospheric O₃ is formed from photochemical reactions involving NO_x and volatile organic compounds (VOCs); CH₄ is the primary anthropogenic VOC in the global troposphere. They simulated global O₃ concentration and estimated that reducing current global anthropogenic CH₄ emissions by about 20%, which is cost-effective and economically feasible, will reduce O₃ mixing ratios globally by ~1 ppbv and prevent approximately 30,000 premature mortalities globally in 2030.

In addition to such modeling studies, solutions for sustainable health have also been proposed and executed. An

example is the case of Chagas' disease (Gürtler et al. 2007). There were two campaigns to reduce Chagas' disease in rural villages in northern Argentina between 1984 and 2006. But because no effective surveillance and control actions followed the first campaign in 1985, transmission resurged in 2–3 years. Renewed interventions in 1992 followed by sustained, supervised, community-based vector control largely suppressed reestablishment of the disease. Singer and de Castro (2007) concisely proposed three routes for sustainable health. One is bridging the engineering and health communities, for example by implementing clean water and sanitation on a broad scale to prevent reworming. The second is to build an integrated human and animal disease surveillance infrastructure based on reporting and solid scientific evidence. Education is also important in reducing risk factors (Reddy et al. 2007; Workeneh and Mireles 2007). The third is developing an independent and equitable organizational structure for health impact assessments as well as monitoring and mitigating the health consequences of economic development projects.

Lifestyle

Traditionally, due to the absence of a well-founded understanding of consumer motivation, policies for sustainability have focused on the supply side, but not on the demand side, of economic activities. Therefore, instead of debating consumption, political debate has been devoted to fostering technological innovations aimed at incremental environmental improvements (Cohen 2005). Although the situation has not changed markedly, sustainable consumption is becoming a definable area of international environmental politics, especially since the Rio Declaration on Environment and Development, which encourages the reduction and elimination of unsustainable patterns of production and consumption (Cohen 2005). There have been reports on sustainable consumption policies in France (Sanches 2005), The Netherlands (Martens and Spaargaren 2005), and the United States (Cohen et al. 2005). They mainly involve the following tools (Sanches 2005; Cohen et al. 2005): public policy initiatives, economic incentives, social and political protest campaigns, and lifestyle reinventions.

A typical example of public policy initiatives is green procurement. Eco-taxation is another effective tool to enforce economic incentives. Social and political protest campaigns include eco-labeling, anti-consumerism, anti-television, anti-advertising, and education campaigns. Lifestyle reinventions include changes of consumption patterns and work style. Examples of consumption pattern changes are the slow food movement, relocalization of

food production and consumption, and the simple life. Gram-Hanssen (2007) investigated the process by which the habit of cleanliness, such as showering and laundering, is formed in the lifestyle of a teenager. Family structure is also a factor affecting consumption patterns. Divorced households spend more per person on resources such as electricity, water, and accommodation than married households (Yu and Liu 2007). An example of a change in work style is the realignment of working hours in France. In fact, such realignments lead workers to spend more time with their families and hence appear to contribute to social cohesion, an essential feature of social sustainability (Sanches 2005). Teleworking is another example of a work style change that potentially impacts environmental, social, and economic sustainability (Moos et al. 2006).

Consumption patterns and lifestyle are keys to the sustainability of other resources, and their sustainability is in turn a good indicator of human welfare. But current studies tend to focus on the former, i.e., the impact of consumption on the sustainability of other resources. The suppression of consumption to sustain other resources is called sustainable consumption in this context. An example of the latter research, focusing on social sustainability, is a study by Rogerson and Kim (2005) of changes in regional population distribution in the United States. Their focus is on the population distribution of the baby boom cohort and intergenerational care giving. Many members of the baby boom cohort are beginning to care for their parents just after they finish child rearing. But because baby boomers have had fewer children than their parents, the spatial distribution of aging baby boomers and their spatial separation from their (relatively few) children will become even more important during the next few decades. Currently we see little research linking the sustainability of society, of lifestyle itself, and the happiness of individuals, but such research is desirable insofar as one of the ultimate goals of sustainability research is the pursuit of our and future generations' happiness.

A research framework for sustainability science

We have summarized research efforts in each of the aforementioned domains, but other papers also deal with general or methodological issues in sustainability science. For example, Newman (2005) cited the following steps as the essence of sustainability science: understanding the principles of sustainability, locating unsustainable processes and determining the gain in changing them, forming a vision of how to change them by backcasting from the final goal, identifying a series of paths leading to that goal, and then picking a path. Similarly, Martens (2006) identified the following procedural elements in sustainability

science: analysis of deeper-lying structures of the system, projection into the future, assessment of sustainable and unsustainable trends, evaluation of the effects of sustainable policy, and the design of possible solutions through sustainable strategies.

Brewer (2007) referred to Lasswell (1971) and maintained that the following questions should be addressed: “What goal values are sought and by whom? Or, who are the relevant participants/stakeholders and what do they want? What trends affect the realization of these values? Or, from where did the problem originate? What factors are responsible for the trends? Or, what are the driving, influencing, and conditioning factors? What is the probable course of future events and developments, especially if interventions are not made? Or, on what problems or opportunities should we focus attention? What can be done to change that course to achieve more of the desired goals, and for whom?”

Figure 2 is a schematic illustration of a framework addressing these questions. This framework is based on that of Parris and Kates (2003), who explicitly distinguished between goals, indicators, targets, trends, and driving forces. In their framework, goals are broad, qualitative statements about objectives. Examples of goals are reducing hunger, stabilizing climate, and improving health. Indicators are quantitative measures selected to assess progress toward or away from a stated goal, and targets are quantitative values of indicators for attaining the goal at a specific time or within a certain timeframe. The historical trend of the value of an indicator is measured by a variety of methods, and is extrapolated to predict the future. Trends are changes in the values of indicators over time, and driving forces are the processes that influence trends and our ability to meet agreed targets that work as the principal drivers toward or away from sustainability goals and targets. But “target” is also used to mean the focal subject, in other words, what to sustain; examples are

Fig. 2 Principal components of sustainability science in time-series analysis: goal, indicator, target value, trend, and driver

WEHAB targets. In our discussion we use the latter meaning of “target” and hence have renamed the original usage of the word in Parris and Kates (2003) to “target value of an indicator.” For example, when we aim to stabilize climate, the goal is stabilization of the climate, so climate is the target, and the annual emission rate of CO₂ is one of the indicators. Reducing CO₂ emissions by 50% by 2050 compared to 1990 is the target value of the indicator.

Other studies repeatedly stressed the importance of modeling human–environment systems (Clark and Dickson 2003; Turner et al. 2003a, 2007; Perrings 2007; Ostrom 2007). A simple quantitative model of a human–environment system is the IPAT identity (Ehrlich and Holdren 1971): the equation $I = PAT$, where I , P , A , T are the impact of any population on the environment, population size, its affluence or per-capita consumption, and environmental damage per consumption unit. This has recently been extended to include market exchange rates and purchasing power parity (Raupach et al. 2007). According to the IPAT identity, options to mitigate the human impact on the environment are reducing population, reducing consumption per population, and improving technology to reduce environmental damage.

Researchers are attempting to build a common modeling framework for sustainability science. Ostrom (2007) proposed an analytic framework consisting of a resource system (for example, fishery, lake, grazing area), resource units generated by that system (for example, fish, water, fodder), the users of that system, and the governance system, where all these components and their interactions are bound by other related ecosystems and constrained by social, economic, and political settings. Turner et al. (2007) raised the importance of observing, monitoring, and understanding system dynamics in a coupled human–environment system, spatially explicit modeling of the focal system, and assessment of the system outcomes such as vulnerability, resilience, or sustainability. In the context of vulnerability and resilience, an understanding of perturbation or stresses/stressors to a system is crucial to understanding the hazards and risks of the system (Turner et al. 2003b). Under the uncertain conditions of such systems, control of robustness is a critical challenge to balance the tradeoff between robustness and vulnerability, and between robustness and performance (Anderies et al. 2007). Complexity, vulnerability, and resilience are the key concepts to understanding and modeling a coupled human–environment system.

Needless to say, modeling is a fundamental and indispensable scientific activity. In the absence of a full understanding of implications for a system, there is a risk of unintended consequences, such as the production of grain-based biofuels having hidden effects upon agricultural outcomes (Fiksel 2006). To employ the terminology of the

framework introduced above, modeling is necessary to understand drivers and improve the accuracy of forecasting. Moreover, modeling based on a deep understanding of a system can lead to new and effective ways to control the system through the so-called causal chain (Grosskurth 2007). The practical importance of modeling studies is found in this function. However, ability in modeling does not equal controllability of the system. The system becomes controllable only when the input of the model is controllable. Synthesis to design and provide solutions involves difficulties unlike those found in analysis. Morioka et al. (2006) discussed the necessity of a dynamic innovation system for sustainable development that adopts a highly solution-driven approach using backcasting techniques based on long-term visions and mid-term strategic goals. Perrings (2007) stated that the principal challenge in sustainability science is the development of predictive models of system change that enable society to evaluate mitigation options alongside adaptation.

Summarizing the above discussions, we can identify the following basic components of sustainability science:

- Goal setting
- Indicator setting
- Indicator measurement
- Causal chain analysis
- Forecasting
- Backcasting
- Problem–solution chain analysis

Goal setting is a normative process based on visions and social and political processes rather than on scientific activity per se, but it should have some rational basis. In this regard, Martens (2006) suggested the following paradigm shifts from existing disciplines that sustainability science should have: from supply-driven to demand-driven, from technocratic to participant, from objective to subjective, from predictive to exploratory, and from certain to uncertain. These characteristics highlight the importance of the issue-driven approach of sustainability science. Through this approach, science can contribute to goal-setting by supplying information for public debate with the aim of formulating rational consensus and supporting deliberative democracy (Åström 2001). Thus sustainability science can help select prior targets by providing scientific data obtained in an explicit and open manner. Leveling out climate change is the most common target, but it is not the sole target. Kates and Parris (2003) review trends in a variety of targets for sustainability, including peace and security, population change and patterns, production and consumption, globalization, governance and institutions, affluence and poverty, well-being, and global environmental change. We must also note that global climate change may become a focal point of international politics

and increase tensions and conflicts between countries (Lie 2007). War, conflict, crime, and corruption are also major threats to a sustainability transition in myriad ways (Kates and Parris 2003). Despite this fact and its obvious importance, the issue of national security/cultural conflict is rarely studied in sustainability science, but it is one that we must address.

Indicators can play an important role in measuring, assessing, and informing the extent to which we move toward a goal or away from it. Different indicators are needed to evaluate our various sustainability foci, such as health, well-being, economic activity, the ecosystem and its function. In certain cases, a mix of indicators is necessary to effectively work toward a goal, even within a single sustainability focus. To advance sustainability as a science we must develop new, efficient, and effective indicators that are optimally suited to our purposes. A recent example of research in indicator building is the national climate change indices developed by Diffenbaugh et al. (2007).

Measurement of indicators is usually performed by a variety of methods, including aggregating economic data or questionnaires, remote-sensing data, experimental data, and so on. Rindfuss et al. (2004) stressed the importance of measurement of micro-level data with detailed spatial-temporal resolution. The issues associated with sustainability differ on both temporal and spatial scales, and micro-level data are necessary to understand the behavior of the coupled human–environment system. Because analysis at the aggregated level cannot deduce a theory at the disaggregated level (Robinson 1950), the level of aggregation in measurement needs to match the level to be examined. More importantly, through micro-level data, local people can be provided with regional data, enabling them to think of sustainability as their affair, change their behavior, adapt to change, and select mitigation and adaptation options.

Analysis of causal chains is a fundamental scientific activity. Causality is the relationship between causes and effects. A cause is in turn controlled by other causes, and we can regard this as a causal chain. Indicator measurements are an indispensable step; however, descriptions offer little guidance for action and do not say what is a cause and what is an effect (Kates and Dasgupta 2007). By analyzing the relationships between qualitative and quantitative variables, precedence conditions, and underlying mechanisms, we can induce or deduce causality. Analysis must take into account the broad range of factors that shape outcomes, not only identifying the most important factor (Ascher 2007). More than identifying the most important factor, it is necessary to identify the conditions under which a factor becomes the most important.

Forecasting is a descriptive approach to predicting the future based on retrospective data from past to present. By

extrapolating current trends to the future, we can predict future trends and obtain a prospective perspective. Modeling increases accuracy in forecasting. Scenarios are also used for forecasting by setting certain drivers to change trends.

Backcasting is a normative approach to the realization of a goal by working backward to show pathways between the goal and the present status. While forecasting is evidence-based, backcasting is vision-driven. Here, the approach of transition management may prove useful (Kemp and Martens 2007). While the forecast approach starts with the current situation, identifies paths into the future, and chooses one path for a scenario, the backcast approach starts with the current situation and a desirable future state based on defined parameters, then deduces possible future paths (Morioka et al. 2006). In backcasting, drivers changing trends are subjective, based on our will, not objective plausible scenarios. After setting medium- and long-term goals, mismatches between forecasts and backcasts are analyzed, and short- and long-term plans and policies are then aligned to realize the path set by backcasting.

In order to establish a path for future sustainability, problem–solution chain analysis is essential. Mulder (2007) discussed the importance of backscattering to sustainable development and the role of innovation. One problem unique to sustainability science lies in the process of shifting from the stage of phenomena identification and analysis to that of problem solving (Komiyama and Takeuchi 2006). For sustainability science, this process necessarily differs from the conventional transition from basic to applied research, because solutions to problems may have to be sought before those problems have been sufficiently analyzed or even identified. Global warming is the prime example of this dilemma. We must note that analysis of the problem–solution chain is not the same as analysis of the causal chain. When input determines output, there is a causal relationship between them, but it is not always the case that input is controlled. We must also note that there are no panaceas. A core aspect of panaceas is the tendency to apply a single solution to many problems (Ostrom et al. 2007). Plausible solutions are dependent on the temporal and spatial scale. If we fail to be vigilant, we can become trapped by an inclination to apply panaceas regardless of the circumstances (Brock and Carpenter 2007). Many papers have proposed a variety of solutions to the problems they address. When there is a solution, the problem is already solved or will be easily solved. When a problem remains, we can infer that solving the problem is hampered by certain obstacles, that is, the existence of other problems. Therefore, understanding the problem–solution chain is necessary to truly solve the root problem. Evaluation of the feasibility and unintended results of

plausible solutions is a subtask of this problem–solution chain analysis.

Concluding remarks

In this paper, we analyzed and organized papers published in three selected core journals of sustainability science: *Sustainability Science*, *Proceedings of the National Academy of Sciences of the United States of America*, and *Sustainability: Science, Practice, & Policy*. We organized them into three categories: sustainability and its definition, domain-oriented research, and a research framework for sustainability science. First, we provided a short history and defined the basic characteristics of sustainability. We then reviewed current efforts in each of the following domains: climate, biodiversity, agriculture, fishery, forestry, energy and resources, water, economic development, health, and lifestyle. This categorization was devised heuristically rather than by a well-founded schema, but we hope it offers a certain perspective on the current status of research in sustainability science and promotes further discussion of what we should study in the future. Finally, we proposed a research framework for sustainability science based on existing discussions. The value of any framework is not in its elegance or cleverness, but rather in its utility in yielding insights that otherwise might not emerge. Thus, a fair test of a framework's usefulness for guiding policies to enhance sustainability is whether some "value added" comes about from applying the framework (Ascher 2007). The framework will be tested and improved as sustainability science and its transdisciplinary activities proceed. In concluding this paper, we discuss anticipated roles and obstacles for sustainability science.

The first contribution of sustainability science is its problem-solving perspective. Komiyama and Takeuchi (2006) stated that a problem unique to sustainability science is the process of shifting from the stage of phenomena identification and analysis to that of problem solving. But the commitment of sustainability science to a problem-driven agenda setting does not mean that we should focus only on applied research. To attain a goal we must also seek a fundamental understanding of the system as well as solutions. Indeed, the pursuit of practical solutions to the pressing challenges of sustainability has driven the field to tackle an array of fundamental questions (Clark and Dickson 2003). We must keep employing a problem-solving perspective, without which elucidation of the deep structure underlying the system cannot be attained.

Currently, scientists engaged in sustainability science tend to focus on the social and political aspects of solutions. O'Connor (2006) added a fourth element to the three-pillar model: the political system, which is constituted

through the emergence within society of conventions, rules, and institutional frameworks for the regulation of the economic and social spheres and, indirectly, the environmental sphere. The role of scientists when assisting policy development should be to provide the best evidence available as information for the development of policy, to help monitor the effects of current policies, and to provide solutions to unexpected events and policy failures (Lyytimäki and Hildén 2007). We should study social and psychological perspectives as well as the technological. Ascher (2006) stated that the shift from strictly economic and ordinary policy levels to constitutive, institutional, and psychological levels is a very important expansion. This effort must combine psychology, economics, institutional design, legal studies, political science, and other social sciences. For example, Allenby (2006) discussed the role and importance of macroethics. But we must also keep in mind that these social, political, psychological, and economic studies usually lack an elucidation of obstacles to solutions. If these are real solutions, why have they not been adopted and already solved the problem? It is clear that we must elucidate the deeper structure of problem–solution chains to recognize the essential issues that hamper the realization of solutions. This is not limited to sociopolitical solutions; obstacles to the technological solutions discussed in each domain are also seldom reported. Although proposing solutions from a different perspective from those of existing disciplines is a necessary role of sustainability science, it is also important to gather solutions proposed in those disciplines, to structure the current relationships among them, and to elucidate obstacles and problem–solution chains. These points are precisely those we should address as part of sustainability science, even if this still happens all too rarely. Engineering research is clearly needed to provide plausible solutions, but has yet to play a prominent role in sustainability science. Research on research is also necessary to collect and structure the problem–solution chains reported in fragmentary fashion in different research papers.

Another important role of sustainability science is the distribution of knowledge to society through communication among experts, decision-makers, and the rest of us (Sumi 2007; Brewer 2007; Brand and Karvonen 2007). Many studies reveal that the participation of diverse stakeholders in setting and implementing solutions is indispensable. As science and technology advance, knowledge tends to become centralized; in other words, essential information and knowledge tend to be monopolized by a particular group. Government actions are usually discussed among specialists, i.e., scientists, bureaucrats, and politicians. Their decisions are then reported to the public through the media. When we are informed only of results after the fact, we are less likely to

be convinced of their necessity, merits and origin. This tends to cause suspicion among citizens about government decisions, and this suspicion is an obstacle to the achievement of consensus in society. Consequently, outreach activities and information sharing are crucial. In addition to pursuing basic research, we must therefore also focus on education so as to foster a diversity of experts. Examples include the outreach expert who communicates effectively to non-experts, the interdisciplinary expert who understands the overlap of neighboring technical disciplines, the meta-expert who brokers multiple claims of relevance between different forms of expertise, and the civic expert who engages in democratic discourse with non-experts and experts alike (Brand and Karvonen 2007). We must use education and outreach to inform people of the current and future status of sustainability issues, to motivate them, to create the social context for action, and finally to move our society to action for sustainability (Koehler and Hecht 2006).

Further research is needed to keep the knowledge base growing and to ensure that sustainable development becomes ever more effective (Wilderer 2007). An ever-growing base of knowledge is necessary because new developments will bring new risks that cannot be anticipated and sustainable development is a long-term, open-ended project (Kemp and Martens 2007). But, as the body of academic and scientific research continues to grow, the disciplines engaged in this research will continue to fragment. As the knowledge base grows and fragmentation proceeds, it will become almost impossible for the individual researcher or research group to gain access to and utilize this vast accumulation of data and knowledge (Komiya and Takeuchi 2006). Therefore, it is necessary to promote the collection and availability of high-quality data for sustainability indicators in addition to the development of appropriate new indicators (Koehler and Hecht 2006). All relevant data should be available and communicated in a clear and accessible form, including information that highlights the uncertainties associated with the scientific evidence. We also need to construct a framework within which individual disciplines can provide quantifiable criteria and indicators related to sustainability. Structuring issues and knowledge about causal chains and problem–solution chains is also an essential point to be addressed. New publication formats such as structured abstracts and structured keywords may be necessary (Kajikawa et al. 2006). By integrating these, we can structure our data and knowledge and the issues we address.

Although the interdisciplinary, multidisciplinary, and transdisciplinary nature of sustainability science has the capacity to provide fruitful outcomes to society in a manner that existing disciplines have not, it also faces some difficulties. Kostoff (2002) pointed out eight general difficulties

in performing interdisciplinary and multidisciplinary work: culture, time, evaluation, publication, employment, funding, promotion, and recognition. Some of these difficulties hold true for sustainability science. Indeed, in a survey, scientists engaged in sustainability research responded that major obstacles to sustainability research are: low financial support (68%), differing priorities (63%), lack of interdisciplinary cooperation (50%), lack of publicity (47%), and a diffuse understanding of the term “sustainability” (42%) (Kastenhofer and Rammel 2005).

Some of these circumstances may be improving, but others are not. Employment in the field is not sufficient to form a distinct discipline. Burns et al. (2006) pointed out that a general feature of many centers of sustainability science is the relatively small size of their tenured leadership and core administrative teams. Research teams of variable size are assembled on a project-by-project basis and comprise a few leaders with insight into and political connections with sustainable development issues, and team members who maintain their specialist skills within various disciplinary home bases. Necessary preconditions are mutual motivation for cooperation, mutual awareness of the limited contribution that single disciplines can make to problem solution, and a mutual ability to cooperate and communicate successfully across these boundaries (Kastenhofer and Rammel 2005).

Sustainability research has struggled with structural barriers that are specific to each scientific discipline. But publishability now seems to be improving insofar as we now have journals dedicated to sustainability. Research on sustainable development relies on the crossing of boundaries between disciplines, as well as those between science and society. When conducting interdisciplinary research, publishability is usually a problem, because each discipline has its own validation boundary (Fujigaki 1998; Fujigaki and Leydesdorff 2000). One solution to promoting publishability is to eliminate the validation boundary, but this is not feasible because sustainability science is, after all, a science, and we must offer a scientific basis for the complex problems of sustainability. Therefore, we must promote publications with credibility, salience, and legitimacy. Where credibility involves the scientific adequacy of the technical evidence and arguments, salience deals with the relevance of the assessment to the needs of decision-makers; legitimacy reflects the perception that the production of information and technology has been respectful of stakeholders’ divergent values and beliefs, unbiased in its conduct, and fair in its treatment of opposing views and interests (Cash et al. 2003). The core journals of sustainability science are expected to play this vital role.

There is an ongoing debate on the relationship between sustainability science and other scientific disciplines, and on the point of whether sustainability science should be

labeled a distinct discipline or not. Some might even regard sustainability science as a political agenda disguised as a scientific field of research. But more important than such debates is the accomplishment of scientific work on issues of sustainability and whether it is respected or not. Much effort in the past has been put into the debate over what constitutes a discipline and the effort to stress the trans-disciplinary nature of this science and the importance of outreach activity, as summarized in this overview. But the first thing we should do is to achieve fruitful outcomes through scientific research itself, and then publish the results to disseminate them in society. This will lead to a positive feedback loop of high quality research in sustainability science, publishability of the research output, its dissemination, recognition of and respect for sustainability science as a scientific discipline, provision of admissible data as evidence in litigation (e.g., regarding environmental laws and regulations), a growing share of funding, employment, and education, and ultimately the attainment of sustainable global, social, and human systems.

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