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Four Major Task Domains of Science for Sustainability

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Abstract

We propose a research agenda integrating environment-related science, technology, and innovation (STI) using a problem-solving approach to sustainable development. We argue that STI for sustainability encompasses four major task domains: (1) ecological modernization and transformation, (2) ecosystem management, (3) environmental risk assessment, and (4) adaptation to environmental change, each posing great social challenges. For each domain, nature–society interaction increasingly relies on knowledge acquisition. The proposed agenda focuses on the investigation of R&D capacity and linking knowledge and action within and among societal spheres (i.e., science, politics, business, law, mass media, and education). While today the disciplinary niches of environment-related STI research are still fragmented, with this broader framework, STI research could develop into a major social science field of human–environment relations.

Keywords: human dimensions of global environmental change; environmental sociology; science for sustainability; STI research; innovation research; social studies of science; sociology of knowledge; nature–society interaction; noosphere; ecological modernization; ecosystem management; environmental risk assessment; adaptation to environmental change

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1. Introduction

The term "anthropocene" characterizes the current geological age in which humanity is a strong driver of change in the Earth system. Most ecosystems are now dominated by the human species (Turner II and McCandless, 2004; Vitousek et al., 1997). The accelerating pace of global environmental change is accompanied by an increasing requirement of knowledge on nature–society interaction. The Russian geochemist Vladimir Vernadsky coined the term "noosphere" to highlight the fact that human cognition is significant on the geological level (1945). Conversely, when social systems approach the limits of ecological carrying capacity, these systems require more information and more efficient practices to monitor and maintain services that we derive from natural systems (ecosystem services). Science, technology and innovation (STI) are increasingly being reframed as part of our capacity for sustainable development (Cash et al., 2003; Clark and Dickson, 2003). While progress in knowledge and technology alone is not sufficient to solve the sustainability crisis, there is no doubt that STI has an important role in our achieving targeted sustainable development paths (Berkhout and Gouldson, 2003).

STI research is used here as a term for research on economic, political, sociological, historical, and cultural dimensions of STI in society. The growing importance of knowledge and information (knowledge intensity) for monitoring and maintaining ecosystem services suggests that STI research should devote more effort to questions of nature–society interaction. Yet the relevant parameters of this knowledge have not been delineated in a way that presents a systematic agenda for STI research. The objective of this paper is to present a conceptual map of the knowledge required for achieving sustainability goals. We outline a comprehensive programme that links different topics in environment-related STI research and helps to identify gaps in current understanding. STI research, in our opinion, can evolve into a major social science field of human–environment relations, and we would like to engage in a broader discussion of this potential, with our proposed framework as a starting point.

The challenge of sustainable development is, according to Clark and Dickson (2003: 8059) "the reconciliation of society's development goals with the planet's environmental limits over the long term". A fruitful perspective for sustainability-oriented STI research exists in the investigation of problem-solving capacity (cf. Jacob and Volkery, 2006; Jänicke et al., 1999). This perspective includes problem-solving in science and technology proper, as well as a focus on the coupling of knowledge and action between different spheres of society, i.e., science, business, politics, law, mass media, and education. The coupling of knowledge and action is essential for environmental innovation and social learning and includes the analysis of obstacles to progress in the direction of sustainable development.

There has been a tendency on the part of environmental historians and social scientists to conceptually divide the social construction of knowledge and social discourse about nature from the "material interaction" of humans and their environment which is related to natural resource consumption (e.g. Buttel et. al., 2002, Cronon, 1990). We believe that this separation is flawed and artificial because large portions of relevant knowledge are embedded in the ever more sophisticated technologies used to transform natural resources through the economic processes of production, transport, consumption, and waste disposal; this connection between knowledge and action belies the proposed conceptual divide. In general terms, the knowledge required for a sustainability transition comprises both (a) knowledge about natural systems and anthropogenic changes in these systems and (b) technological knowledge because technologies determine the flux of material and energy, which in turn affects natural systems. The term "material interaction" is inadequate for complex economic processes and should be used only in the more narrow sense of material and energy flows. This can be demonstrated with the help of the "ecological interaction chain".

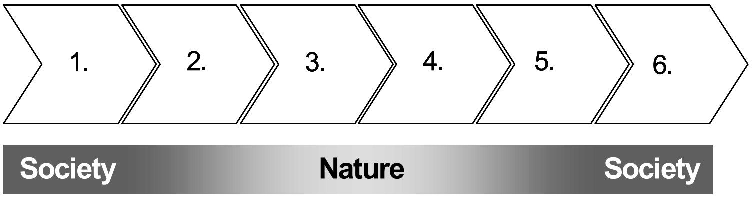
This paper starts with the concept of an "ecological interaction chain", (section 2). We distinguish four domains of problem-solving by their respective focus on this ecological interaction chain: ecological modernization and transformation (2.1), ecosystem management (2.2), environmental risk assessment (2.3), and adaptation to environmental change (2.4). Each domain encompasses the problem-solving capacities of natural sciences, engineering disciplines, and social sciences in various combinations. The proposed agenda for STI research involves observation and analysis of the societal problem-solving capacity in each of these domains (section 3). Together, the four domains present a coherent outline of sustainability related STI issues to address at the beginning of the 21st century.

2. Task domains of STI for sustainability

The "ecological interaction chain" is a generalized representation of the causal linkages between society and nature. This scheme was originally developed by William Clark and colleagues in the context of research on hazard management (Clark et al., 2001: 10ff.). The chain consists of six causal steps, as described in Figure 1. A similar concept of a causal interaction chain is used in the well-known DPSIR framework. DPSIR stands for driving forces, pressures, states, impacts and responses (http://glossary.eea.europa.eu/EEAGlossary/D/DPSIR). However, Clark's scheme is more amenable to the purposes of STI research because it cites technology as a causal linkage and makes more explicit use of social concepts (such as demand, choice, practice, valuation, and vulnerability).

In the past, many environmental sociologists and historians divided knowledge and communication about nature from "material" relationships of humans and their environment (e.g. Buttel et al., 2002; Cronon, 1990). With the help of the ecological interaction chain, we propose to show that STI research requires a very different approach. Rather than artificially separating anthropogenic modifications of natural systems from knowledge and discourse, we use the interaction chain to distinguish four domains in terms of problem content while including both physical relationships and knowledge. Each domain demarcates a suite of problem-solving tasks involving knowledge creation, technological development, innovation, and related social discourse for sustainability, and each covers a certain section on the interaction chain. These four "task domains" are labelled: (1) ecological modernization and transformation, (2) ecosystem management, (3) environmental risk assessment, and (4) adaptation to environmental change.

Figure 1 The causal chain of nature–society interaction[1]



(1) *Demand for goods and services:* The causal chain starts with human demand. This comprises demand for artefacts and services created by society, as well as demand for natural resources and ecosystem services.

(2) *Choice of technologies and practices:* Humans develop and employ technologies and practices to satisfy demand. Technologies are embedded in institutions and infrastructures.

(3) *Flux of materials and energy:* Depending on the choice of technology, practice and location, flows of materials and energy occur (extractions and emissions).

(4) *Environmental properties and ecosystem services:* Anthropogenic flows alter the flux of material and energy in the geosphere and biosphere. The modification is not confined to direct effects but includes catalytic reactions, e.g., the greenhouse effect of CO_2 emissions, as well as the removal or addition of biological agents, such as the introduction of alien species. These modifications affect environmental properties and ecosystem services.

(5) *Vulnerability to risks of environmental change*: Change in the behaviour of natural systems may have unintended consequences for people and the things they value. Vulnerability is the differential susceptibility to damage from hazards and environmental change.

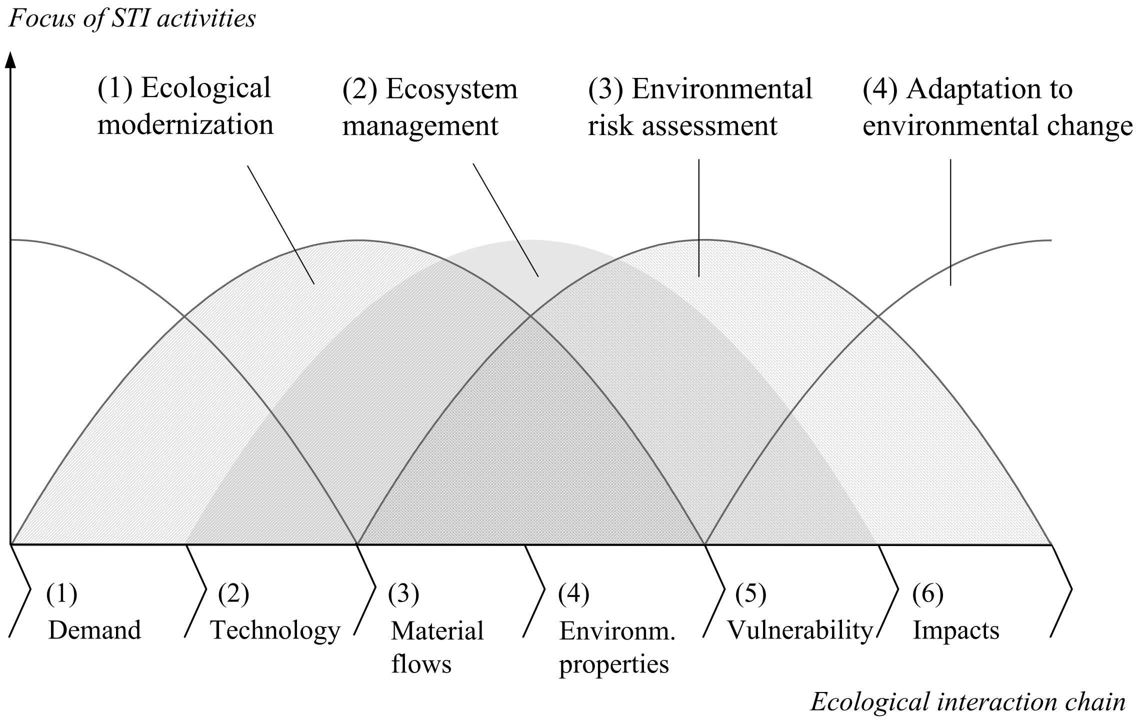
(6) *Consequences to people and things they value:* Mediated by their vulnerability or resilience, people are subject to the adverse consequences of changing environmental conditions. The chain may be conceived as a closed loop because many impacts of environmental change cause shifts in human demands (step 1).

1 The causal chain is adapted from Clark et al. (2001).

The basic idea displayed in Fig. 2 is that different task domains of STI for sustainability investigate different causal links of the ecological interaction chain. Research and development (R&D) often does not deal with all steps of a complex causal chain simultaneously but concentrates on selected causal links. This focus on specific causal relations is represented in Fig. 2 as the maximum of a schematic distribution curve. The idealized distribution shows that each task domain is focused on a specific causal link, while also considering links with the preceding and the subsequent causal step. For example, the focus of research in the domain of "ecological modernization and industrial transformation" (domain 1) is on "technologies and practices" (step 2) and the resulting "flux of materials and energy" (step 3). The causal connection between the design and choice of technologies and the resource efficiency and emissions of technical processes is at the core. More peripherally, the task domain also includes research on the conditions of "human demand" (step 1), which determine the choice of technologies, and on "environmental properties"(step 4), for example the CO_2 concentration in the atmosphere. In contrast, issues of vulnerability (step 5) and consequences of environmental change (step 6) rarely figure prominently in R&D for ecological modernization. The four domains shift in relation to each other.

STI capacity is an essential part of society's overall capacity for sustainable development. The four task domains help to gain a more systematic view of respective STI problems and capabilities. Such an overview is useful for STI research. Fig. 2 is based on an extensive review of current STI research topics in the areas of environmental innovation research, environmental sociology, and social studies of science, history of environmental sciences, and research in the human dimensions of global environmental change. However, the content of each domain is much broader, encompassing knowledge from natural sciences, engineering and social sciences. The scheme as such does not distinguish internal subdivisions of nature (e.g., geosphere–biosphere, ocean-atmosphere-land, or ecosystems) or society (e.g., actors, social groups, social arenas, or social systems). Thus, neither natural nor social science constructs are singled out in a fundamental way.

Figure 2 Task domains of STI for sustainability



Source: author

Fig. 2 visualizes the role of knowledge in nature-society interaction. Four domains of science, technology, and innovation (STI) for sustainability are distinguished (task domains). Research in different task domains focuses on different causal links of the ecological interaction chain (horizontal axis). This focus of STI activities is represented as the maximum of an idealized distribution curve (vertical axis). A detailed description of the ecological interaction chain is given in Fig. 1.

Using examples, Table 1 shows how STI capacity can be disaggregated for the purposes of empirical study. We distinguish between R&D capacity and the societal capacity to link knowledge and action. R&D capacity encompasses (a) the cognitive and technological capabilities which are defined by scientific theories, methods, data, instruments, models, terminologies, and practices of a research field (b) the scientists, engineers, and social scientists; (c) the financial resources allocated to R&D; and (d) private and public R&D organizations dedicated to the area of interest. R&D capacity is commonly subdivided by S&T fields or disciplines, although it may also refer to multidisciplinary problems (first row in Table 1).

Defining the societal capacity to link knowledge and action is less straightforward. Each task domain represents challenges of sustainable development, which means that the task is derived from a societal perspective and not confined to research and development alone. The challenge for STI research is to investigate the interplay between scientific and technical developments with capabilities for environmental action in other realms of society. The coupling of science and other functional social systems, primarily business, politics, law, mass media, and education, is still an under-researched field in contemporary sociology (Heinze, 2006; Luhmann, 1995; Weingart, 2001). Table 1 presents a selection of societal categories that appear particularly useful for the study of problem-solving capacity in this broader sense, without being comprehensive (second row in Table 1). These examples are also further elaborated in sections 2.1–2.4 below.

Table 1 Disaggregation of task domains for the study of STI capacity (selected examples)

STI Task Domain	**(1) Ecological modernization**	**(2) Ecosystem management**	**(3) Environmental risk assessment**	**(4) Adaptation to environmental change**
R&D capacity	- Development of green technologies **- *S&T fields***, e.g., engineering, industrial ecology, environmental economics, political sciences	- Knowledge of ecosystems and management practices **- *S&T fields***, e.g., ecology, soil sciences, agronomy, marine & freshwater biology, sociology, anthropology	- Knowledge of environmental risks and management options **- *S&T fields***, *e.g.,* atmospheric sciences, meteorology, hydrology, ecology, epidemiology, social sciences	- Knowledge of impacts and response options **- *S&T fields***, e.g., climate sciences, agronomy, hydrology, medicine, economics, migration studies
Capacity to link knowledge and action	***- Economic sectors*** e.g., energy, mining, construction, transport, production industries, waste management ***- Socio-technical regimes*** e.g., automobile, personal computer, nuclear energy, large technical infrastructures as for communication, water, electricity, gas - ...	***- Economic sectors*** e.g., agriculture, fishery, forestry, water management, ecotourism, ecosystem restoration ***- Environmental regimes*** e.g., agricultural subsidies, river basin management, exclusive economic zones in the sea, nature protection - ...	***- Risk communication and policies*** e.g., acid rain, stratospheric ozone depletion, climate change, biodiversity loss ***- Vulnerable groups or regions*** e.g., people on small islands or near coasts, underprivileged people, vulnerable age groups, -…	***- Economic sectors*** e.g., insurance & reinsurance, construction, water management, energy, agriculture, biotechnology ***- Markets*** e.g., natural resources, emission rights, technical substitutes for ecosystem services, changing consumer demands - ...

A focus on social challenges and problem-solving inevitably introduces normative dimensions to STI research. Because there is no forceful social consensus on how to attain a "sustainability transition" (Parris and Kates, 2003), a certain danger exists that sustainability-oriented STI research would become so politicized that it would lose scientific credibility. On the other hand, STI research can offer valuable contributions to identifying and implementing feasible next steps. In any case, the recognition of normative dimensions in STI research does not necessitate suppression of the empirical diversity of actors' views on what constitutes environmental problems and viable solutions in different social contexts. There are some good models in the literature for the treatment of normative dimensions in studies on the application of knowledge to social problems. For example, Clark and colleagues (2001) recommend the use of metacriteria. These are "criteria for evaluating efforts to link knowledge with action" and have been summarized under the headings of "adequacy, value, legitimacy, and effectiveness" (definitions of criteria p. 15). According to the authors, this approach offers an "uneasy middle ground" between "imposing on our empirical material a rigid normative framework of our own making" and "giving up on the normative discussion by simply assuming that all outcomes are equal" (ibid: 14). Because normative aspects can rarely be circumvented altogether in research on progress for sustainability, addressing them explicitly is certainly advisable.

We contend that the four task domains together give a comprehensive picture of STI in nature–society interaction, on a high level of aggregation. The schematic distribution in Fig. 2 does not express quantitative estimates for the respective knowledge demand or output, which are questions for empirical study. Rather, our purpose is to provide a cognitive map for diverse STI research topics that are currently often fragmented by the boundaries of traditional disciplines such as economics, political sciences, sociology, engineering sciences, and Earth and environmental sciences. We argue that problem-solving capacity is suited to providing a common framework for STI research on nature–society interaction. Among all four domains, probably the largest share of current STI literature can be classified under the categories of ecological modernization and transformation, and there is a substantial amount of mainly sociological literature on topics of environmental risk assessment. Even a cursory review of the STI research literature shows that these two domains have received far more attention by social scientists than have ecosystem management and adaptation to environmental change. In this sense, our aim is not only to systematize current research topics but also to highlight upcoming and comparatively neglected themes.

The following sections (2.1–2.4) explain the content of the four STI task domains in more detail. Each section gives a definition and refers to selected literature in STI-related research. Most contributions come from a background in innovation economics, political science, and sociology, and some from history. An example illustrates the "task" in each domain. These illustrations are taken from engineering sciences (2.1), ecology (2.2), social sciences (2.3), and climate research (2.4).

2.1. Ecological modernization and transformation

The defining task of the first STI domain is to reduce the environmental impacts of socio-economic metabolism and to disconnect growth of the economy from natural resource consumption. Correspondingly, the focus of knowledge creation is on the choice of technologies and practices and the resulting flux of material and energy (Fig. 2). This focus is explicit in the definition by Martin Jänicke:

Ecological modernization" refers to the wide spectrum of environmental improvements that can be attained through technical innovations beyond end-of-pipe approaches (Jänicke, 2004: 201).

"Environmental innovation" means the invention, adaptation, and diffusion of new technologies, products, and practices that are beneficial for the environment, and includes both radically new solutions and incremental improvements.

> Modernisation, in economic terms, is the systematic, knowledge-based improvement of production processes and products. The urge to modernise is a compulsion inherent in capitalistic market economies, and the increasing competition for innovation in industrialised countries has led to the continuing acceleration of technological modernisation. (…) The task is therefore to change the direction of

technological progress and to put the compulsion for innovation at the service of the environment (Jänicke, 2006: 11).

Strategies of ecological modernization emphasize the exploitation of environmental–economic win–win situations where gains in eco-efficiency are connected with enhanced competitiveness at the level of firms, industrial sectors, or national economies (Porter and van der Linde, 1995; Taistra, 2001). Ecological modernization includes improving the management of material and energy flows in production processes as investigated by "industrial ecology" (Daniels, 2002; Haberl et al., 2004). These efficiency-oriented modernization strategies are distinguished from deep change in technological and economic structures. "Industrial transformation" or "transition" refers to the adoption of radically different technological development paths, or "radical changes at the level of socio-technical regimes" (Smith et al., 2004: 113). As Jänicke stated, "Problem-solving in the form of ecological restructuring affects systems of behaviour which – irrespective of technical eco-efficiency improvements – stand out by their high environmental intensity" (2005: 205).

There are few explicit treatments of R&D capacity for ecological modernization and transformation (cf. Legler et al., 2006), but there are feasibility studies of modernization strategies which make assessments of current technological capabilities. An example, described below, is provided by the Swiss study on a "2000 Watt per capita industrial society" (Jochem et al. 2004). Inventions on the part of engineering sciences play a central role in ecological modernization, where they contribute to the development of greener technologies. Yet technological developments are too often treated separately from the economic and political aspects of modernization capacity. This observation leads us to the question of how the dynamics of knowledge and action have been conceptualized for this domain (Table 1).

STI capacity is part of society's broader capacity for sustainable development. Policy analysts have shown that in the absence of strong price signals on resource markets (e.g., high oil prices), "eco-innovations invariably require political support" (Jänicke and Jacob, 2006: 12). Yet although the relationship between firms' innovativeness and environmental policy has been a topic of some debate among economists and political scientists (Hemmelskamp et al., 2000; Klemmer, 1999), there is little systematic research on capacity building for environmental innovation. We believe that economic and socio-technical meso-scale concepts, such as economic sectors or socio-technical regimes, are useful tools for the combined analysis of technological, economic, political, legal, and other social aspects. Inspired by Malerba's definition of sectoral innovation systems (Malerba, 2004), economic sectors are understood here to delineate a combination of technologies, actors, and institutions that is relatively stable over timescales of years to decades. Compared to sectors, the notion of socio-technical regimes is geared to the study of more dynamic shifts or transitions in technology (Berkhout et al., 2005; Kemp and Loorbach, 2006, Elzen et al., 2005). "Socio-technical regimes are relatively stable configurations of institutions, techniques and artefacts (…) that determine the 'normal' development and use of technology in order to fulfil socially-determined functions" (Smith et al., 2004: 114). The concept is also applied to large technical infrastructures, such as those for traffic, communication, water, or energy (Konrad et al., 2004; Markard and Truffer, 2006). On the basis of these and similar ideas, a more explicit and detailed approach to the study of modernization capacity could be developed.

2.1.1 Example of of ecological modernization and transformation: energy efficiency

Energy efficiency is an example of ecological modernization and restructuring that cuts across economic sectors. The scope of the efficiency challenge was recently specified by the vision of a "2000 Watt per capita industrial society", advanced by the board of the Swiss Federal Institutes of Technologies (Jochem et al., 2004). An energy demand of 2000 Watt, or 65 GJ, per capita per year, equals one-third of today's per capita primary energy use in Europe. Assuming a 70% increase of GDP (gross domestic product) per capita by 2050, the challenge of a 2000 Watt/cap society is to improve energy efficiency by a factor of five. According to the study, an efficiency increase on this order of magnitude is technically feasible within five decades.

The authors maintain that pertinent sectoral interest groups and political actors are still not sufficiently aware of the economic opportunities and co-benefits of a shift towards resource efficient development paths. In particular, there is a conspicuous lack of strategic energy and STI policies. Energy-related R&D is still focused on the supply side, i.e., on the efficiency of conversion steps from primary to useful energy and on renewable energy sources. By contrast, the saving potentials of the demand side are often neglected, i.e., the reduction of the demand for useful energy per energy service (e.g., through low-energy buildings or lightweight vehicles) and options to reduce or substitute certain energy-intensive uses (e.g., energy-intensive materials, motorized mobility). Overall efficiency gains of 60%–80% are deemed feasible in the aggregated demand sectors of industry, transportation, residential uses, and commerce, public, and agriculture. In total, reducing energy intensity is the most underestimated option in the face of the pending peak of oil production and the need to reduce CO_2 emissions (Jochem, 2004).

The authors conclude that both energy and climate policy should be redefined as part of an innovation policy that is essentially sustainability-driven. "The transition to a 2000 Watt per capita industrial society would need the support of a fundamental change in the innovation system (e.g., research policy, education, standards, incentives, intermediates and entrepreneurial innovations" (Jochem, 2006: 268, italics added).

2.2. Ecosystem management

The central task of the second problem domain is the long-term maintenance of essential ecosystem services. Palmer et al. (2004: 1253) stress that "our future environment will largely consist of human-influenced ecosystems, managed to varying degrees, in which the natural services that humans depend on will be harder and harder to maintain." The concept of ecosystem management does not refer only to the harvest of specific natural resources, such as agricultural produce, but also includes our total dependency on natural systems. The Millennium Ecosystem Assessment distinguishes the following ecosystem services:

"An ecosystem is a dynamic complex of plant, animal and microorganism communities and the nonliving environment interacting as a functional unit. (…) Ecosystem services are the benefits people obtain from ecosystems. These include provisioning services such as food, water, timber, and fibre; regulating services that affect climate, floods, disease, wastes and water quality; cultural services that provide recreational, aesthetic, and spiritual benefits; and supporting benefits such as soil formation, photosynthesis, and nutrient cycling. The human species, while buffered against environmental changes by culture and technology, is fundamentally dependent on the flow of ecosystem services" (Millennium Ecosystem Assessment, 2005: v).

The growing human influence on the planet's ecosystems is accompanied by an increasing knowledge intensity of ecosystem management. R&D capacity refers to the scientific understanding of ecosystem functioning and to the development of more sustainable management practices (Fig. 2). More knowledge is required not only to intensify the harvest of targeted services, as in agriculture or fisheries (see example below), but also increasingly to avoid degradation or collapse of valuable functions and for ecosystem restoration. Topsoils offer a good illustration of this growth in knowledge intensity. Although some techniques to combat erosion and nutrient depletion have been practiced since ancient times, today’s soil scientists claim that "soil ecosystems are probably the least understood of nature's panoply of ecosystems and increasingly among the most degraded" (McNeill and Winiwarter, 2004: 1629). Desertification, erosion, salinization, pollution, sealing, compaction, and nutrient depletion of soils restrict agricultural production in many regions worldwide (Anon., 2004: 1614f.). The U.S. Geological Survey in cooperation with agencies in the U.S., Canada, and Mexico recently initiated a project with the long-term goal of a continental-scale soil geochemical survey of North America. This project has been long awaited by scientists who maintain that soils "are a sponge for pesticides and other nasty compounds filtering down from the surface", but have "only a sketchy idea of how the ground copes with this toxic trickle" (Proffitt, 2004: 1617). More generally, an important element of R&D capacity consists of technologies and observation networks to monitor natural system behaviour.

Compared to the domain of ecological modernisation and transformation, there is much less STI research on the dynamics of knowledge and action in ecosystem management. One way to look at this empirically is through economic sectors that centre on the management of renewable resources (Table 1). A sectoral approach is not confined to agriculture, forestry, and fisheries but involves many other sectors dealing in different ways with ecosystem services, including management of freshwater, urban planning and construction, control of pests and diseases, tourism, and nature reserves. Again, economic sectors are understood here to encompass a set of socio-technical practices, a set of diverse actors, including firms, regulating agencies, research organizations, and diverse stakeholder groups, as well as institutions and policies that influence actors' behaviour and the evolution of technologies.

To some extent, the domains of ecosystem management and ecological modernization overlap in a sectoral perspective. For example, intensive agriculture and fishery depend on cheap fossil fuels, and agricultural innovation systems could be vastly improved in terms of material and energy efficiency (Clark, 2002; Pauly et al., 2003; Raina et al., 2006). Yet ecosystem management typically requires specific knowledge of natural system functioning, a demand for knowledge that is not inherent to the domain of ecological modernization.

Another way to look at relationships between science and decision-making is through institutions that govern the use and management of natural resources (Table 1). Institutions that deal explicitly with environmental or resource issues have also been called "environmental" or "resource regimes" (Young, 2002). The analysis of environmental institutions has made progress in recent years. An influential line of thinking features generalizable design principles of common property institutions for "common pool resources", such as the oceans or the global atmosphere (Dietz et al., 2003; National Research Council , 2002). More recently, "institutional diagnostics" has been advocated as a more case-specific approach to the analysis of existing institutions on local to global scales. Institutional diagnostics seeks to identify important features of ecosystem management issues "that can be understood as diagnostic conditions, coupled with an analysis of the design implications of each of these conditions" (Young, 2002: 176). Diagnostic conditions are specific combinations of ecosystem properties, actor attributes, and implementation issues.

Although the role of knowledge is a recurring topic in this institutional literature (e.g., Young, 2003), we believe that STI research has much to contribute to a more systematic understanding of interactions among environmental knowledge, innovation, actor constellations, and environmental regimes. In this respect, STI research could also build upon a rapidly growing body of literature that emphasizes the importance of citizen participation and local knowledge in ecosystem management (Fischer, 2000; Kasemir et al., 2003).

2.2.1 Example of ecosystem management: agriculture and fishery

The meaning of ecosystem management is well illustrated through practices with a long history that continue to change the Earth's ecosystems at a rapid pace, such as agriculture and ocean fisheries. In some 10,000 years, humans moved from the invention of plant cultivation to global changes in vegetation cover (Turner II and McCandless, 2004). Today, "croplands and pastures have become one of the largest terrestrial biomes on the planet (…) occupying ~40% of the land surface" (Foley et al., 2005: 570). Agricultural production must be further expanded and yields increased in order to reduce hunger (there are 852 million chronically hungry people in the world today) and to feed a growing global population (an estimated increase of 2 billion people by 2030; figures from the UN Food and Agriculture Organization FAO). According to the International Food Policy Research Institute, "global cereal production is estimated to increase by 56% between 1997 and 2050, and livestock production by 90%" (Rosegrant and Cline, 2003: 1917). Yet intensive farming has strong adverse effects on the environment. Among the pervasive negative impacts are soil degradation, overexploitation of water resources, eutrophication of freshwater and coastal ecosystems, global biodiversity loss (ranging from rainforests to agro-biodiversity), and the release of greenhouse gases.

While agriculture is based on the maintenance of impoverished terrestrial ecosystems, fisheries continue to overexploit the world's marine biological resources. "The past decade established that fisheries must be viewed as components of a global enterprise, on its way to undermine its supporting ecosystems" (Pauly et al., 2003: 1359). Global marine fisheries landings are estimated to have peaked in the late 1980s at 80 to 85 million metric tons and are declining by about 500,000 tons per year. Marine ecologists describe present trends as "fishing down marine food webs" (ibid.). Ecosystem-based fishery management would essentially "reverse the order of management priorities to start with the ecosystem rather than the target species" (Pikitch et al., 2004: 346). Apart from a massive reduction in fishing effort, abatement of coastal pollution and the establishment of networks of marine reserves are deemed necessary to return to sustainable yields and reduce the threat of species extinction (Pauly et al., 2003: 1359-1361).

2.3. Environmental risk assessment

The central task of the third domain is the anticipation, analysis, and evaluation of environmental risks—those risks caused by variability and change in environmental phenomena—and effective response options. Environmental hazards such as storms, floods, droughts, or pests have always threatened human life and prosperity (Nigg and Mileti, 2002). In addition to natural variability, this domain encompasses all hazards caused or increased by anthropogenic environmental change, including risks of anthropogenic climate change or health risks caused by the spread of toxic chemicals and radiation. STI activities are focused on variability and change in environmental properties on different temporal and spatial scales and on the vulnerability of people and things to hazards or the negative consequences of altered environmental conditions (Fig. 2).

In a landmark comparative study on the management of global atmospheric risks, the Jäger et al. give the following definition of risk assessment:

> A risk assessment provides information about the causes, possible consequences, likelihood, and timing of a particular risk. Risks by definition involve uncertainties, and especially for global environmental processes these uncertainties are so large that the usual features of risk assessment – namely, the calculation of probabilities of specific harm from particular activities, natural or manmade – are swamped by larger uncertainties and ignorance about key processes, interactions, and effects (Jäger et al., 2001: 7).

In the context of STI research, risk assessment means more than just scientific reports or policy recommendations. Following Farrell and colleagues (2006), risk assessment is understood here as a social process that bridges scientific knowledge creation and decision-making by governments or industries: "Environmental assessment refers to the entire social process by which expert knowledge related to a policy problem is organized, evaluated, integrated, and presented in documents to inform policy choices or other decisionmaking" (Farrell and Jäger, 2006: 1).

From the perspective of sociological systems theory, risk assessment is a mechanism to communicate about new or complex environmental problems in the context of a functionally differentiated society (cf. Luhmann, 1986; Luhmann, 1993). As a consequence of an environmental problem's novelty or complexity, the available scientific knowledge is often incomplete or uncertain and in part contentious. Yet in an apparent paradox, this scientific uncertainty frequently augments the expectations that the legal and political system, the mass media, and the public direct at scientific experts and expert knowledge (Weingart, 2003). Ever since environmental consciousness arose in the 1960s and early 1970s, the demand for this type of assessment has been on the increase.

Since the time of the United Nations Conference on the Human Environment (UNCHE) in Stockholm in 1972, industrialised countries enormously expanded their R&D capacity for environmental risk assessment, including scientific knowledge of environmental risks, the underlying behaviour of natural systems, and options for risk prevention and mitigation. While sociologists showed great interest in the topic of risk and risk perception (e.g., Beck, 1992; Grundmann, 1999; Luhmann, 1993), this expansion of R&D capacity has rarely been studied by sociologists of science or STI research. To our knowledge, there are no detailed studies on the socio-technical development of observation systems that monitor conditions on land, in the oceans, and in the global atmosphere and provide input for simulation models. Yet new observation systems such as the establishment of a Global Earth Observation System of Systems (Lautenbacher, 2006) will change our view of the global environment in fundamental ways.

Policy analysis offers a rich conceptual toolkit to dissect the evolution of socially contested issues, and this toolkit has been adapted and refined in studies of risk-related policies. One of the largest undertakings in this area is the study by the "social learning group", an international group of 37 scholars who investigated policy development in three atmospheric risks across nine countries and in two international arenas between 1957 and 1992 (see example below). A major objective of their study is to trace processes of "social learning", a concept that is similar in some respects to the idea of capacity building (Social Learning Group, 2001b: 13f.). Another influential idea in this context is the notion that communication between science and politics can be enhanced through skilful "boundary management". Determinants of effective boundary management have been investigated for boundary organizations (Guston, 1999; Guston, 2001), issue domains (Social Learning Group, 2001a), and assessment processes (Farrell and Jäger, 2006). Actors who take this problem seriously are found to invest overall more time and resources in "communication, translation, and/or mediation" between scientists and decision-makers and "thereby more effectively balance salience, credibility, and legitimacy in the information that they produce" (Cash et al., 2003: 8089).

A different way to think about the capacity to link knowledge and action is to focus on social groups or regions believed to be particularly vulnerable, for example coastal areas vulnerable to the risk of sea level rise. Vulnerability is a term for the differential susceptibility to loss from a given insult (Kasperson et al., 2001: 24). Vulnerability analyses explain why certain individuals or populations are more likely to be exposed, are more sensitive to adverse impacts, or have less adaptive capacity in the face of changes in environmental conditions or environmental hazards. As Kasperson et al. (2001, p. 5) described it, "Vulnerability is a function of variability and distribution in physical and socio-economic systems, the limited human ability to cope with additional and sometimes accumulating hazard, and the social and economic constraints that limit these abilities". The Intergovernmental Panel on Climate Change describes vulnerability as a function of the sensitivity of a system to changes in climate, its adaptive capacity, and the degree of exposure to climatic hazards; and "resilience" as "the flip side of vulnerability" (IPCC, 2001: 89). STI research on vulnerable groups or regions could contribute to the investigation of social responses and adaptive processes triggered by the expectation of increased environmental risk and long-term change in environmental conditions. The concepts of vulnerability and resilience have also been used to build bridges between ecological and social sciences (Berkes et al., 2003; Luers, 2005; Turner II et al., 2003).

2.3.1 Example of environmental risk assessment: policy evolution in three cases of global atmospheric risks

The social learning group investigated the three atmospheric risks of acid rain, stratospheric ozone depletion, and climate change in the period from the International Geophysical Year in 1957 to the United Nations Conference on Environment and Development (UNCED) in 1992 (Social Learning Group, 2001a). The study compares issue evolution across eleven political "arenas", including nine countries, the European community, and the family of international environmental organizations. The study describes policy along two dimensions: one focusing on "problem framing, agenda setting, and issue attention in individual arenas"; the other comparing management functions across arenas: "risk assessment, option assessment, goal and strategy formulation, implementation, evaluation, and monitoring" (Clark et al., 2001: 6). By means of this empirical design, a constructivist analysis of issue development in social arenas is successfully integrated with a realist perspective of problem content as defined by the contemporary state of knowledge in Earth and environmental sciences.

2.4. Adaptation to environmental change

The central task of the fourth domain is the adaptation of society to long-term environmental change. In relation to the other three task domains, knowledge creation is focused on the consequences of environmental change and their implications for human demand in goods and services. Adaptation is more difficult to demarcate as a domain of STI because adaptation is located on the social pole of the ecological interaction chain (Fig. 2). To date, the term is most common in the context of climate change, as illustrated by the example below.

In the book "Earth System Analysis for Sustainability", leading scientists in international research on global environmental change give a clear but very general definition of societal adaptation:

> Throughout history, society has responded in two principal ways to environmental vagaries, flux, hazards, and drawdown, including resource depletion: *move*, either through designed mobility as in pastoral nomadic systems or 'forced' relocation owing to environmental or resource degradation (…) and *change techno-managerial strategies*, as in the adoption of fossil-fuel energy or genomics. (…) The second option – to modify or transform biophysical conditions in order to gain a measure of 'control' over some portion of the environment or to deliver a substitute for a depleted resource (…) [is] labelled technological fix and substitution (Steffen et al., 2004: 331).

From a macro-historical perspective, it becomes apparent that the two options of relocation and changes in techno-managerial strategies are inseparably bound in the history of the modern world. In the 18th century, Europeans expanded the agricultural resource base of their economies to distant continents: North and South America for food, fibre, and timber production, and Africa for a slave labour force. Leading scholars of world history argue that this earlier expansion of the renewable resource base is essential to explain the later take-off of the industrial revolution and the historical divergence between development centres in western Europe and east Asia (Pomeranz, 2000). In other words, Europeans combined the "move" strategy of territorial expansion with the "techno-managerial" innovations of early capitalism. As a result, the most developed centres of the West escaped the growth constraints of limited renewable resources within their home countries, long before agricultural technologies were revolutionized in the 20th century. Kenneth Pomeranz (2000) argues that in the early modern world, limits in the regional output of renewable resources constrained technology-based economic growth in the most-developed regions and that different ways to cope with this problem are essential to explain the historical divergence of development paths in China and western Europe.

Viewed from this angle, long-distance trade has substantially supplanted "move" strategies in the modern world, at least for those who enjoy affluence in a globalized economy (cf. Pomeranz, Topik, 1999). External trade in agricultural and manufactured goods implies exchange relations among countries with regard to their ecological carrying capacity. However, to date this ecological balance of trade is not explicitly accounted for. Although accounting tools are being developed to determine the overall "ecological footprint" of nations (http://www.footprintnetwork.org), it remains methodologically challenging to quantify export and import relations among countries for particular ecosystem services. Recent studies of "green water" flows are a good example (SIWI; IFRI; IUCN; IWMI 2005.) Markets and long-distance trade are among the most basic mechanisms for society to perceive and to adjust to changes in the abundance of non-renewable (e.g., oil) and renewable natural resources. At the same time, "globalization enhances the likelihood that those parts of the world involved in active trade with each other will reach many of their limits more or less simultaneously" (Meadows et al., 2004: 222). This situation only underlines the difficulty of separating broad issues of adaptation from the analysis of economic and power relations among nations and social groups.

The contours and core themes of this STI task domain will manifest themselves as the 21st century advances. For the more narrow purposes of STI research, "adaptation" can be confined to technological fixes of environmental problems and new economic opportunities that arise from altered environmental conditions and reduced abundance of natural resources. Adaptation processes in this narrow sense are often incremental, at least initially, and determined by multiple social factors (Smit et al., 2000). Furthermore, adaptive responses are likely to trigger innovations in the STI domains of "ecological modernization" or "ecosystem management". For instance, an adaptive response to regional climate change might consist in technologies that increase the efficiency of agricultural water use. Thus, adaptation pressures might act as positive feedback that propels the ecological interaction chain towards more sustainable socio-technical trajectories.

2.4.1 Example of adaptation to environmental change: studies in regional climate change

Climate change is the topic that dominates the current literature on adaptation. "Climate changes are likely to manifest in four main ways: slow changes in mean climate conditions, increased interannual and seasonal variability, increased frequency of extreme events, and rapid climate changes causing catastrophic shifts in ecosystems" (Tompkins and Adger, 2004: without p.).

Adaptation to slow changes in variation can be expected to at least initially rely upon similar means and strategies that were developed to cope with natural variability (Smit et al., 2000). Today, most regional impact assessments focus on climatic extremes (e.g., droughts or floods or hurricanes). Further research is needed on methods to integrate regional and global climate modelling because the resolution of global climate models is currently too coarse for regional impact assessments (Steffen et al., 2004: 327). Yet various countries are beginning to integrate regional climate change scenarios into strategies for long-term natural resource management, e.g., for water supply, agricultural crops, and energy demand.

Adger et al., stated that "There have been documented adaptations in markets such as insurance and reinsurance, coastal planning, health interventions, built environment, water resources and adjustments and adaptations within resource-based livelihoods" (2005: 85). For example, in many river basins worldwide, mountain snow cover functions as a natural reservoir that stores winter precipitation and gradually releases water during the spring and summer seasons. If mountain snow is permanently reduced as a result of warmer or drier climates, it may become necessary to build more artificial reservoirs, to transfer water from more distant rivers and aquifers, or to reduce substantially water consumption during seasonal dry periods (e.g., Carle, 2004).

3. Conclusion

This paper presented a comprehensive outline of the problem space of STI research for sustainability. We distinguished between four major task domains:

(1) ecological modernization and transformation: reducing the environmental impacts of the socio-economic metabolism and disconnecting growth of the economy from natural resource consumption;

(2) ecosystem management: long-term maintenance of essential ecosystem services;

(3) environmental risk assessment: anticipation, analysis, and evaluation of environmental risks and response options; and

(4) adaptation of society to long-term environmental change.

For all four respects, knowledge is bound to become increasingly important in humanity's relationship to the natural environment over the coming decades, related to the fact that society is approaching ecological limits on regional and global scales (Meadows et al. 2004; Clark and Dickson, 2003). This increase in knowledge intensity deserves more attention from STI researchers. One way to achieve this focus is to investigate the societal development of STI capacity, understood to encompass both R&D capacity and the capacity to link knowledge and action between different spheres of society. This paper does not discuss the global distribution of STI capacity, but targeted presentation of a cognitive map of STI research topics. Today, environment-related STI research is still fragmented in what are often peripheral niches of major disciplines, such as economics, political science, sociology, and the history of science. We argue that by linking related ideas and findings from social sciences and connecting them with research in engineering sciences and Earth and environmental sciences, STI research could move to the heart of human–environment relations to enhance our understanding of the creation and uses of knowledge for sustainability.

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