Knowledge about the Spaceship Earth:
A Sociological Perspective on Capacity Development

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The title refers to Kenneth Boulding's "Economics of the coming spaceship Earth" (1966).

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Acronyms

DIVERSITAS: An international programme in biodiversity science.
FRIEND: Flow Regimes from International Experimental and Network Data Programme
GARP: Global Atmospheric Research Programme
GEC: Global Environmental Change
GCM: General Circulation Model
GWSP: Global Water Systems Projekt
ESSP: Earth System Science Partnership
IBP: International Biological Programme
IC: Intergovernmental Council
ICSU: International Council for Science
ICSU-SCOPE: ICSU-Scientific Committee on Problems of the Environment
IGBP: International Geosphere-Biosphere Programme
IGFA: International Group of Funding Agencies for Global Change Research
IGY: International Geophysical Year
IHD: International Hydrological Decade
IHDP: International Human Dimensions of Global Environmental Change Programme
IHE: Institute for Water Education, Delft, the Netherlands
IHP: International Hydrological Programme
IOC: Intergovernmental Oceanographic Commission
IPCC: Intergovernmental Panel on Climate Change
ISI: Thomson Scientific, formerly Thomson Institute of Scientific Information
ISSC: International Social Science Council
IUBS: International Union of Biological Sciences
IUMS: International Union of Microbiological Societies
NC: National Committee
SCI: Science Citation Index
SSC: Scientific Steering Committee
SSCI: Social Science Citation Index
UNESCO: United Nations Educational, Scientific and Cultural Organisation
WCRP: World Climate Research Programme
WMO: World Meteorological Organisation
WWW/GOS: World Weather Watch/Global Observing System
IAEA: International Atomic Energy Association
IAH: International Association of Hydrogeologists
IAHS: International Association of Hydrological Sciences

Introduction

In November 2006, the daily newspaper *Stuttgarter Zeitung* published an interview with Dennis Meadows, one of the authors of the "Limits to Growth" report of the Club of Rome (Meadows et al. 1972; Meadows et al. 2004). At the beginning of that conversation, Meadows states that in 1972, when the study was originally published, he "could not have imagined how difficult it would be for some people to follow our ideas".

I interpret Meadows' statement as referring to limitations in our powers of imagination. We have difficulty imagining a future that differs so radically from the social reality of the present (cf. Boulding 1966). Perhaps the distance between our world today and a sustainable society some time in the future could be compared to the distance between the modern industrial age and the system of estates in the European High Middle Ages. This development has taken several centuries and went far beyond anything conceivable for medieval men.

Against this background, the model of the Club of Rome captivates through its simplicity and its high degree of abstraction. The model distinguishes three factors which preempt indefinite growth of the human population and industrial production on our planet: firstly, limited reserves of non-renewable resources (e.g. fossil fuel), secondly, limited maximum yields of renewable resources (e.g. grain), and thirdly, a limited capacity of the environment to absorb harmful emissions. According to the model, each of these factors solely or in combination can cause a breakdown in the development of global industrial production and population. Currently, 35 years after the first edition, we find ourselves talking more about limited emission sinks, especially in the context of greenhouse gases and global warming, than about limited oil or gas reserves. But this does not place us outside the range of simulated scenarios.

Consequently, one of the most central tasks for the sociology of science, technology and innovation is to enhance our understanding of the role of scientific and technological change in achieving more sustainable nature-society interaction. Yet any such endeavour faces several challenges. As soon as we go into empirical detail, the overall picture of relationships between society and nature becomes very complex and unclear (cf. Luhmann 1986). Besides, technological change is predictable only to a very limited extent.

Certainly, social sciences are expected to enhance our imagination through the observation of facts and not by writing science fiction. One way of accomplishing this task might be to investigate weak trends, i.e. developments that do not yet constitute important drivers of social change, but are expected to gain importance in the future, and where this expectation appears to be reasonably well-founded.

The present study investigates the concept of scientific, technological and innovation (STI) capacity and develops ideas for capacity research within a sociology of science framework. In empirical terms, we investigate international collaboration in environmental sciences, using bibliometric methods and a comparison of two major international collaboration programmes.

STI capacity, as the concept is used here, means the capability to create, develop and use knowledge and technology for sustainable development. STI capacity includes original invention as well as adaptation and diffusion of ideas and technologies. Sustainability is understood as the long-term development of society within the ecological limits of the planet (for a discussion of the concept of sustainability, see National Research Council 1999; Parris/Kates 2003; Sachs 2000). In the present study, the concept refers mainly to the second and third factor of the cited model, i.e. to renewable resources and emission sinks. In contrast, the finite supply of non-renewable resources is outside the scope of the current study, since it constitutes a different domain of science and technology, e.g. exploitation of oil resources or substitution of non-renewable resources by alternative materials.

At least two arguments can be adduced to support a research agenda for social sciences on the subject of STI capacity. Firstly, the expansion of environment-related science and technology is an empirical phenomenon which has been observed since the formation of geophysics in the early 20th century and has accelerated with the rise of modern environmental consciousness since the late 1960s (cf. Küppers et al. 1978). Yet in contrast to the formation of environmental consciousness[1] (Brand 2000) or to the diffusion of environmental institutions (Kern 2000; Tews 2005), the development of environment-related STI capacity has hardly been studied systematically, except for studies in the history of environmental disciplines (Bocking 1997; Bowler 1992;

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[1] Cf. opinion polls on environmental issues on www.worldpublicopinion.org

Oreskes/Doel 2003). Furthermore, the capacity concept lends itself to the analysis of developments that are as yet in their early stages, e.g. the increase of energy efficiency or the introduction of river basin institutions, which is advantageous from an empirical research perspective.

The second argument for a research agenda on STI capacity is a more normatively coloured. It consists in the assumption that social science discourse could help to accelerate the development of STI capacity in science and society. Undoubtedly, the objective of speeding up environment-friendly technological change is well justified. For the faster industrialized countries succeed in reducing their ecological footprint, the more scope is left for additional economic growth, for growth in developing and catching-up countries, and the more time remains for socio-political adaptation in the face of irreversible environmental change.

Different arguments can be made for a strong role of political support in STI capacity building. An important insight of environmental economics is that markets frequently fail to provide accurate information on the real costs of environmental consumption, with the result that economic incentives for investment in environmental innovation are set too low on a systematic basis (Ekins 2006). Moreover, political science studies have shown that the success in introducing environmental innovations to the market frequently hinges on accompanying political measures (Beise et al. 2003; Jänicke/Jacob 2006; Klemmer 1999; Porter/van der Linde 1995). Both arguments indicate that vast potentials remain unused today in terms of increasing resource efficiency through science and technology (Jochem et al. 2004; Weizsäcker et al. 1997).

Where the development of STI capacity is backed by science and innovation policy, such policies should be scrutinized by social scientists. STI research could perform an advisory function also in the business sector. The notion of capacity is as suitable for independent basic research as it is for applied research that is carried out in direct interaction with stakeholders from environmental sciences, business or politics.

In this normative interpretation of the concept, we refer to the model of environmental policy performance as developed by Martin Jänicke (Jänicke 1997; Jänicke et al. 1999). Jänicke introduced the notion of capacity as a heuristic in order to redirect the focus of policy analysis from the political debates of the day to the more systemic framework conditions for national performance in environmental policy. According to

Jänicke, an environmental problem may exceed the present objective capabilities of those who want to solve it. In such cases the priority task consists in improving capacity, not in the choice between instruments or policy targets (1999: 112). He distinguishes capacity, as "a relative stable condition of action", from the actual employment of capacities which leads to the "subjective and situative aspect of environmental policy" (1997: 8).

In reference to this model, STI capacity is understood here as one partial aspect of society's overall capacity for sustainable development, namely the improvement of framework conditions for action by means of research and development and by means of diffusing environmental knowledge and innovation. This is a broad definition with strong overlaps to issues of environmental policy and innovation policy. In chapter 2 we go into more detail to show how Jänicke's original idea may be adapted for the purpose of STI research.

The goal of this dissertation is to elaborate the concept of STI capacity for sustainable development to the point where it becomes fruitful for sociological research. Under this unifying objective, different aspects are investigated which join and complement each other in several ways. In the following, we give an outline of the dissertation by introducing the research question of each chapter as well as the coherence of the parts, and conclude with suggestions for further research.

In the context of the whole project, the function of the first chapter is to sharpen the notion of STI capacity in content. Chapter 1 investigates two connected questions. Firstly, we ask what is the role of knowledge in the relationship between society and environment, concerning the transition to a sustainable development path? The second question is: what are current approaches in social sciences that have advanced our understanding of knowledge for sustainable development?

Methodologically, the first chapter is a selective literature review on the current state of STI capacity research. The study proceeds in two steps. First, a taxonomy of major task domains in environment-related knowledge production is drafted, which is then interpreted and used as a cognitive map of current approaches in social science research.

In response to the first question concerning the role of knowledge for sustainable development, we distinguish four major tasks of knowledge production, labelled as: (a) ecological modernization and transformation, (b) ecosystem management, (c) environmental risk assessment, (d) adaptation to environmental change. We claim that an expansion of scientific and technological capacity within each of these four domains is among the necessary conditions for a transition to sustainability. However, this categorization should not be taken as an absolute definition. As with any other taxonomy, it has to be judged by its usefulness for the purpose at hand, which is to give an overview of STI capacity research as an emerging social science field.

We criticize the view sometimes taken by sociologists that sociology should only deal with "social communication about nature", but not with the "material" or "physical" relationships between society and nature. (A related argument was advanced by Luhmann, cf. Schimank 2000: 293; Luhmann 1986: 63). We argue that this distinction is flawed. The terminology of "material interaction" is at most suited to denote physical flows of material and energy in a narrow sense, but should not be used with reference to complex economic conditions, such as agricultural production. On the contrary, much of society's knowledge about nature is embedded in all those technologies and practices by means of which our natural environment is physically transformed, and these technologies and practices can not be separated in any meaningful way from ideas, discourse, and conflict about nature. (Think of dams or airports or genetically engineered food, for example). This argument is made in chapter 1 with the help of the "ecological interaction chain". The point we want to stress here is that each of the aforementioned task domains explicitly encompasses the analysis of social communication, as is evident also in the literature review.

The value of the literature review in chapter 1 consists firstly in the selection regarding the quality of the cited works and the range of disciplines considered, and secondly in the interlinkages that are partly drawn explicitly and partly merely hinted at. For the reviewed approaches do not so far regard themselves as members of one research field, but rather tend to inhabit "green" niches at the margins of more established disciplines, such as sociology, political sciences, and economics. The proposal to elaborate these linkages further is captured in the slogan of "an agenda for STI research".

Subsequent to the clarification of major task domains in chapter 1, chapter 2 treats the question of how STI capacity might be operationalized. Three different methodological approaches are discussed. These methods can be triangulated and complement each other. The methodological discussion shows that the notion of capacity is not just an empty phrase, but it also avoids lacing up the concept in a tight corset of operational definitions. The choice of method should be guided by the specific research objective. The second chapter is to be understood foremost as an elaboration and completion of the first, where we refer to a number of excellent studies without explicitly considering methodological issues.

The first approach to operationalizing STI capacity is to adapt science and technology indicators (S&T indicators) to the subject matter, i.e. indicators developed and used by innovation research. S&T statistics look at the quantity of S&T results produced and the amount of resources invested in research and experimental development (R&D). Thus S&T statistics are used primarily for the quantitative comparison of performance, i.e. in comparisons of national economies, business enterprises or research organizations, but they abstract to a large extent from the actual content of scientific and technological progress. Chapter 2 refers to recent studies with patent indicators adapted for environmental technologies and presents own findings regarding the adaptation of publication indicators on the basis of the database Science Citation Index (SCI).

Although the comparative study of scientific and technological performance – and resulting competitive advantages – is an important building block in the measurement of capacity, it is not sufficient by itself. In the context of sustainability, capacity needs to be measured against content criteria also, which means foremost dimensions of environmental consumption (e.g. amount of water used) and environmental quality (e.g. water quality). In our view, measuring eco-efficiency, e.g. energy efficiency, material efficiency, surface efficiency, etc. and measuring the diffusion of environmental innovations are two important methodological issues for future capacity research which merit more attention. Both aspects, i.e. efficiency and diffusion, are illustrated by the case of the Japanese Top-Runner programme in chapter 4.

The third approach, which is a more genuinely social science one by comparison, connects to the topic of task domains as described in chapter 1. Here, capacity is understood as a set of systemic conditions for action in a constellation of actors. The notion of systemic or relatively stable conditions for action comes from the aforementioned model of environmental policy performance. By connecting this model to a meso-level concept which circumscribes a field of actors, technologies, and institutions, the concept is made fruitful for empirical STI research. Chapter 2.3 presents three examples of this approach, explaining in each case how to delineate the object of research, i.e. the relevant constellation of actors, technologies and institutions, and how to adapt the concept of capacity. The meso-level concepts used here are the notion of the "sectoral innovation system", the "technological regime", and the "environmental" or "resource regime". Although reference to these meso-level concepts does not constitute an operationalization in the narrow sense of measurement, an outline is presented of what a viable research design might look like. Besides, the methodological affinity between the three meso-level concepts is stressed.

It follows from the broad layout of the capacity discussion in the first part of this work that only a sub-set of the presented methods will be applied in the second, empirical part. However, the methodological discussion provides additional suggestions for further research that are summarized at the end of chapter 2.

While the application fields of environmental knowledge are placed in the foreground in the first part of this work, the second part focuses on environmental science fields as segments of the science system. While the first part developed an interdisciplinary concept of STI research, connecting different approaches, mainly from social studies of science, environmental policy analysis, and innovation research, the empirical chapters 3 and 4 contribute to the sociological study of science in a narrower sense. The latter investigations constitute building blocks or examples within the larger framework that is described in the first part. In addition to the dimensions of content and methodology (chapter 1 and 2) a geographical dimension of capacity is introduced.

The second part proceeds from the observation that scientific capacity is distributed extremely unequally and is still concentrated in the most advanced industrialized countries, while many pressing environmental problems are global in character. This leads us to the questions (a) how the social organization of science is influenced today by the global extension of environmental problems and (b) what form of organization is capable of globalizing environmental knowledge? These questions are investigated in two complementary studies on international scientific collaboration.

We define international collaboration as the collaboration between two or more scientists with institutional affiliations in different countries. If the social organization of a scientific field is pictured as a network of communicative and cooperative ties between individual scientists as nodes, then international collaboration denotes a part of this larger network, namely the sub-set of all ties across national borders. It is characteristic for the organization of public science that these network structures of the intellectual field are combined with research institutions (i.e. research organizations, funding mechanisms) that are confined to national boundaries in most cases (Stichweh 1999; Whitley 2000). The propensity for international collaboration is thus a dimension of the intellectual field.

This dissertation investigates international collaboration on two levels, firstly on the level of the whole field in a comparison of different environmental science fields (chapter 3), and secondly on the level of international, i.e. multilateral collaboration programmes (chapter 4). The cases investigated are the International Geosphere-Biosphere Programme (IGBP) sponsored by the International Council for Science, and the International Hydrological Programme (IHP) which is administered by the UN Educational, Scientific, and Cultural Organization (Unesco). These two collaboration programmes represent contrasting organizational models for institutionalizing collaborative ties within an intellectual field.

Chapter 3 presents a bibliometric analysis, i.e. a comparison of the internationalization of different environmental science fields on the basis of publication data. International collaboration is measured as the percentage of papers with international co-authorship in all papers. It is known from the literature that different science fields diverge in their propensity for international collaboration. This observation also applies for the small number of earth and environmental science fields which have so far been investigated. Some of these are among the most strongly internationalized fields of science, yet so far no coherent explanation for this finding has been given. Furthermore, prior research usually neglected the question of how the geography of the research object relates to collaboration – an issue which is especially relevant for earth and environmental sciences.

We hypothesize that differences in the level of internationalization across environmental science fields can be explained by differences in the cognitive structure of the research object (Whitley 2000). As an independent variable, we introduce two types of cognitive problem structure: environmental changes that are "globally systemic" in contrast to environmental changes that are "cumulatively global" (Turner et al. 1990). The first type refers to changes in a global system, such as the global climate system, while the second type refers to the global spread of local or regional environmental changes, such as water pollution, soil degradation or biodiversity loss. The distinction characterizes the cognitive perspective of research, but implies no physical separation in nature. We investigate three independent variables: (a) frequency of international collaboration, defined as the rate of international publications, (b) output concentration field on the largest scientific producing countries, and (c) participation from developing, emerging or transition countries, defined as the rate of publications with authors from these countries in relation to all international publications.

With reference to Whitley's theoretical concept of mutual task dependence among scientists, we explain why the globally systemic problem structure leads to higher levels of collaborative organization in the respective science fields. In order to test this hypothesis empirically, we compare two SCI fields of systemic global change research (meteorology & atmospheric sciences; oceanography) with two fields of cumulative global change research (ecology; water resources). Our results show significant differences in the expected direction of all three dependent variables. "Meteorology & atmospheric sciences" belongs to the most internationalized fields of science, whereas internationalization in the cumulatively global field of "water resources" conforms to the database average. In line with expectations, the relative participation from the group of developing, emerging and transition countries is much higher in the field of "water resources" than in the three other fields, with co-authors from one of the countries in close to 50 % of all international publications.

Chapter 3 is written as a contribution to bibliometric research on international scientific collaboration, a literature that is to a large extent a-theoretical. But in the context of capacity research it is important to understand how the social organization of scientific fields is influenced by their cognitive structure. The differences observed with regard to the level of internationalization indicate that the distinction between globally systemic versus cumulatively global problems is important for the social organization of environmental sciences and thus by implication also plays a role for the development of scientific capacity.

In chapter 4, the focus of analysis shifts from the field level to an institutional comparison of two scientific collaboration programmes. This analysis identifies an important research gap, since the sociology of science so far has neglected international collaboration programmes as a form of organizing environmental research, nor has the role of these programmes for capacity development been investigated.

The principal purpose in analyzing these cases is to open up the topic by identifying relevant dimensions and questions for sociological research. Thus, we first take each single programme as an historical example for capacity building in environmental sciences and aim to understand its objectives and institutional design. By means of a systematic case comparison, we then seek to indentify organizational factors of more general importance for the successful development of collaboration initiatives in environment-related fields of knowledge.

Methodologically, this research is based on an analysis of the scientific literature, published by historians of science and by participating natural scientists, grey literature, programme websites, and official documents, as well as interviews and participant observation during a three-month research stay at Unesco-IHP secretariat in Paris. During this period, we were also able to attend sessions of the 33rd Unesco General Conference and an international scientific conference on the history of Unesco marking the occasion of the organization's 50th anniversary.

The case of the International Geosphere-Biosphere Programme (IGBP) was selected as example for a whole tradition of scientific internationalism that is associated with the International Council for Science. This institutional tradition of large collaboration programmes leads from precursors in the late 19th century over the famous International Geophysical Year in mid-century up to contemporary programmes in global environmental change research (Greenaway 1996). The International Hydrological Programme (IHP) was selected because it originated in the same institutional tradition, but has evolved in a different direction since the time when the programme secretariat became a permanent part of Unesco in 1974.

Our analysis explains the different meanings of capacity development in these two cases. IGBP is a programme that investigates global change in the earth system. It aims for international and interdisciplinary coordination in order to create synergies between the scientifically most advanced countries as its main contributors (cf. analysis of participation in section 4.2.4). In this context, capacity means the scientific cababilities to observe, to understand and to predict changes in global life support systems. The programme was set up in the mid-1980s in order to study a topic that had not been systematically addressed before, i.e. the interaction of physical, biological and chemical processes on the global scale. IGBP works as an institutionalized network of scientists. It has been estimated that approximately 10,000 scientists participated in associated research (1990 until ca. 2003/04). This figure indicates that IGBP is very successful in terms of participation and scientific allegiance to programme objectives.

The analysis shows that the organizational design of IGBP has many advantages, e.g. with respect to expansion over time. Yet we argue that the capacity of the IGBP scheme to coordinate the work of hundreds or even thousands of scientists cannot be understood solely in terms of its lean and flexible organizational structure. Rather, the organizational model is so powerful because IGBP's research field is characterized by high levels of mutual task dependence. The history of IGBP and other programmes in the ICSU tradition suggests that large-scale collaborative organization and the cognitive integration of systemic global change research are mutually reinforcing social and cognitive developments. Consequently, it seems unlikely that a simple transfer of the same organizational blueprint to cumulatively global research fields would result in comparable levels of participation and allegiance. This conclusion also seems to be in line with the experiences from the international programmes "Diversitas" (biodiversity research) and "International Human Dimensions Programme" (social sciences) which have a similar organizational design, but different cognitive structures.

In contrast to the preceding case, the International Hydrological Programme (IHP) frames international scientific collaboration as a means to enhance member states' capacity for sustainable water management. In a sense, the field of regional hydrology is much more representative for most environmental knowledge than the interdisciplinary research area of earth system science, and this is because the topics of regional hydrology are usually investigated on local and regional scales, while similar problems are rapidly accumulating worldwide. Most environmental problems are perceived and worked on by society as local or regional issues while they are also in fact cumulatively global. Other examples, apart from water management, include biodiversity loss, soil degradation, uncontrolled urbanization, depletion of ocean fisheries, etc.

The case of IHP shows that it is not at all self-evident how international scientific collaboration as a feature of the science system can be successfully linked – institutionally

– with the objective of scientific capacity building in developing countries and emerging economies (also cf. examples discussed in Hamblin 2005). In contrast to IGBP, the formal structure of IHP centres on the collaboration of states. The main structural components are national committees which function as formal interfaces with national governments and at the same time with national scientific and professional communities. As a consequence of IHP's intergovernmental design, IHP relies to a large extent on its permanent professionals to connect science and bureaucracy. Yet perhaps the main problem is that IHP's intergovernmental structure severely restrains programme growth because all extra-budgetary funding that is offered by states or other development agencies must be formally administered by one central Unesco-based secretariat.

The analysis also brings out the organizational strengths of IHP with regard to collaboration and capacity enhancement in the developing world. The main strengths are the institutional linkage with a higher education institute that specializes in university education of students from developing countries in hydrology and related fields, Unesco IHE. Through its longstanding focus on training, education and collaboration, IHP has been able to build a strong expert network in many developing countries. Furthermore, the prestige of Unesco can help scientists from developed countries to gain access to collaboration partners in countries that lack a highly developed science system or that do not disclose environmental information to the public.

This leads us to the more general question: what lessons can be drawn from this comparison for collaboration initiatives in cumulative global change research? We conclude the paper by highlighting five dimensions that are vital for organizational capacity development: (a) scientific allegiance to a programme's research objectives; (b) mutual task dependence among scientists; (c) decentralized administration to enable programme growth; (d) careful boundary management between science and politics; (e) institutional linkages between research funding and development policy. While there is often tension between scientific rationales for collaboration and developmental policy objectives, there are many other collaborative approaches apart from IGBP and IHP that are worthy of more systematic study in this respect.

This dissertation project set out to investigate the concept of STI capacity for sustainable development. The main insights and results of this work can be summarized as follows:

1. STI research for sustainable development can be conceived as a coherent field of social science that investigates capacity development in four major task domains: (a) ecological modernization and transformation; (b) ecosystem management; (c) environmental risk assessment, and (d) adaptation to environmental change.
2. An overview is given on three methodological approaches for the operationalization of capacity: (a) by adapting S&T indicators, e.g. patents, publications or research expenditures; (b) by measuring performance against standards of environmental consumption and environmental quality. Indicators of resource efficiency and indicators measuring the diffusion of environmental innovations are especially important for capacity research; (c) by conceiving capacity as systemic or relatively stable conditions for action in constellations of actors, technologies, and institutions. Suitable meso-level concepts are needed to delineate the actor constellation.
3. We provide an overview on environmental science fields in the SCI, including their size, overlaps and categorization in biosphere, geosphere, and environmental management & engineering research.
4. We present empirical evidence for the claim that international organization in climate and earth system research is a special case of scientific capacity development that can not simply be transferred to other environmental science fields. Integration through standards and GCM models and collaborative international organization are mutually reinforcing cognitive and social tendencies in tackling globally systemic problem structures.
5. We analyze two historical cases of collaboration programmes in terms of their objectives and institutional design – IGBP and Unesco-IHP – and identify dimensions that are relevant for future research on international collaboration in cumulatively global fields: scientific allegiance, mutual task dependence between scientists, decentral administrative organization, growth capacity, and boundary management between science and policy.

An issue that comes to mind naturally in the context of STI capacity is the comparison of nation states. This topic is beyond the scope of this work, but is investigated by the author and collaborators in an ongoing study on future areas for S&T collaboration between Germany and the so-called BRICS countries in the context of national strategies for sustainable development. The group of the BRICS countries includes Brazil, Russia, India, China, and South Africa.[2]

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[2] This study is directed by Dr. Rainer Walz, Fraunhofer Institute Systems and Innovation Research, Karlsruhe, (9/2006-9/2007), and is commissioned by the Sustainability Council (Rat für nachhaltige Entwicklung) of the German federal government.

1 Four major task domains of science for sustainability

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.

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An earlier version of this paper was presented at the "Science and Technology Policy Research SPRU 40th Anniversary Conference – The Future of Science, Technology and Innovation Policy", September 11–13, 2006, University of Sussex, Brighton, UK and at the 33rd congress of the German Sociological Society (DGS): "The Nature of Society", October 9-13, Universität Kassel, Germany.

1.1 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/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/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/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/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 1.2). We distinguish four domains of problem-solving by their respective focus on this ecological interaction chain: ecological modernization and transformation (1.2.1), ecosystem management (1.2.2), environmental risk assessment (1.2.3), and adaptation to environmental change (1.2.4). 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 (cf. chapter 2). Together, the four domains present a coherent outline of sustainability related STI issues to address at the beginning of the 21st century.

1.2 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.[3] 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.

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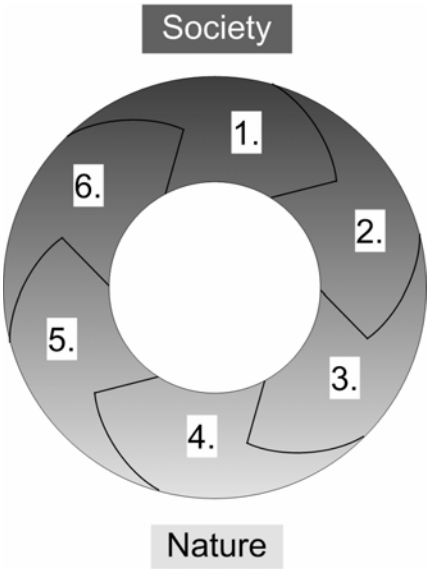
[3] http://glossary.eea.europa.eu/EEAGlossary/D/DPSIR

Figure 1: The causal chain of nature–society interaction



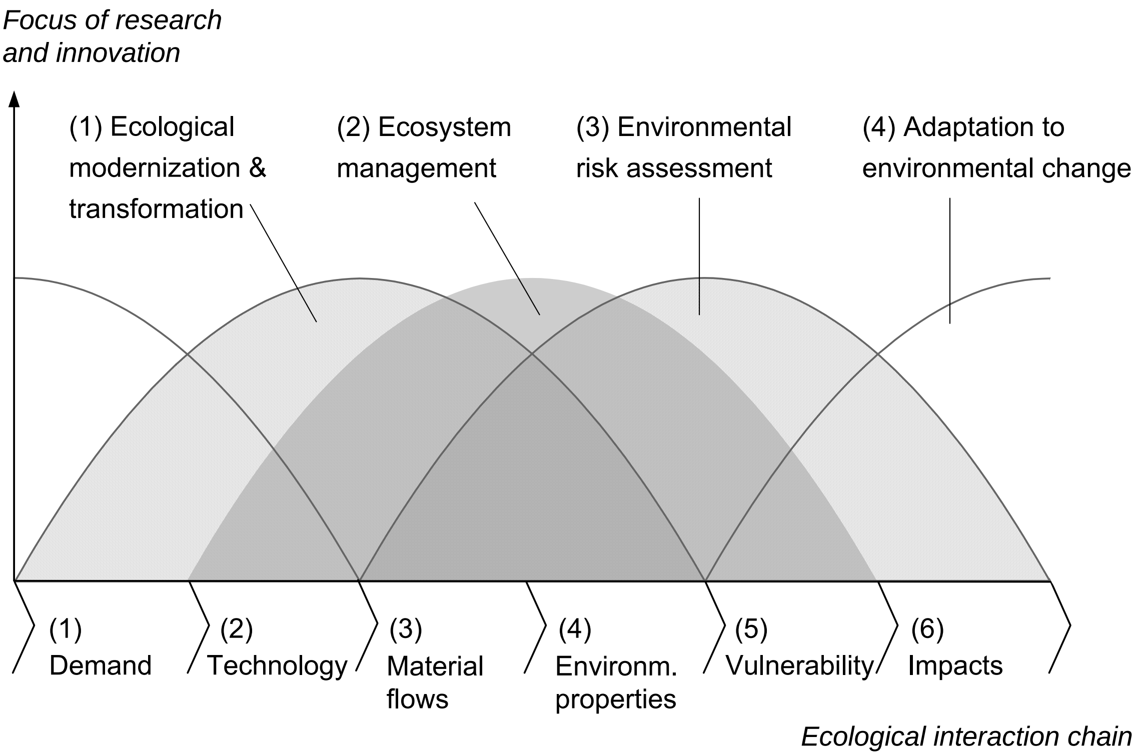
1. *Demand for goods and services:* The causal chain starts with human demand. This comprises demand for artefacts and services created by society, as well as demand for natural resources and ecosystem services.
2. *Choice of technologies and practices:* Humans develop and employ technologies and practices 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).

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

The basic idea displayed in figure 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 figure 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. Figure 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

Figure 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 research and innovation is represented as the maximum of an idealized distribution curve (vertical axis). A detailed description of the ecological interaction chain is given in figure 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 1.2.1–1.2.4 below. In chapter 2 we discuss how these concepts can be operationlized.

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/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 et al. (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.

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 (cf. chapter 2.1-2.2)	• 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 (cf. chapter 2.3)	• **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, eco-tourism, 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 • - …

Source: author

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 figure 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 (1.2.1–1.2.4) 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 (1.2.1), ecology (1.2.2), social sciences (1.2.3), and climate research (1.2.4).

1.2.1 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 (figure 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.

> Modernization, 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 modernization. (…) 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/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" (Elzen et al. 2005; 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" (Jänicke 2005: 205).

There are few explicit treatments of R&D capacity for ecological modernization and transformation from an innovation research perspective (cf. Legler et al. 2006), but there are technological feasibility studies of modernization strategies which make assessments of current technological capabilities. An example, described below in section 1.2.1.1, 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/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 (cf. chapter 2). 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/Loorbach 2006). "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/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.

1.2.1.1 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).

1.2.2 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 bene-

> fits 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" (Millenium 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 (figure 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/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 modernization 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 (NRC) 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). 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).

1.2.2.1 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/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/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).

1.2.3 Environmental risk assessment

The central task of the third domain is t*he 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/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 (figure 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/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 2003b). 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 (e.g. 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 section 1.2.3.1). 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 2001a: 13f.). Another influential idea in this context is the notion that communication between science and politics can be enhanced through skillful "boundary management". Determinants of effective boundary management have been investigated for boundary organizations (Guston 1999; Guston 2001), issue domains (Social Learning Group 2001a; 2001b), and assessment processes (Farrell/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).

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: 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" (Houghton et al. 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 et al. 2003).

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

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; 2001b). 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.

1.2.4 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 (figure 2). To date, the term is most common in the context of climate change, as illustrated by the example below (section 1.2.4.1).

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. 2004b: 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 et al. 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.

1.2.4.1 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/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. 2004b: 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" (Adger et al. 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).

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 (Clark/Dickson 2003; Meadows et al. 2004). 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 (chapter 2).

This chapter did not discuss the global distribution of STI capacity (chapter 3), 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.

2 How can capacity development be operationalized?

Capacity is a vague term. Its vagueness originates from the fact that the "capacity" of a country or an organization is based on human, mental powers which are augmented by technologies (see Harré 2002). It is not possible to definitively fix the meaning of the term because it is charged with the diversity of values and cultural practices through which people are first enabled to perform outstandingly in the fields of science, technology and art (see MacIntyre 1985). Capacity is therefore closely linked with the diverse conceptions of scientific and technological, but also more generally, cultural achievement.

Despite the fact that the term capacity is open and vague, it is still the most appropriate for the task before us. This chapter examines the question of how STI capacity for sustainable development can be understood and operationalized, i.e. made measurable. We propose three different approaches presented in the order of increasing methodological complexity, although it is also possible to combine all three approaches.

The first approach is a quantitative description modelled on science and technology statistics. Patents and scientific publications are the most important indicators of this way of measuring performance. The second approach looks at the content and application context of scientific and technological achievement. This is mainly concerned with environmental efficiency and environmental quality criteria as well as with measuring the diffusion of environmental innovations. The third approach regards capacity as relatively stable conditions for action in constellations of social actors. The starting point for this view is Martin Jänicke's model of environmental policy performance (Jänicke 1997; Jänicke/Jacob 2006). Following on from table 1, chapter 2 explains the operationalization of the term of environmental policy capacity with the help of the meso level concepts of "sectoral innovation system", "technological regime" and "environmental or resource regimes".

2.1 Science and technology indicators

Science and technology indicators (S&T statistics) form a sub-field of innovation research, the methods and insights of which can be used to form a basis for measuring sustainability STI. We have the following questions in mind: What should S&T statistics record? How are the constructs involved usually operationalized? What can be learned from this for developing S&T statistics of sustainability and how can existing methods be adapted to sustainability research?

S&T statistics regard the scientific and technological performance of national economies or organizations. They define "performance" as the quantity of produced S&T outputs. These outputs are differentiated, among others, by science and technology fields, product groups or sectors. Both the absolute quantity and the efficiency of producing the results are considered: S&T statistics aim to depict the input and output of innovation processes as well as the ratio of the two. This form of performance measurement is an instrument for information, benchmarking and consequently for the optimisation of innovation processes.

As a statistical measurement theory, innovation statistics has only a very limited interest in scientific or technological accomplishment as such, i.e. in the content and benefits of S&T performance; this applies to both individual discoveries and to performance on an aggregated level. Here, the quantitative comparison of one type of object, mainly of national economies, research institutions and companies with regard to their performance and efficiency replaces any evaluation of content.

Measuring quantities presumes a uniform "currency" in which S&T achievements are able to be compared. Scientific publications and patents of technical inventions are among the best known S&T indicators. The citation of publications or the production of university degrees, e.g. of masters or PhDs, are also conventional indicators of the science system's output. Other examples on the output side are the share of R&D-intensive[4] goods in the foreign trade of an economy or the share of newly developed products in the turnover of a company. The variables mentioned last measure the significance of innovations for market success.

The input side concerns the supply of resources for producing new S&T outputs, i.e. investments in the innovation process. Usually indicators of R&D expenditures and R&D personnel are listed here, or, for example, the share of highly qualified employees in total employees (e.g. human resources in science and technology occupations HRSTO). At the national level of analysis, R&D expenditures are distinguished accord-

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[4] R&D means "research and experimental development".

ing to the sector of origin and the sector of performance (public, corporate sector, universities, others). The standardization and diffusion of S&T statistical methods is being driven primarily by the OECD and also by the EU Commission (OECD 2002; OECD et al. 2005). Standard references on the methodology include Moed et al. (2004); van Raan (1988), and the journal "Scientometrics". S&T indicators are also widely used outside of scientific publications, mainly in policy related documents. The history of S&T statistics is described in Cozzens (1997).

To summarize, it can be stated that scientific and technological performance can be described statistically. S&T statistics are suitable for comparing the performance of countries or organizations albeit at a level which abstracts from the content of scientific and technological achievement and its application possibilities.

In order to transfer the methods of S&T statistics to measuring the performance of sustainability research, to start with, already tried and tested indicators can be adapted to the different subject area. In addition, new databases should also be created because the existing ones show methodological restrictions with regard to the subject of sustainability. The first attempts to adapt established indicators have already been made. The creation of new databases is more difficult because this is associated with higher investment costs.

In a study on behalf of the German Federal Environmental Agency, Legler et al. (2006) examined the performance of the German environmental industry and used innovation indicators to analyse environmental technologies, including patent applications and foreign trade with environmental goods. The background to the study is the current political debate about the environmental industry as a promising export-oriented sector and job machine which builds on Germany's recognized technical specialization in mechanical and systems engineering.

As far as the input side is concerned, i.e. investment in STI capacity building, this study found that the availability of internationally comparable data is still very limited. According to OECD data, the share of public spending on environmentally-related R&D in Germany in 2001 amounted to 3.4 % of total, civilian public R&D spending compared with 3.2 % in the EU (EU-15) in total and 2.3 % as an average of the OECD countries (Legler et al. 2006: 62). So far, there are no statistics available on specific personnel capacities.

The patent analysis of Legler et al. is a good example for the adaptation of conventional STI indicators. The objective of this patent analysis is to describe the position of the German environmental industry in international technology competition, i.e. a comparative measurement of capacity. The methodological adjustment consists in the definition of suitable technology fields based on the system of international patent classification (IPC). Legler et al. examine six fields of technology: waste technology, water pollution control, noise control, air pollution control, recycling, and measurement and control technology. An analysis was made of patent applications to the European Patent Office from all over the world. The results show the development of patent numbers over time, Germany's share in total European patents and demonstrate in which of the cited fields Germany and other industrial nations show an above average patent activity (specializations).

The IPC classification system makes a detailed categorization of technology fields possible which can be further refined using keywords. Since all patent applications to a patent office are recorded in full in the patent databases, there is nothing to stop a search for sustainability-relevant technologies. However, there are methodological limitations from the fact that technologies which greatly increase the efficiency of environmental consumption and whose use thus greatly benefits the environment cannot always be subsumed under a separate category of "environmental technology". Refrigerators running on propane gas, for example, are more environmentally-friendly with respect to protecting the stratospheric ozone layer than fridges using CFCs as the cooling agent, without the propane gas fridge itself being able to be labelled an environmental technology. The same thing is true for industrial production processes. The sustainability discussion usually deals with this issue by distinguishing between "integrated" and "additive" environmental technologies (Jänicke et al. 1999). Additive environmental technologies are understood to be downstream, add-on technologies which have hardly any effect on the original process, e.g. emissions filters.

When constructing patent indicators, there is the problem that an additive technology can be comparatively easily identified and recorded as an environmental technology, whereas the demarcation based on IPC classes causes problems for integrated technologies. In some cases the environmental benefit only results from the application, not from the invention itself. In any case, the selection of "integrated" environmental inventions, i.e. having to distinguish between comparatively clean technologies and their environmentally more harmful alternatives, places high demands on the researcher's knowledge of the technology involved. This problem is also evident in Legler et al.'s operationalization since four of the six technology fields examined here clearly refer to additive technologies (waste technology, water pollution control, noise control, air pollution control), while the other two (recycling, measurement and control technology) could include both kinds of environmental technology.

With the limitations cited, patents can already be used today to measure performance in the field of environmentally-relevant technologies as shown by the example. However, considerable research still has to be done in order to be able to better describe the development of integrated environmental technology using patent indicators because precisely these integrated or clean technologies comprise a core part of the innovation activity in the task domain (1) "Ecological modernization and transformation".

Another example for the adaptation of conventional indicators is given in the second, empirical part of this study. Chapter 3 deals mainly with the question of why environmental research fields are internationalized to a differing extent. Further, we also examine the suitability of the database Science Citation Index (SCI) for the purposes of sustainability-related S&T indicators. The SCI is a multidisciplinary database with a focus on the field of biomedical sciences. Currently a total of approximately 5,900 journals of science and technology are covered in the database. There are clear statements about the suitability and the limits of the SCI in general as a base for measuring and evaluating science in the literature (Barré 2004; van Raan 2004; Weingart 2003a; Zitt et al. 2003). However, the coverage of environmental research topics in the SCI has not yet been systematically described.

Our examination of the SCI arrives at the following results (see 3.2):

1. Of the total approximately 170 subject categories of the SCI, 21 refer explicitly to environmentally-related research topics (individual fields are listen in figure 3). In 2003-04, these 21 categories contained approximately 8 % of the total number of publications in the database. Since the specialist scientific journals are operationalized into subject categories oriented towards a particular community of experts, the subject categories represent an organization of specialist environmental knowledge in the SCI.

2. The environmental science fields in the SCI can be grouped into three main categories as regards content: geosphere, biosphere and environmental management & engineering. This categorization of the contents is supported empirically by an analysis of the field overlaps (figure 6).
3. The four task domains described in chapter 1 deal with interdisciplinary application contexts which do not match the specialist differentiation of science in the SCI. The operationalization resulting from the SCI subject categories is too coarse to be able to allocate publications to task domains. However, individual fields can be classified in terms of their main focus, e.g. environmental engineering to task domain 1 (ecological modernization), marine and freshwater biology and ecology to task domain 2 (ecosystem management).
4. Subject categories in the SCI can be used for a comparison of national specialization profiles in environmentally-related research. Figure 3 shows the specialization profile of Germany in comparison to Australia, Canada, and Sweden, as three countries with marked specializations in earth and environmental sciences.[5] Germany has a negative specialization (-10.5) concerning the total of all 21 fields, but there is a positive specialization (+21.8) in research on the geosphere. Further information on the 21 fields is given in table 3.
5. The SCI subject categories are primarily suited to capacity comparisons within the environmental fields of the natural sciences. In contrast, environmental technologies are only weakly represented with less than 6.7 % of the publications in all 21 environmental fields (2003-04). Thus there is insufficient coverage in the SCI database of scientific innovations in ecological modernization.

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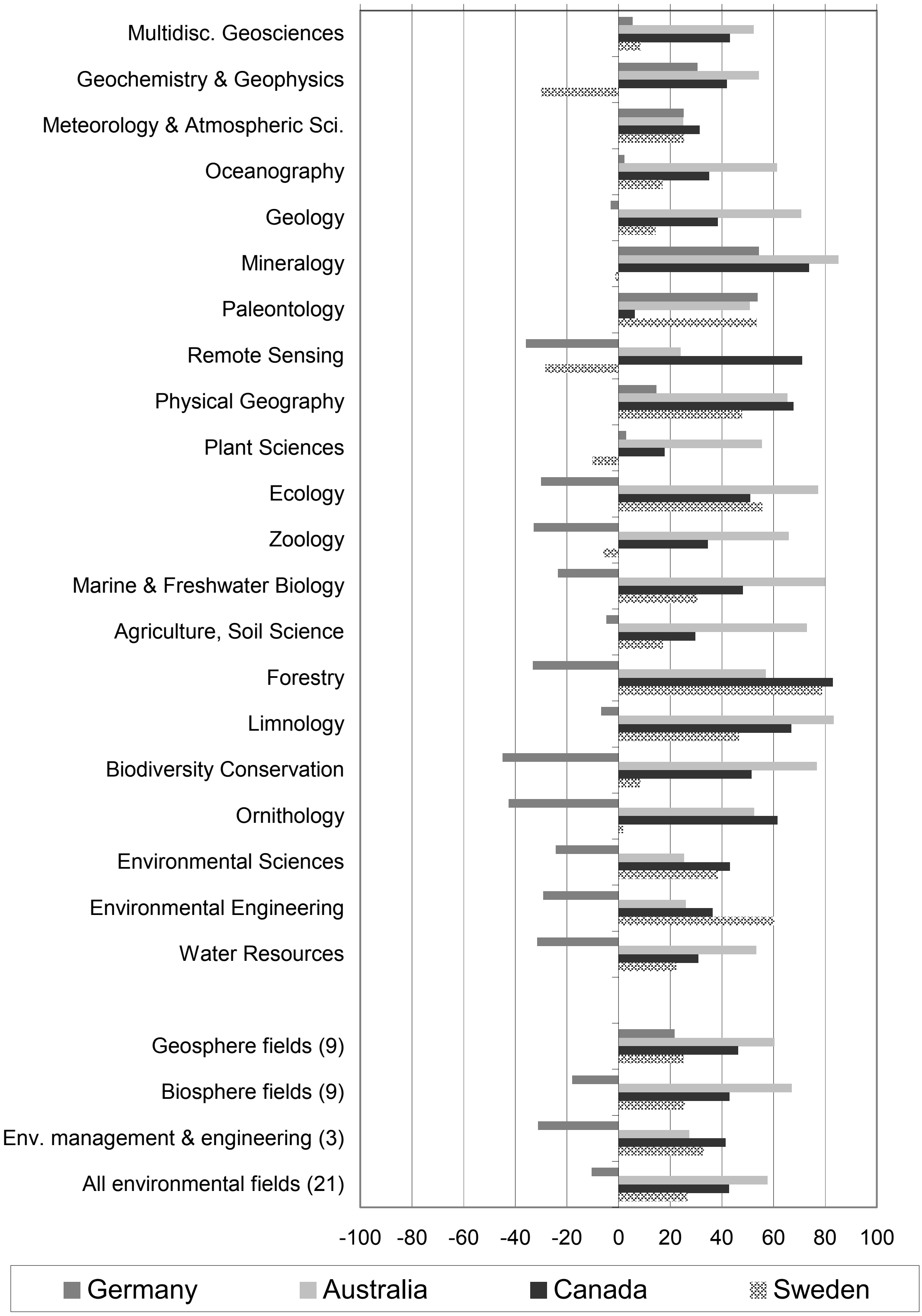
[5] National specializations are represented by the relative literature advantage (RLA) which is defined as:

$$\mathrm{RLA} = 100 * \tanh \ln [(P_{kj} / \Sigma_j P_{kj}) / (\Sigma_k P_{kj} / \Sigma_k \Sigma_j P_{kj})]$$

P_{kj} refers to the number of publications from country k in the field j.
The hyperbolic index is symmetrical and bounded to ± 100 (cf. Grupp 1998: 158).

Figure 3: Specialization in earth and environmental sciences, 2003-04: Comparison of Germany, Australia, Canada, and Sweden



Source: SCI via host STN

In order to place the bibliometric capacity measurement on an improved methodological base, new literature databases should be set up to record specialist journals with environmental science and technology topics. More reliable and more differentiated statements about the R&D capacity could then be made based on this kind of an extended database including research in applied science domains and in non-English speaking countries.

Two extensions are recommended to the SCI in its present form. First, the choice of specialist journals should be less selective than in the SCI and instead aim at complete coverage of all subject areas related to sustainability. This is because application-oriented journals and science domains also play a substantial role in sustainability research. Secondly, and related to this, the languages covered should be greatly extended. Today, the majority of journals in the SCI are written in English, which means that scientific results from many other countries are underrepresented (van Leeuwen et al. 2001). It is conceivable that all the languages used by large groups of scientists as their native tongue could be incorporated in a joint database, e.g. Japanese, German, French, Chinese, Spanish, Russian and Arabic specialist journals. As a countermove, the specialist subject group could be defined more tightly than it is in today's SCI.

In order to be able to make international comparisons, the bibliometric search on the basis of keywords would have to be possible in each main language used. For this reason, alongside the issue of multi languages, there are also high demands placed on the indexing of publications using keywords, although the translation of keywords can be automated to a large extent. For bibliometric analysis, it is also desirable to have a complete record of the institutional affiliations of all the authors involved and possibilities for citation searches. The last two functions are now distinctive characteristics of the SCI database and related products of its provider Thomson Scientific (SSCI, AHCI).

2.2 Eco-efficiency and diffusion of environmental innovations

The most obvious objective of capacity measurement is to assess science and technology performance as such, in terms of its content and its application possibilities. This view is also closest to the perspective of researchers and inventors. From an environmental perspective, an important role is played by the achievable degree of efficiency or of environmental protection and the diffusion of environmentally-friendly technologies. The perspective with regard to content is complementary to the S&T statistics discussed in section 2.1, which abstract from content and are geared to the quantitative comparison of the output of publications, patents etc.

Methodologically, the capacity of S&T for sustainability does not differ in principle from any other S&T capacity. It is primarily a measure of how human needs are satisfied and human abilities extended by means of scientific discoveries and technological innovations. In a societal framework, each S&T capacity can in addition be assessed according to its value in economic exchange relationships (market potential, e.g. new products) as well as according to its strategic value in the political-military constellations of its age (political-military potential, e.g. more dangerous weapons). In addition to this, other symbolic meanings may be linked with S&T capacities, e.g. as symbols of social status or religion.

The evaluation of the contents of S&T capacity faces the basic problem that the human needs and abilities which are satisfied or extended by S&T are infinitely varied. Sustainable development concerns mainly, but not exclusively, the basic human needs for food, shelter, clothing, security, health, knowledge, communication, mobility etc. How should this variety of capacities be conceptualized and progress evaluated?

A central principle in the evaluation of cultural achievements is that the terms in which these achievements are described and the benchmarks against which they are measured only evolve themselves in the course of cultural practices and are not predetermined externally. This principle applies to achievements in science and technology as a subset of all cultural capacities. The capacity description evolves with the technology, the criteria are "internal" to this context: What exactly the capacity consists of in its essence cannot usually be described without reference to the underlying (or another comparable) science and technology practice. You can only evaluate achievement if you have at least a rudimentary command of the practice (see MacIntyre 1985).

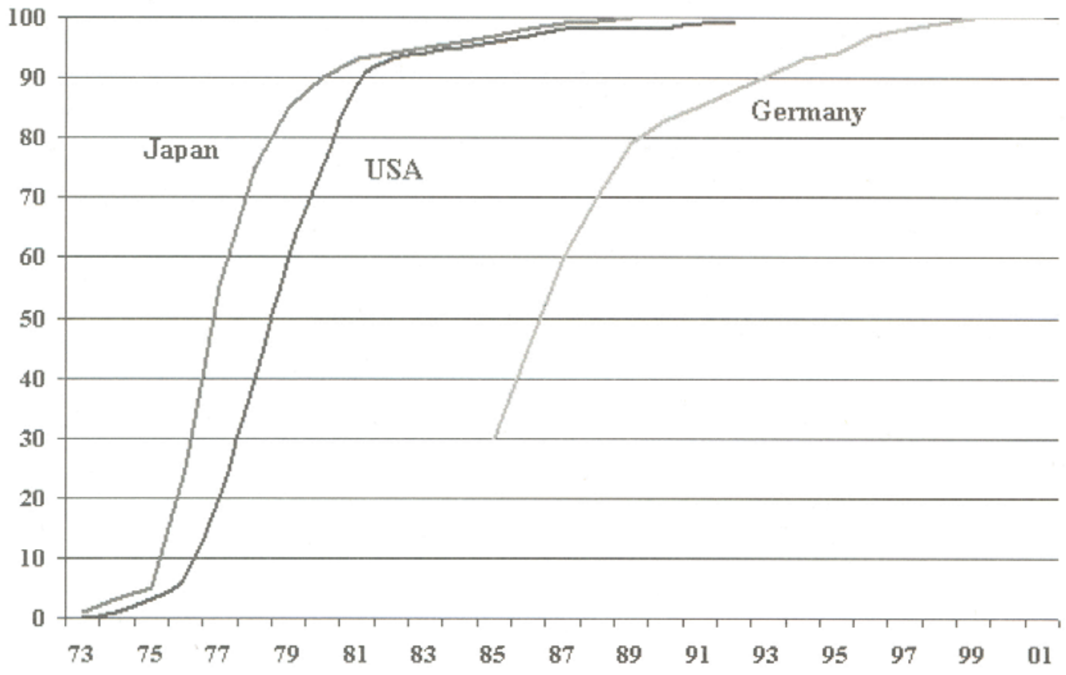
An everyday example for technology-specific categories of judging capacity are PS, acceleration and cubic capacity as criteria for a passenger car; or the evaluation of airplanes according to speed, altitude and range. The same principle of defining internal capacity also applies to knowledge and inventions which can contribute to sustainable development, e.g. the filtration capacity of a nanotechnological membrane in wastewater technology.

Characteristic for the topic of sustainability is the additional external reference to ecological criteria when regarding capacity, i.e. to the state of ecological life support systems on a planet with finite resources and a finite capacity for absorbing emissions. Concrete requirements for S&T outputs can be derived from this external reference point: first the requirement to manage the consumption of resources and environmental sinks as carefully and efficiently as possible and secondly to recognize the state of vital ecosystems, to monitor these and if possible to manage them. These ecological requirements function as external criteria which can be used to evaluate a great variety of S&T achievements.

Chapter 1 proposes specifying the subject matter in more detail and distinguishes the four task domains: (1) Ecological modernization and transformation, (2) Ecosystem management, (3) Environmental risk assessment and (4) Adaptation to environmental change. This distinction also represents a system of the demands made of science and technology for sustainable development. On the basis of external criteria such as the efficiency of environmental consumption and the ability to manage ecosystem services or to forecast environmental risks, concrete operations can then be developed to measure performance.

Capacity can then be interpreted in different ways. First, "capacity" can mean the best available technology world-wide or the best available practice. This concerns the maximum efficiency or the maximum environmental benefit which can be achieved with the respective current state of knowledge. In this sense, building capacity refers to absolute capacity increase and advances in universal knowledge independent of where these results are applied and whom they benefit. Second "capacity" can refer to the range of the application, i.e. to the diffusion of new knowledge and technologies. The second aspect is especially important for social science STI research because significant environmental effects usually only result from the diffusion of environmental innovations. A current policy instrument that aims to promote both kinds of capacity increase, i.e. an absolute increase in performance and increased technology diffusion, is the Japanese Top Runner programme (table 2).

Figure 4: Share of passenger cars equipped with catalytic converters (%).



Source of data: Beise et al. (2003); Figure in Jänicke/Jacob (2006: 32).

The national and international distribution of environmental innovations can be measured using diffusion indicators. There are already several studies on the diffusion of individual environmental technologies in the literature on innovation research (cf. overview in Beise et al. 2003 on automobile catalytic converters, fuel-efficient passenger cars, wind energy, substitutes for CFCs in domestic refrigerators) and on the generation of lead markets (see table 2 for this term). Figure 4 shows one example of a diffusion indicator from a study by Beise et al. on the diffusion of automobile catalytic converters. Suitable data sets on technology diffusion probably also exist in the form of market studies in environmental technology sectors, but these have not yet been evaluated from the perspective of capacity building.

Table 2: Increasing performance and diffusion via dynamic standardization: the example of the Japanese Top Runner programme

The Top Runner programme of the Japanese government is regarded as groundbreaking internationally for its dynamic efficiency standards.[6] The Top Runner approach splits technologies into different product groups and sets the standard for each group based on the currently best available product on the market within a group (e.g. water consumption of a 5kg washing machine: 45 l). This new standard then has to be achieved by all products of the same category within a certain limited period (e.g. 5 years). Products which do not comply with the efficiency standard may no longer be sold on the market after this deadline has passed.

The simple standardisation illustrates the operationalization of environmental criteria. In the Japanese case, this mainly concerns the energy efficiency of electrical and electronic appliances including refrigerators, electrical rice cookers, air conditioning systems, DVD recorders, computers, copiers, water boilers but also passenger cars and lorries. The current standards and methods used to determine and evaluate them are presented on the website of the responsible ministry.[7]

The main innovation of the Top Runner approach consists in the institutionalization of an efficiency competition in which the standards can be increased dynamically by the market suppliers themselves. A company which succeeds in beating the efficiency level of rival products sets the obligatory standard within that product group for the next period. From a company perspective this means a strategically calculable competitive advantage. The procedure provides for a periodic increase in the standard, where each new standard is defined by the best product on the market. In this way, the diffusion effect of the standard is combined with an incentive for far-reaching environmental innovations.

The Top-Runner Programme is not only targeting this diffusion effect on the national market. The Japanese government aims to use this instrument to develop the Japanese market into a global lead market for energy-efficient appliances. In other words, the intention is that Japanese products become technology leaders in international competition as a result of the stricter national standards. Behind this is the expectation that high energy efficiency will become a competitive advantage on foreign markets, too, in the near future, and that important trade partners like the US or Europe will also raise their statutory efficiency standards in future.

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[6] http://www.bmu.de/produkte_und_umwelt/oekodesign/top_runner_ansatz/doc/39038.php

[7] http://www.eccj.or.jp/top_runner/index_contents_e.html

Overall there is still a considerable need for research into applying diffusion measurements as indicators of capacity. Questions of S&T diffusion not only affect the task domain of ecological modernization, but equally the field of ecosystem management, for example with regard to the diffusion of measurement and monitoring methods (e.g. monitoring water quality), but also methods of resource management (e.g. avoiding soil erosion, efficient irrigation techniques, flood management) and the other two task domains as well.

The question arises as to whether the broad reference to the external criteria of environmental consumption and environmental state represents a new stage in the normative evaluation of science and technology performance, a new normative catalogue of requirements for science. It is our opinion that the subject matter of sustainability criteria may still be young from a historical perspective, but that normative external evaluation has been around for a long time. As a matter of fact, the normative character is comparable with evaluating advances in one of the oldest science domains that exists, that of medicine. The main difference is that a person's physical and mental health and lifespan forms the external reference point for medicine, whereas the ability of ecological life support systems to function despite anthropogenic demands is the external benchmark for sustainability research.

The normative relationship of knowledge advances and performance assessment is comparable in both cases: (a) Science and technology progress is not identical with the success of a cure or the environmental benefit. This first requires the successful application of a therapy or a measure. (b) The assessment of the cure is not just left to the specialist community of doctors and medics, the patients and potential patients themselves also have to be able to ascertain improvements in order for the medical innovation to be counted socially as progress. Contentious cases exist, e.g. chemotherapies against cancer. Neither is sustainability a criterion which remains intrinsic to science. (c) The structural similarity becomes especially clear in that the evolution of medicine like the progress made towards sustainability depends on the diffusion of its innovastions. The development of a new vaccine, or an aids or cancer therapy does not constitute the benchmark on its own but rather the diffusion of this innovation among all those who are sick or vulnerable world-wide. (d) Just as the sustainability debate demands of society, medicine also demands of the individual a responsible "management" of his/her body and health as indispensable "resources". But this analogy is not targeted at the ecological life support systems quasi as the organism of society, but only at the ratio of internal scientific to external criteria when evaluating the achievements of science and technology.

2.3 Structural framework conditions and constellations of social actors

From a genuinely social scientific perspective, capacity can be described as relatively stable, structural conditions for action in constellations of social actors. This paper develops two different lines of thought on this topic. Chapter 4 deals with the question of how international (multilateral) scientific collaboration can be organized in order to build environmental capacity. The comparison of two international collaboration programmes refers to the social organization within a science system without going into the question of the application and social impact of the scientific discourse.

In contrast to the focus on the science system in chapter 4, a systematization of the most important application fields was presented in chapter 1. In the application context this concerns a social innovation capacity in the sense of implementing new insights and inventions for sustainable development. The question of operationalization was dealt with only briefly in chapter 1, namely in the form of table 1. The following section 2.3 explains the underlying methodological concept.

2.3.1 International collaboration programmes in the science system

The case study in chapter 4 investigates organizational dimensions of scientific capacity and thus belongs to the field of institutionalist sociology of science (cf. Hohn 1998; Schimank 1995). The research design consists in a comparison of two collaboration programmes that also represent different programme types.

When comparing the two programmes we find strong contrasts in two dimensions. The first dimension describes the mutual task dependence among scientists in a research field in connection with different cognitive problem structures. The second dimension is defined by the distinction between the science system and political system – IGBP belongs to the science system while IHP is conceived as an institutional hybrid between the science system and intergouvernmental politics.

The concept of mutual task dependence was developed by Whitley in his theory of scientific work organization (Whitley 2000). Task dependence is stronger in the globally systemic field of earth system science (IGBP) than in the cumulatively global field of regional hydrology. The level of task dependence is not directly measured but the findings of the bibliometric field comparison in chapter 3 support this conceptual distinction. The bibliometric analysis shows significantly higher rates of internationalization in the globally systemic compared to the cumulatively global science fields (table 6).

By analyzing each case individually and by contrasting the two cases (Kelle/Kluge 1999) we investigate implications of the two dimensions for capacity building. Furthermore, the objective of the comparison is to identify additional organizational dimensions that are relevant for the success of international collaboration programmes in general. This analysis has an exploratory character since it does not begin with the definition of independent and dependent variables but seeks to decipher a complex pattern of relationships. This open methodological approach was chosen because hardly any studies exist so far in the sociology of science literature from which specific hypotheses on the organization of international GEC research might be derived.

The dimensions discussed in chapter 4 can be used as a starting point for metric operationalizations in future research. Quantitative operationalizations would be needed for more comprehensive surveys, for example in order to generate primary data on the number of scientists who participate in a programme from different countries, on amounts of funding, funding sources, attitudes towards collaboration, reputation of the programme in the respective intellectual field, research activities in developing countries, and scientifc publications resulting from associated research. In this way, such an investigation would assume the character of a comprehensive programme evaluation.

The fact that the institutional tradition of the ICSU programmes has been more or less neglected by sociology is probably related to the more general situation that interest in complex patterns of institutional factors, actor constellations and modes of governance has declined in social studies of science. Therefore, we agree with the appeal by Uwe Schimank for a "renewal of an institutionalist sociology of science" (Schimank 1995: 55). However, with few exceptions (Heinze et al. 2007; Hollingsworth 2002; Laudel

2006) this proposal did not resonate positively. The question of governance and steering in the science system becomes even more important if viewed in the light of political long-term goals – such as building up knowledge for sustainable development.

2.3.2 Improving context conditions for environmental innovation

The question of social innovation capacity in the sense of sustainable development is much more complex than the previously discussed operationalization of STI capacity. There is definitely no one superior method here; instead various social scientific concepts come into question. The first chapter of this study listed and discussed several pioneering studies in this respect. The following section extends the discussion of social capacity from chapter 1 by concepts which may serve the methodological implementation of sociological research. This is mainly liked to the phrase "Capacity to link knowledge and action" in table 1, line 2 and explains the intended use of the meso level concepts listed there (economic sector, technological regime, environmental or resource regime, region at risk etc.).

A good starting point for STI research is the "model of environmental policy performance" by Martin Jänicke (Jänicke 1997). Jänicke defines capacity as "structural framework conditions" for action in conflicts between opposing advocacy coalitions (Sabatier 1999), whereby the focus of interest is on improving the capacities of the proponents of environmental protection interests. So far, this model was mainly applied at the macro level for comparative analyses of the environmental policy capacities of nation states (Jacob/Volkery 2006; Jänicke/Weidner 1997).

2.3.2.1 Starting consideration: a model of environmental policy performance

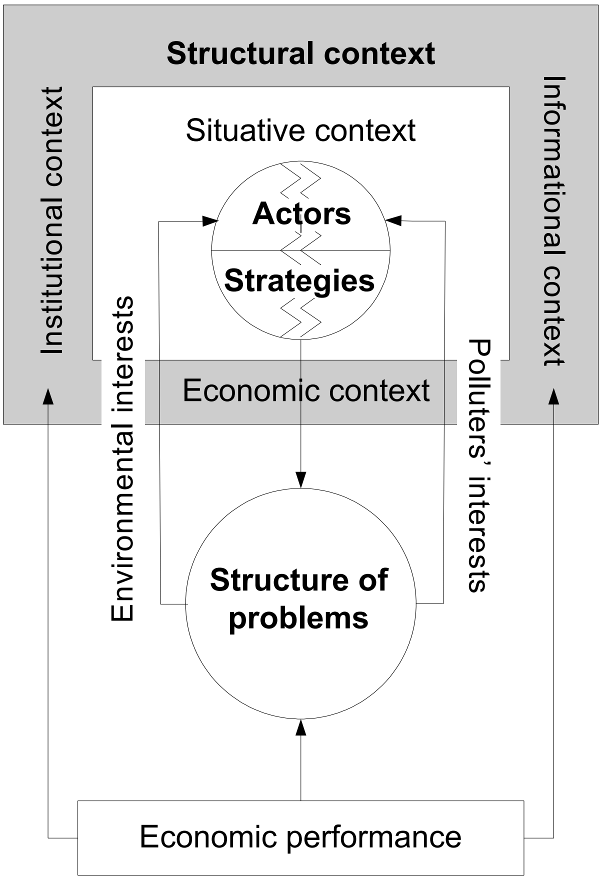
The model of environmental policy performance (figure 5) assumes that environmental policy development is determined by the conflict between the advocates and opponents of political innovations (e.g. the introduction of new legal regulations). Therefore the contest between two (or more) advocacy coalitions with conflicting interests (e.g. environmental protection vs. polluter interests) is at the centre of the model. Furthermore, the model acknowledges characteristics of environmental issues (problem structures). "Strategies" is the general term applied to describe how these actors design their action, including their motivations, belief systems, objectives and means (e.g. policy instruments). From the perspective of the actors involved, the field of contest is characterised by opportunities for and obstacles to them carrying out their strategies.

The "problem structure" is mainly determined by the perceived urgency of an environmental problem and the available options for its solution. The problem structure of environmental problems for which a technical solution exists (e. g. the ozone hole) is generally easier for the political system to deal with than environmental problems which require fundamental behavioural changes of those addressed by the policy (e. g. climate change). Environmental problems which are caused by a small group of companies in a few economic sectors (e.g. production of CFCs) have a different political structure than problems which affect practically the entire economy (e.g. emission of greenhouse gases). The level of a country's wealth is regarded as having a significant but ambivalent effect on the problem structure because it influences both the extent of the problems to be solved and the resources available for environmental protection.

The successes or failures of actors are dependent on both "situational" and "structural conditions for action" according to the model. Situational conditions for actions comprise the sum of opportunities and obstacles which result from changing political, economic or informational situations and events and which may vary in the short term. Structural (also: system or framework) conditions for action are, in contrast, the sum of opportunities and obstacles encountered by these actors in the relatively stable cognitive-informational, political-institutional and economic-technological conditions in their country (or arena for contest).

This is where the term of capacity or capacity building comes into play. Capacity building according to Jänicke means improving the "structural framework conditions" for action. The capacity of proponents of environmental protection results from (a) their organizational strength, competence and their support groups and (b) the sum of opportunities and obstacles encountered in the cognitive-informational, political-institutional and economic-technological framework conditions (Jacob/Volkery 2006: 72; Jänicke et al. 1999: 79). Elsewhere he says: "Basically this is to do with the stable resources for action which political advocates of environmental protection themselves command or encounter in the systemic conditions" (Jänicke et al. 1999: 112).

Figure 5: Determinants of environmental policy performance



Source: Jänicke (1997)

Even if the term capacity is not able to be operationalized precisely, Jänicke justifies its introduction in that he is looking at the more basic question of the conditions governing action and how to improve them rather than the question of making the correct individual political decision or selecting individual policy instruments:

> A problem can exceed the available objective possibilities of those wanting to solve it. In this case, it is not the choice of instrument or the creation of a target but the improvement of capacity which is the primary task. Possibilities to do so range from improving the knowledge base through developing institutions up to opening previously closed policy networks of polluters, improving policy integration or extending the advocacy by a policy of alliances.
>
> (…) capacity extensions are also necessary because in growing economies environmental problems – up to now at least – are seldom able to be solved permanently. For Luhmann, the existing environmental problems make it 'completely clear that politics would have to be able to do a lot and is able to do little' (Luhmann 1986: 169). (…) This is where environmental policy strategy should make a constructive start (Jänicke et al. 1999: 113).

Jänicke's model of environmental policy conflict clearly moves within the disciplinary framework of the political sciences. But the term "structural framework conditions for action" or "structural context" (strukturelle Handlungsfähigkeit) itself points beyond the political system in its narrower sense. This is where STI research comes in by interpreting the structural conditions in the sense of innovation-oriented capacity building. This does not actually involve a fundamentally different interpretation of the original concept, but only an opening and shifting of the focus. The closeness of the political science model to a concept of social innovation capacity was already obvious in the citation above, in which Jänicke refers explicitly to the structural significance of the knowledge base. In addition, the significance of technology options is emphasised by the concept of the problem structure. The term social innovation capacity should cover both technological and institutional innovations which also includes new legal regulations. This broader interpretation was also emphasized in chapter 1.

What we have gained theoretically by introducing this model is first of all the reference to a field of social contest. This basic concept of contest or conflict is particularly suited on the one hand to the requirements of policy analysis in its narrowest sense, e.g. for analyzing legislative procedures in a parliament under the influence of antagonistic lobby groups. On the other hand, the conflict model can also be generalized beyond the political system, for example, in order to analyze new technological paradigms. One should consider, e.g. the introduction and development of renewable energies in competition with fossil and nuclear energy sources, which also includes contest between economic actors and interests.

The empirical investigation of innovation capacity thus faces the task of *defining more exactly the boundaries of the field of conflict or the field of social forces*. This definition of the research object has major methodological implications for designing empirical studies. Which institutions, actors, strategies, discourses, knowledge and technologies, actions and consequences of actions should be included in the respective study and where should the analysis cut off? Is it possible to describe arenas in which actors with conflicting interests come up against each other and decisions are made about their success or failure? Only in the simplest case can the analysis be restricted to an institutionally predefined arena such as the legislative procedure in a democratic parliament.

The concepts shown in the second line of table 1, (p. 23) are to be understood as different ways of marking the boundaries of the empirical object under study. In the following, the examples cited there "economic sector", "technological regime" (table 1 first column) and "environmental or resource regime" (table 1 second column) are explained in more detail. These concern three meso level concepts with a comparable empirical scope.

Environmental risk policy is another example in table 1. Since this topic corresponds closely to the original model of policy analysis, its adoption here does not require additional explanation. The example of a risk policy study with an elaborated policy analytical set of tools was described in section 1.2.3.1 (Social Learning Group 2001a; 2001b). In the case of adaptation research, suitable STI concepts are less easily recognizable as explained in section 1.2.4.

2.3.2.2 Using the concept of the sectoral innovation system to operationalize the field of social contest

As far as we are aware, the approach of sectoral innovation systems has not yet been used to measure the capacity for environmental innovations and ecological modernization in environmentally-intensive sectors (polluting sectors). However, Jochem (Jochem 2004; 2006) did demand a systematic treatment of innovation capacity with regard to the energy efficiency of consumption sectors (see example 1.2.1.1).

Defining the object of study: According to Malerba (2005), a sectoral innovation system is made up of three main components: (a) knowledge and technology, (b) actors and networks, (c) institutions. The shared knowledge base and technologies are the main references used to define the sector. The sector is often operationalized using product groups: Malerba (2005) examined the sectors of pharmaceutics, chemicals, telecommunications, software and machine tools. It is also possible to use more strongly disaggregated definitions, i.e. for subsectors or product segments (e.g. fuel cell vehicles).

The innovation system approach emphasizes that firms do not innovate in isolation. In the innovation process firms interact with other firms just as they do with other types of organization (e.g. universities, research institutions, authorities, banks etc.). Therefore the interest here centres on the concept of the innovation network. There is empirical evidence to show that networks mainly link actors who share complementarities with regard to knowledge, abilities and specializations (Malerba 2005: 68).

Transferring the term capacity: The innovation system approach conceives of the social contest between innovators and the forces of inertia ranged against them not as a political conflict but as an evolutionary process of selection. Economic events are described using terms taken from evolutionary theory including variation, replication and selection, where these refer to the variation and selection of companies as well as that of products and technologies. The most important selection mechanism from the viewpoint of evolutionary economics is the demand on the markets.

The evolutionary-economics vocabulary is neutral regarding the content and the use of an innovation (cf. section 2.2) which prevails as a result of the competition. This is different to the environmental policy view. However the contrast between evolutionary economics and classical and neoclassical economics is of greater importance. Unlike classical economic theory, evolutionary economics does not assume that selection is determined solely by market forces on perfect markets, but emphasizes the influence of institutions and actor networks for the continued existence of companies and technologies.

By conceding, and even emphasizing the significance of institutions and actor networks, evolutionary economics allows a fundamental connection to be made between the innovation system approach and an ecological economic policy which is more strongly defined by normative objectives. In its present form, the innovation systems approach is already frequently used to inform and to legitimise economic policy measures. The usual focus here is on measures which aim to strengthen the innovation capacity and thus the competitiveness of economic actors (Miettinen 2002).

Transferring the innovation system approach to sustainability research purposes can be done in a simple and in a complex way. The simple form consists of selecting sectors which can be defined by environmental technologies and environmentally-friendly products. There are already several examples for this in the literature (e.g. the previously cited study on the environmental sector by Legler et al. 2006). The analysis can then proceed without major changes to the original conceptual framework, but remains restricted to a relatively small segment of the economy, i.e branches of environmental industries. The really interesting, but methodologically also more complex variant consists of examining capacity for ecological modernization in environmentally-intensive sectors which then mainly involve the manufacturing industry but also service sectors and the agricultural sector.

STI-capacity then means the aptitude for ecological modernization and transformation within polluting sectors. Studies of this topic could for example relate to unexploited efficiency potentials and technology alternatives, the available knowledge base, actor coalitions of environmental innovators, sector-based training and further training, sector-specific regulation, shaping demand using market incentives, diffusion channels and obstacles to environmentally-friendly technologies, international lead markets and intermediary institutions for knowledge and technology transfer. In analogy to this, the term capacity can also be defined as the sector-related ability to manage ecosystems or to adapt to climate change (table 1).

The focus of the innovation system approach on relatively stable combinations of technologies, institutions and actor networks is eminently suited to studies of ecological capacity development. An argument in favour of this form of sector-based capacity research is the fact that markets frequently fail as far as information about the costs of environmental consumption and related efficiency potentials are concerned (Ekins 2006).

2.3.2.3 Using the concept of the technological regime to operationalize the field of social contest

A topic related to the innovation system approach is the research on technological regimes (table 1, first column). The term "technological regime" was originally used by Nelson and Winter (1977, 1982), who investigated the influence of technological characteristics on the development of market structure and in particular how technologies are influenced by their closeness to science. Recently, the term has also been transferred to sustainability topics in order to describe the socio-economic transition to alternative technologies. Here, the environmental intensity of a technology regime is the main characteristic used to distinguish between individual regimes and not knowledge intensity as was previously the case.

Defining the object of study: Similar to the sectoral approach, the regime approach also looks at relatively stable combinations of knowledge, technologies, actors and institutions. In contrast to the sectoral innovation system, the regime approach often refers to the choice between two technological alternatives, i.e. to a cohesive set of existing technologies and institutions which is contrasted with a new alternative set held to be advantageous from an ecological viewpoint.

Transferring the term capacity: In the regime approach, the field of conflict (in the sense of Jänicke's model) is determined by the desired transition from the old, environmentally-intensive regime to the new, environmentally-friendly regime. The regime approach is consequently also much more normatively coloured than the original innovation system approach. A large part of the literature on technological regimes and "transition management" clearly takes the stand as supporting such a transition and demands participative modes of governance for steering transition processes ("reflexive governance", Voß et al. 2006). The political planning horizon involved may be very long indeed (decades).

The regime approach is well suited to large infrastructure systems such as water supply, transport infrastructure or energy supply which often come under state provision and whose further development has to be planned years and decades in advance. A good example is the current discussion of sustainable wastewater disposal in the Netherlands. This concerns the transition from centralized sewage systems which have a high demand for drinking water and energy to decentralized closed systems in which solid faces, urine and wastewater are collected and treated separately (eco-sanitation). This question was examined from the perspective of "transition management" in order to advise policy makers (Vliet 2006).

As in the case of eco-sanitation, it is often not possible for the transition to alternative regimes to occur gradually, but for technological reasons a radical change of direction is required. In this context, capacity refers to the political and economic ability to induce a technological change of direction in spite of immense existing investments in the old regime (sunk costs).

2.3.2.4 Using the concept of the environmental or resource regime to operationalize the field of social contest

The term environmental or resource regime was developed specifically for sustainability research (see Young 2002). Similar to the already discussed concepts, this subject can also be described as a relatively stable combination of actors, technologies, knowledge and institutions. The research interest relates to changes of the regime in the direction of greater ecological sustainability.

Defining the object of study: Whereas the borders of the sectoral innovation system and the technological regime are set mainly with regard to technologies and economic activities, in an environmental regime, priority is given to the ecosystem and the institutions determining its utilisation and exploitation. Rights of use play an important role in renewable resources and environmental sinks. To this extent, the environmental regime approach can be classified under the task domain (2) ecosystem management (table 1). The regular setting of catch quotas to limit the exploitation of fish stocks is one example for an environmental regime (Young 2003). Another example is the trade with water rights or with CO_2 emission allowances.

Defining the object usually starts with an institutional (e.g. administrative) demarcation, i.e. the scope of a regime. However, this can also be a combination of institutional and natural borders. Based on the scope or the area covered, a set of economic activities, technologies and actors can then be determined which influence the ecosystem and are influenced by the form of the institutional regime. However, it is usually no trivial matter to define the object.

The fact that institutions, economic activities and ecosystem borders do not necessarily match should not just be treated as a methodological definition problem but is actually part of the analytical core of environmental regime research. The environmental regime approach according to Oran Young follows the concept of improving the institutional fit between an institutional regime and its ecosystem in such a way that sustainable resource use can be guaranteed. This is why reflecting on varying demarcation possibilities (natural and social) makes up such a large part of the institutional analysis, e.g. in cross-border ecosystems or in multi level governance systems.

Transferring the term capacity: The starting point for research is frequently the observation that an existing environmental regime results in an overuse of resources and the degradation of the respective ecosystem (Buck 1998; Dolsak/Ostrom 2003). The innovations targeted within the regime may be institutional and technological in nature (e.g. limiting the right of use, extending monitoring, simulations of ecosystem development).

As long as we can find any proponents of environmental protection, the model of environmental policy performance can be applied to the reform of an environmental regime.

All studies agree that the knowledge base is a central component of an environmental regime. Knowledge base here means observing and forecasting a environmental quality as well as monitoring compliance with the rules of use. As an example, Young describes the methodological problems with observing fishing stocks in the world's seas, but also in implementing the limited knowledge available in operational measures (Young 2003). An important field for STI capacity research is therefore once again in this case the diffusion of suitable methods and the effective application of the best available knowledge (see section 2.2). Questions of the links between scientific expert knowledge and practical experience (e.g. farmers, fishermen) and the legitimacy of their different knowledge claims also play an important role (e.g. Ebbin 2004).

2.4 Conclusion

Subsequent to the clarification of the task domains in terms of content in chapter 1, chapter 2 examined how STI capacity might be operationalized. Three different methodological approaches were presented. These methods can be triangulated and complement each other. The methodological discussion shows that the notion of capacity is not just an empty phrase, but also seeks to avoid lacing up the concept in a tight corset of operational definitions. A number of topics for further methodological research have emerged from this discussion:

1. Adapting patent and publication indicators through appropriate field definitions and the construction of suitable, multi-lingual publication databases,
2. Measuring the diffusion of environmental innovations as an operationalization of STI capacity,
3. Investigating innovation capacity in constellations of social actors on the meso-level of sectors, technological regimes or environmental regimes, guided by the conceptual model of environmental policy performance.

3 Explaining international collaboration in global environmental change research

Abstract

This paper maps the domain of Earth and environmental sciences (EES) and investigates the relationship between cognitive problem structures and internationalization patterns, drawing on the concepts of systemic versus cumulative global environmental change (GEC) and mutual task dependence in scientific fields. We find that scientific output concentration and internationalization are significantly higher in the systemic GEC fields of Meteorology & Atmospheric Sciences and Oceanography than in the cumulative GEC fields Ecology and Water Resources. The relationship is explained by stronger mutual task dependence in systemic GEC fields. In contrast, the portion of co-authorships with developing, emerging and transition countries among all international publications is larger for Water Resources than for the three other fields, consistent with the most pressing needs for STI capacity development in these countries.

The text of this chapter is published in the journal "Scientometrics", Vol. 71 (3); (June,(Jappe 2007) pp. 367-390. This research was presented as a poster on the "9th International Conference on Science & Technology Indicators" at the Katholieke Universiteit Leuven, Belgium, 7-9 September 2006. An image of the poster is attached at the end of this chapter (Figure 10).

3.1 Introduction

The earth's surface is large and heterogeneous, yet scientific activity is highly concentrated in a limited number of industrialised countries. How does this situation influence international collaboration in earth and environmental sciences (EES)? This paper investigates international co-authorship in EES by a combination of theoretical considerations and bibliometric methods. We start from three observations: a) Some EES disciplines are among the most internationalized fields of science, but this finding has not been explained so far. b) The geographical location and extension of research objects can influence decisions to collaborate. c) Since environmental problems and related innovation needs are ubiquitous, collaboration between scientifically advanced and less developed countries is an important issue.

According to Whitley (2000), the social organization of scientific fields is strongly linked to their cognitive problem structures. A general distinction in this respect is between fundamental versus applied research. With regard to EES disciplines, another important distinction was introduced by Turner et al. (1990): systemic global environmental change (systemic GEC) and local or regional environmental changes that become global by worldwide accumulation (cumulative GEC). Our analysis shows that these spatial problem structures can explain different levels of internationalization across environmental fields.

The paper gives for the first time a comprehensive overview of all EES fields based on relevant subject categories in the SCI (section 3.2). After a review of the bibliometric literature on internationalization in EES (section 3.3), the main part investigates the relationship between spatial problem structure and internationalization by comparing four SCI subfields in depth: Meteorology & Atmospheric Sciences, Oceanography, Ecology and Water Resources (section 3.4). This includes the theoretical discussion of spatial problem structures and their influence on collaboration decisions, the formulation of hypotheses, a description of the bibliometric methods used and a discussion of results. The main conclusions are presented in section 3.5.

3.2 Earth and environmental fields in the SCI

This section gives an overview on earth and environmental research as covered by the Science Citation Index (SCI expanded). The SCI contains about 170 subject categories, from Acoustics to Zoology. Each SCI subject category is composed of a set of journals. 21 subject categories were selected that are directly related to knowledge of the environment.[8] SCI subject categories are a good starting point for bibliometric mapping, because such field delineations are easy to interpret and replicable. On average, a subject category contains ca. 35 journals (i.e. 5,900 journals divided by 170 categories), ranging from 5 (andrology) to 277 (biochemistry and molecular biology). The total set of the 21 earth and environmental research fields accounts for 9.3 % of all SCI publications in 2002.

Table 3 gives an overview of all 21 earth and environmental subject categories (EES fields). The fields are grouped in three content domains: 36.7 % of all environmental publications cover the *geosphere*, the non-living environment on earth. Research on the *biosphere*, encompassing life and organic matter, accounts for 49.7 % of the total environmental output, whereas research related to the *management of environmental resources and environmental engineering* amounts to 22.5 % (some journals are assigned to more than one domain). For each domain, table 3 lists the number of articles per field in descending order, as well as a comparison of output growth rates.

In the period from 1990-2002 publication output grew more strongly in the environmental management & engineering and in the geosphere fields than in the biosphere subset. The growth rate in the biosphere set (135) is slightly below that of the SCI total (147), whereas the growth in the set of all 21 EES fields (152) is similar to the database average (the SCI contained 886,981 publications in 2002). Behind this broad comparison lie very different growth rates of individual fields. Six fields showed a doubling in volume or more since 1990: Meteorology & Atmospheric Sciences, Oceanography, Paleontology, Ecology, Environmental Engineering and Water Resources. Three fields were newly introduced to the database during this period: Remote Sensing, Geochemistry & Geophysics and Biodiversity Conservation.

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[8] A few additional fields could be included in a still broader definition of environmental research (e.g. Agronomy, Energy & Fuels, or Toxicology).

Table 3: Earth and environmental research fields in the SCI

SCI Subject Categories	Publ. 2002	% 21 fields	Growth (1990=100)
1. Geosphere	30,135	36.7	164
Multidisciplinary Geosciences	12,382	15.1	141
Geochemistry and Geophysics*	9,358	11.4	n.a.[1]
Meteorology & Atmospheric Sciences	7,439	9.1	*226*
Oceanography	5,608	6.8	*223*
Geology	1,750	2.1	48
Mineralogy	1,675	2.0	141
Paleontology	1,643	2.0	*213*
Physical Geography	1,277	1.6	157
Remote Sensing	1,171	1.4	n.a.[2]
2. Biosphere	40,805	49.7	135
Plant Sciences	14,311	17.4	122
Ecology	9,189	11.2	*195*
Zoology	7,631	9.3	118
Marine & Freshwater Biology	6,728	8.2	143
Agriculture, Soil Science**	2,813	3.4	101
Forestry	2,406	2.9	145
Biodiversity Conservation	1,714	2.1	n.a.[3]
Limnology	1,177	1.4	127
Ornithology	951	1.2	127
3. Env. Management & Engineering	18,458	22.5	201
Environmental Sciences	14,446	17.6	188
Environmental Engineering	4,664	5.7	*429*
Water Resources	5,709	7.0	*203*
All 21 fields	82,139	100	152

Source: SCI via host STN; calculations by author

* Before 1996, this research was partly included in the category "Geology"

** Field contains only agricultural research in connection with soils

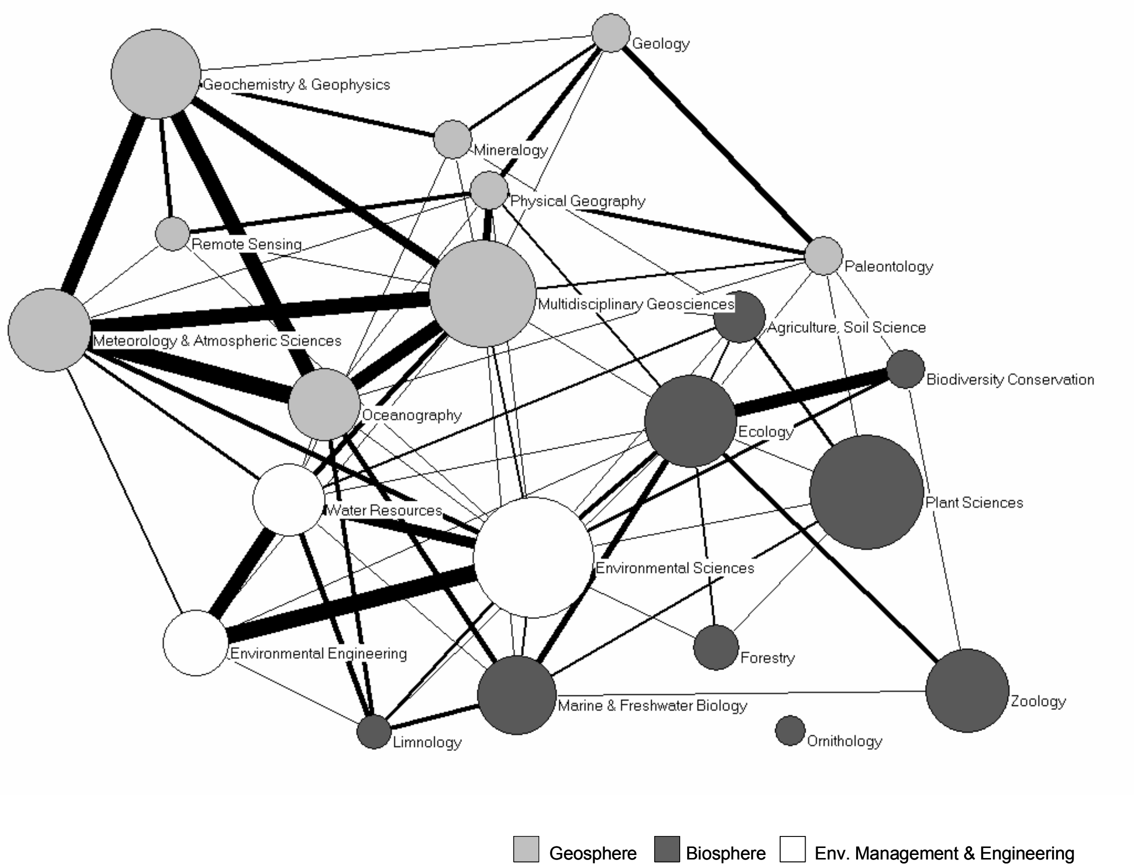
[1] Field introduced in 1996; [2] in 1992; [3] in 2000

The 21 EES fields do not include all technological knowledge pertinent to sustainability. The more eco-efficiency criteria are integrated in the development of technologies, the more difficult the separation between environmental engineering and other engineering tasks (cf. chapter 2.1). As a consequence, engineering literature which is relevent for sustainable development is often found in other subject categories. The same holds for agricultural technologies (e.g. biotechnology).

Figure 6 maps the 21 EES fields as a network. Circle size represents the number of articles in each field in the period 2001-2003. Linkages represent the degree of overlap among pairs of fields. Overlap occurs because some journals are assigned to more than one subject category, but for methodological reasons we count the number of articles that belong to more than one subject category as a result. Overlap between two fields is measured by the number of shared articles divided by the mean size of the two fields. For example, 8,000 articles belong to both Oceanography (field size 16,796 articles) and Meteorology & Atmospheric Sciences (23,193 articles) in 2001-2003. A linkage of 0.4 results, which is the strongest linkage observed among the environmental categories. An overlap of subject categories does not imply that each individual article in the intersection of sets reports multi-disciplinary research.

The network graph underlines the relevance of the three domains geosphere, biosphere and environmental management & engineering for the cognitive organization of environmental research. It shows two clusters and one pair of strongly overlapping fields. The first cluster is found in the geosphere domain, including the fields Meteorology & Atmospheric Sciences, Oceanography, Geochemistry & Geophysics, and Multidisciplinary Geosciences. The second cluster comprises all three fields of environmental management & engineering (Environmental Sciences, Environmental Engineering and Water Resources). The subject categories in the biosphere domain show weaker overlaps except for the pair of Biodiversity-Ecology. In fact, Biodiversity Conservation is a subfield of Ecology (93.6 % of biodiversity articles also belong to ecology, representing 17.5 % of the latter). Four EES fields are selected for comparison of internationalization in section 3.4: Meteorology & Atmospheric Sciences, Oceanography, Ecology and Water Resources.

Figure 6: Relative size and overlap among 21 EES fields



Source: SCI via host STN, subject categories 2001-2003. Circle areas represent the number of publications in each field. Linkages represent overlap between pairs of fields relative to field size.

3.3 International collaboration in EES fields: review of statistical data and bibliometric studies

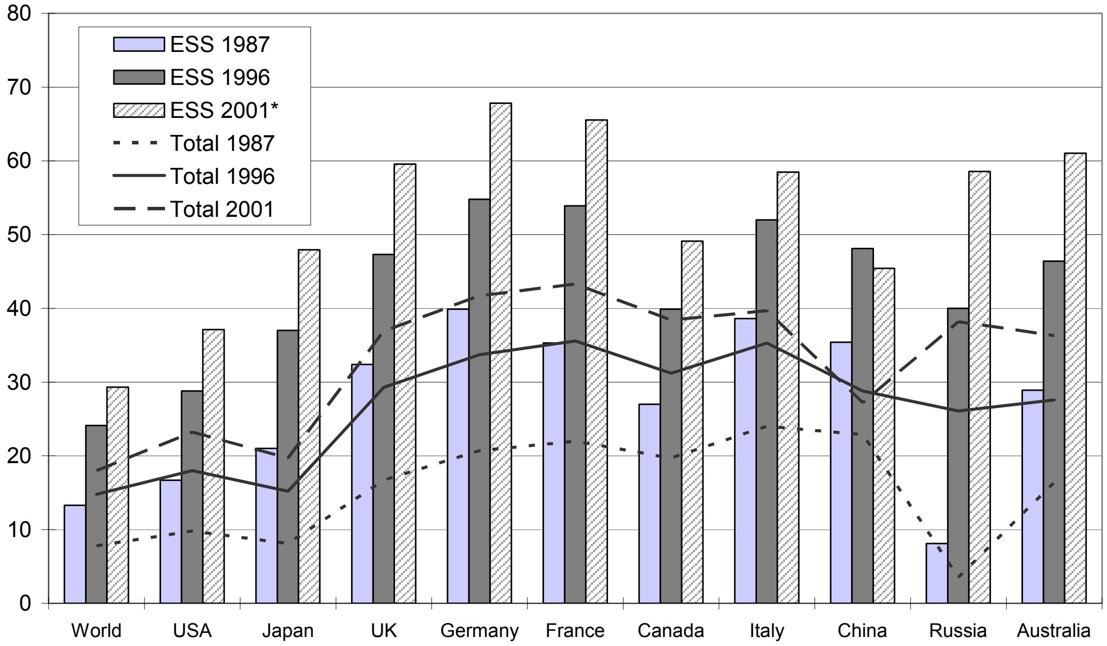
Internationalization in EES fields deserves the attention of STI research for several reasons. Firstly, some EES disciplines are among the most internationalized fields of science, but this finding has not been explained so far. Secondly, the geographical location and extension of research objects can influence decisions to collaborate. Thirdly, since environmental problems and related innovation needs are ubiquitous, collaboration between scientifically advanced and less developed countries is an important issue.

This section first presents data on internationalization in the broad domain of earth and Space Sciences as published by the USA National Science Board in its biennial report Science & Engineering Indicators. Then bibliometric studies on more narrow environmental fields are reviewed, including all published articles that we could identify (Dastidar 2004; Engels et al. 2005; Resh/Yamamoto 1994; Wagner 2005; Wishart/Davies 1998). There are some limitations with regard to the statistical sources, as the most recent data published by NSB on worldwide field-specific internationalization cover the period 1995-97 (National Science Board 2004: A6-60). The third edition of the European Report on S&T Indicators includes a definition of the EES domain, but no original data on international collaboration frequencies across fields (European Commission 2003).

Intellectual exchange in trans-national communities is a central characteristic of scientific work organization (Stichweh 1999). The past decades witnessed a strong increase of international collaboration, as measured in internationally co-authored publications (briefly, international publications). International publications are defined as publications with author affiliations from at least two different countries. Between 1988 and 2001 the total number of international publications more than tripled, while their share of all articles increased from 7.8 % to 18 % (National Science Board 2000; 2004). In 1976 only 4 % of all articles were internationally co-authored. The share of international publications among all publications is commonly called the INI-index.

While growing collaboration is a general trend, the portion of international publications is highly field-specific. In Science & Engineering Indicators, the SCI+SSCI database is subdivided into eleven broad scientific domains, among which Earth and Space Sciences (*ESS*) includes the largest subset of the 21 earth and environmental fields (*EES*) discussed in section 3.2. In the mid-nineties, 24.1 % of publications in ESS worldwide had institutional affiliations from at least two different countries, followed by Physics with 22.4 %. In comparison, Clinical Medicine, the largest field in the database, had only 11.5 % of international publications (14.8 % for database total). ESS covers the subfields of Astronomy and Astrophysics, Earth and Planetary Science, Environmental Science, Geology, Meteorology and Atmospheric Sciences, Oceanography and Limnology but excludes biological research on the environment.

Figure 7: Internationalization of Earth and Space Sciences (ESS) in ten major scientific producing countries (INI %)



* ESS 2001 data are estimates
Data: NSB (2000, 2004). Earlier data refer to three year averages: 1986-88 and 1995-97, 2001 refers to only that year. For 1986-88, the respective values of East and West Germany have been added
Australia (11th in output size) is included instead of Spain (10th)

Figure 7 shows the dynamic increase of internationalization from the mid-eighties to 2001, comparing ESS with the database average. Ten countries with the largest scientific output are listed in descending order. In 1996, ESS INI is more than 20 % higher than the database average for publications from Japan and Germany, and 18 % higher for the United Kingdom, France, China and Australia. If INI growth in ESS continues at the rate of the total database, in 2001 more than 65 % of ESS publications from Germany and France are international and around 60 % from the United Kingdom, Italy, Russia and Australia. Among the group of countries with the largest scientific output, France and Germany have the highest INI (ESS and total database), considerably higher than the INI of the smaller scientific producers Canada and Australia (although the use of English as a national language favours collaboration by the latter). China is the only country where the INI in 2001 had not increased compared to 1996.

In spite of the remarkable degree of internationalization, few studies investigated more narrow EES fields to arrive at an explanation of these internationalization patterns. The findings of four studies are summarised in table 4. While these studies present interesting data, they use different criteria for journal selection and cover different time periods, which limits cross-field comparability.

Table 4: Earlier bibliometrical studies of earth and environmental fields

Study	Field examined	Years analyzed	Journals covered	Number of articles	INI %
Wagner	Astrophysics	2000	14	6547	47.3
	Geophysics	2000	13	2789	34.0
	Soil Science	2000	10	1382	32.8
Dastidar	Oceanography	2000	35	4008	n.a.*
Wishart/Davis	Limnology	1987-1996	10	8960	9.2
Resh/Yamamoto	Freshwater Ecology	100 most recent articles (before 1994)	33	3300	9.0

* Dastidar presents networks of countries and institutes in oceanography but no field INI

Wagner (2005) compares INI across six fields, three of which are of interest in the present paper: Astrophysics, Geophysics, and Soil Science. Dastidar (2004) investigates the SCI subject category of Oceanography in the year 2000. Wishart and Davis (1998) sample articles from ten leading journals in Limnology over a decade. Resh and Yamamoto (1994) select 33 journals specialising in Freshwater Ecology and sample the 100 most recent articles from each journal.

Table 4 clearly indicates that levels of internationalization vary significantly across environmental fields. Since Astrophysics, Geophysics, Oceanography and Limnology are all part of the broader ESS (figure 7), it is apparent that ESS is itself very heterogeneous, with Astrophysics at the top and Limnology at the lower end in terms of internationalization.[9] According to Wagner's findings, INI in Geophysics and Soil Science are even higher than INI in ESS which is estimated at 29.3 % for 2001. Much lower INI in Limnology and Freshwater Ecology are partly due to earlier time periods investigated, and are consistent with the finding that biology on the whole is less internationalized.

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[9] Astrophysics is not among the earth and environmental fields in table 3 but is part of NSB's category of ESS.

The broad category of Biology (as defined by NSB, excluding biomedical research) had 7.4 % of international publications in the mid-1980s and 13.9 % in the mid-1990s, values slightly below database average (7.8 % and 14.8 % respectively; NSB 2000: A6-60). Findings from Glänzel and Schubert (2005: 335) point in a similar direction, with INI ratios of 48 % in the broad field of Geosciences & Space Sciences in 2000 as compared to 29 % in Agriculture & Environment, as defined by the authors.

The bibliometric studies take different perspectives on the topic of international collaboration in environmental research. Dastidar (2004) presents collaboration networks on the level of countries, institutes and scientists. The study demonstrates a strong concentration of oceanographic publications in the USA, but offers little qualitative interpretation of collaboration patterns. Wagner (2005) aims to elucidate field-specific INI growth. She distinguishes four types of motivations for international collaboration ("resource-driven, equipment-driven, data-driven and theory-driven") and postulates different growth rates of internationalization. Country networks are presented for six fields in 1990 and 2000. Yet the findings do not support this hypothesis. Nevertheless, Wagner's attempt underlines the need for a better qualitative understanding of EES fields to explain internationalization patterns. Resh and Yamamoto (1994) carefully select specialised journals and report collaboration frequencies per journal. Their conclusion that internationalization in Freshwater Ecology approximates that of Physics does not seem well-founded because it disregards a time lag of almost a decade between investigated periods. Engels et al. (2005) focus on collaborations between scientific centre and periphery. They analyse INI ratios of a sample of US American and German institutes in "GEC research" with different world regions (1993-2002). The study does not investigate field differences in internationalization in the sub-samples of climate and biodiversity institutes.

Wishart and Davis (1998) is the only investigation that is motivated by a scientific concern about the limited knowledge of phenomena in developing countries. Apart from INI ratios, they analyse the regional origin of senior authors, the regional distribution of membership in professional societies, and the frequency of certain thematic areas in papers with Third World authorship. The authors conclude that "(…) given the widening gulf in terms of personnel and resources, the future of essential research on inland waters in the Third World does not bode well unless in situ capacity building within

Third World countries becomes a target of First World research and funding agencies" (p. 558).

In sum, we conclude from the literature review that (1) some EES fields are among the most strongly internationalized areas of science, (2) only few EES fields have been studied with regard to internationalization, and (3) cross-field comparability among these studies is limited by varying approaches to field definition and by different time periods.

3.4 Systemic versus cumulative global change: A comparison of four scientific fields

We now compare four environmental fields in terms of internationalization and scientific output concentration. According to Whitley (2000), the social organization of scientific fields is strongly linked to their cognitive problem structures. This perspective is applied here to EES research. We follow Turner et al. (1990) who distinguish systemic and cumulative global change. Another relevant distinction is fundamental versus applied research. We explore how both cognitive dimensions as independent variables explain international collaboration and output concentration as dependent variables of social structure in EES. The central hypothesis is that systemic GEC fields show higher ratios of international collaboration than cumulative GEC fields. The relationship is explained by the influence of higher mutual task dependence in systemic fields. The basic-applied distinction influences distributions of scientific activity and collaboration patterns between countries.

Four fields were chosen to represent two different problem structures of GEC research: Meteorology & Atmospheric Sciences (MAS) and Oceanography as examples of systemic GEC research, Ecology and Water Resources as examples of cumulative GEC fields. Together, these four fields account for ca. 30 % of all environmental research in the SCI. The selection also represents different environment-related domains, as MAS and Oceanography belong to the category of geosphere research, ecology is part of biosphere research and Water Resources part of the environmental management & engineering category. All four fields are highly dynamic, with above-average long-term growth rates (1990-2002) ranging from 1.95 in Ecology to 2.26 in MAS, compared to 1.47 database average (table 3).

3.4.1 Spatial problem structures of GEC

Turner et al. (1990) distinguish between two types of GEC. Applied to research problems, their distinction characterises two different spatial problem structures:

> "In the first or systemic meaning, *'global' refers to the spatial scale of operation or functioning of a system*. A physical system is global in this sense if its attributes at any locale can potentially affect its attributes anywhere else, or even alter the global state of the system. (…) Globally systemic changes need not be caused by global scale activity, only the physical impacts of the activity need to be global in scale, manifested through the systemic adjustments that follow. (…) In the second – the cumulative – sense, *'global' refers to the areal or substantive accumulation of localized change*. A change is global in this sense if it occurs on a worldwide scale, or represents a significant fraction of the total environmental phenomenon or global resource. (…) If cumulative changes reach a global scale, it is typically as the consequence of worldwide or wide-spread human activity that may not be directly registered on the major geosphere-biosphere systems" (Turner et al. 1990: 15f.).

In systemic global change, "consequences everywhere follow from production-consumption anywhere, breaking the long-standing spatial linkage in the environmental consequences of production-consumption" (Turner/McCandless 2004: 237). The prime example of a global system is the climate system, defined as follows by the Intergovernmental Panel on Climate Change:

> "The climate system is an interactive system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere, forced or influenced by various external forcing mechanisms, the most important of which is the sun. Also the direct effect of human activities on the climate system is considered an external forcing. (…) Although the components of the climate system are very different in their composition, physical and chemical properties, structure and behaviour, they are all linked by fluxes of mass, heat and momentum: all subsystems are open and interrelated" (Houghton et al. 2001, Vol. I, Ch. 1.1.2).

Over the past 20 years, the importance of biological processes in the regulation of the climate system gained increasing recognition among climate scientists. Consequently, the global systems perspective has been extended in the direction of a total earth system that emphasises the coupling of physical, chemical and biological aspects. "In the context of global change, the earth System has come to mean the suite of interacting physical, chemical and biological global-scale cycles (often called biogeochemical cycles) and energy fluxes that provide the conditions necessary for life on the planet" (Steffen et al. 2001: 10, see also Schellnhuber et al. 2004).

Only a subset among the EES fields described in section 3.2 investigates environmental change from a systemically global perspective. Most systemic GEC research is located in four geosphere fields: MAS, Geochemistry & Geophysics, Oceanography, and Multidisciplinary Geosciences. The label "systemic GEC fields" signifies that these four fields include large portions of research on the systemic understanding of GEC. However, this neither implies that all publications in the respective geosphere categories treat global systemic topics, nor that no other EES subject category contains any global systems research. The components of the physical climate system are long-standing objects of MAS and Oceanography (Weart 2004). Research in Geochemistry & Geophysics is essential for the study of global biogeochemical cycles, along with the establishment of a sub-discipline of global ecology (Mooney 1998). Along the same lines, the category "Multidisciplinary Geosciences" is described by the databank provider as covering "resources having a general or interdisciplinary approach to the study of the earth and other planets." While there is some global systems research in Ecology, the bulk of ecological research is cumulatively global.

The mutual overlap in figure 6 points to important cognitive linkages among the four systemic fields. Some journal titles of multiply assigned journals explicitly refer to connections between fields, e.g. "Tellus Series A – Dynamic Meteorology and Oceanography", "Izvestiya Atmospheric and Oceanic Physics", "Dynamics of Atmospheres and Oceans" (the latter also assigned to the field Geochemistry & Geophysics) or "Marine Geophysical Researches" (assigned to Oceanography and Geochemistry & Geophysics). Systemic global concepts as the "climate system", the "earth system" or global "life support systems" are by definition multi-disciplinary and comprehensive. By contrast, the SCI subject category of ecology shows little overlap with the systemic fields.

In contrast to the systemic perspective, much environment-related knowledge production is focused on smaller spatial scales and is to a greater or lesser extent place-specific. Due to this combination of smaller spatial scales and interest in place-specific conditions this research could also be called "place-based". While systemic GEC research usually implies long-term fundamental research, cumulative GEC research can be either basic or applied. Ecology exemplifies the importance of place-specific knowledge, due to the heterogeneity and complexity of ecosystems on local to regional scales, in combination with a strong basic research orientation (Bocking 1997; Golley 1993). Water Resources has been chosen because it represents a cumulative field that contains both fundamental and applied knowledge (Reuss 2003).

The systemic versus cumulative distinction marks the cognitive perspective and the spatial scale of research, but no physical separation in nature. This is well illustrated by the case of water. While the global hydrological cycle is central for the movement of energy and chemicals in the earth system, little of this systemic research is categorised under the SCI subject category Water Resources. The topics in this field rather refer to the management of freshwater for human needs, such as "desalination, ground water monitoring and remediation, hydrology, irrigation and drainage science and technology, water quality, hydraulic engineering, ocean and coastal management, river research and management, waterways and ports" (database description). The field Water Resources thus covers mostly regional hydrological knowledge and technological knowledge for water resource management.

Technological knowledge usually has no geospatial reference and thus is neither systemic nor cumulative. Yet the effectiveness and sustainability of technological applications for the management of natural resources and ecosystems often depends on site-specific adaptations (e.g. water quality or soil degradation). Thus, environmental research with a strong practical orientation is often partly universal and partly place-specific. This holds not only for the case of Water Resources, but also for Soil Science, Forestry, Marine and Freshwater Biology (fisheries research). Given that anthropogenic interference with the environment and the need for improved management approaches are spread worldwide, these fields are also considered cumulatively global in the sense of Turner et al. (1990).

3.4.2 Influence of problem structures on international collaboration

Three different motivations for international collaboration in EES fields are linked with the spatial problem structure: (1) high mutual task dependence in systemic GEC fields, (2) scientific interest in particular places, (3) capacity building and technology transfer.

(1) The main difference with regard to internationalization is that systemic fields depend on a global perspective, whereas research in cumulative global problems can be conducted independently in many places. The inherently global perspective leads to stronger mutual task dependence among scientists in systemic fields. High levels of mutual task dependence are due to (a) large investments in global scale observation,

including investments in international coordination of data collection, and (b) closer cognitive integration of research efforts through shared global frameworks, i.e. theories and numerical models.

Mutual task dependence is a concept introduced by Whitley (2000) for the analysis of scientific work organization. According to Whitley,

> "modern sciences essentially are systems of jointly controlled novelty production in which researchers have to make new contributions to knowledge in order to acquire reputations from particular groups of colleagues. (…) The degree of mutual dependence has two analytically distinct aspects. The first is the extent to which researchers have to use the specific results, ideas, and procedures of fellow specialists in order to construct knowledge claims which are regarded as competent and useful contributions. This can be called *the degree of functional dependence* between members of a field and refers to the need to co-ordinate task outcomes and demonstrate adherence to common competence standards. (…) The second aspect of mutual dependence refers to the extent to which researchers have to persuade colleagues of the significance and importance of their problem and approach to obtain a high reputation from them. This can be called the *degree of strategic dependence* for it covers the necessity of co-ordinating research strategies and convincing colleagues of the centrality of particular concerns to collective goals." (2000: 85, 88, italics in original).

Two steps connect the systemic problem structure with internationalization patterns. The first hypothesis for systemic GEC is that global observation systems and cognitive integration through theories and numerical models give rise to high levels of task dependence among scientists and working groups in scientifically advanced nations.[10] The second hypothesis is that stronger task dependence results in more frequent collaboration within a research field, and in particular more frequent international collaboration.[11] High international task dependence is manifested in bottom-up collaborations among individual scientists, as measured by international co-authorships, as well as a strong tradition of international scientific collaboration programmes (cf. Greenaway 1996; Jappe 2005; Weart 2005b).[12]

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[10] For the purpose of this paper, we do not distinguish functional and strategic aspects of task dependence.

[11] On the aggregated level of entire disciplines, high collaboration frequencies are probably due to the combined effect of a number of subfields with high mutual task dependence. In cases of non-public research such as industrial big science projects or classified military research, the second hypothesis may not apply (cf. Hamblin 2005: 192f.). This hypothesis has not yet been investigated bibliometrically.

[12] Stronger task dependence is also likely to result in more pronounced stratification among scientists and among research institutions (elite-periphery structures).

International cooperation is central to establishing and enhancing the global observation systems that systemic GEC research depends on. As Edwards notes, "behind the emerging consensus on climate change lie more than 150 years of slow, painful negotiations over global standards for measuring, recording, and communicating about the weather" (2004: 827). The oldest worldwide operational system for meteorology is the World Weather Watch/GOS, established in 1963 under the auspices of WMO. Similarly comprehensive systems are still being developed for the oceanic and the terrestrial domain.[13] International programmes such as GARP (1967-1980) and WCRP (since 1980) complement operational data networks through in-depth investigations and experiments. International data centres serve the collection, storing and processing of data, ensuring open access to scientific information (Greenaway 1996: 160ff., 175).[14]

Mutual task dependence does not result merely from the cooperation required to enhance operational observation systems, but also from the fact that global expert communities operate with highly standardised data products. Due to the complex operations involved in the generation of global data sets, it has been argued that global data and global models are "no longer distinct entities, but parts of a single system for representing the world" (Weart 2005a: 12).

Atmospheric general circulation modelling (AGCM) is a prime example for strong mutual task dependence through cognitive integration.[15] GCMs are at the centre of research on climate change and are used to integrate observations and analytical contributions from diverse specialities (cf. history of AGCM in Weart 2005a; on integration cf. Cox/Nakicenovic 2004). Although observation and experiments are undertaken on a broad range of spatial scales and may include the sun and other planets, their ultimate purpose is to inform understanding of global system functioning. In turn, enhanced simulation of system behaviour is seen as the prerequisite for the prediction of regional impacts.

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[13] For example ongoing planning for a Global Earth Observation System of Systems, http://www.epa.gov/geoss/index.html; last accessed 22nd March 2006.

[14] GOS stands for Global Observation System, GARP for Global Atmospheric Research Programme, WCRP for World Climate Research Programme, WMO is World Meteorological Organization.

[15] "Communities of collaboration among experts had been rapidly expanding throughout geophysics and the other sciences, but perhaps nowhere so obviously as in climate modelling." (Weart 2005a: 27).

Model complexity and the requirements of computing power restrict the number of approaches that are used in parallel within the AGCM field, so that researchers follow the development of a limited number of shared global frameworks (Edwards 2001: 58). Even today, only a limited number of research centres worldwide are capable of developing and running the most advanced earth system models that couple processes of the atmosphere, land surface, ocean and sea ice, aerosols and the carbon cycle.[16] Experiments that systematically compare the performance of different models are part of the research strategy and an additional element of cognitive field integration.

Ecology and Water Resources exemplify fields that typically combine finer spatial resolutions with a stronger adaptation of research approaches to specific local conditions. Certainly, theories and methods contain generalisations which make them applicable in different contexts and allow the accumulation and progress of knowledge across sites. Still, the dependence of scientists at different places on each other's achievements remains weaker relative to systemic fields. Comparatively low mutual task dependence leads to a greater diversity of approaches and reduces the pressure for a standardisation of data, methods and concepts.

(2) In earth and environmental research, the scientific motivation for international collaboration is often connected to particular qualities of a geographic locality. This holds independent of the degree of task dependence in the entire scientific field. For example, ecologists investigate the island Hawaii as a model for the role of nutrient cycles and nutrient limitations in ecosystems (Vitousek 2004). International collaboration also serves to compare objects and to exchange experiences across sites, as in river basin management (e.g. Bressers/Kuks 2004) or to investigate connections between distant places. Synoptic assessments of environmental conditions for large regions or the entire planet are especially demanding in cumulative fields since they require in-depth investigations at a large number of carefully selected places. Models and satellite remote-sensing can substitute for in situ data to a lesser extent than in systemic GEC research. For this reason, global assessments are often compilations of existing knowledge and include only some original research (e.g. the Millennium Ecosystem Assessment).

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[16] Cf. AGCM family tree on http://www.aip.org/history/sloan/gcm/famtree.html; on development stages of coupled modelling see Carson (2005).

(3) Apart from the purely scientific motivations, international collaboration relates to different levels of STI capacity among developed and less developed countries. This is more relevant in research on natural resource management and related technological applications than in fundamental natural sciences. Two approaches to collaboration can be distinguished: to solve a specific problem in a developing country by applying and adapting externally developed S&T solutions, or to support STI capacity building within the developing country itself.

> "At one extreme, it is possible to use the S&T capabilities of developed countries (…) to generate knowledge, technologies and products that address the problem under consideration. (…) At the other extreme, it is possible to support the creation of domestic STI capabilities, which may involve institutional support programs, long-term scientific and technical assistance, information sharing, and graduate fellowships to train S&T researchers, as well as policy-makers and technology managers" (Sagasti 2004: 106).

Pressing environmental problems related to water use, health and food production are likely to receive more attention in emerging and developing countries than long-term environmental risks that are characterised by high scientific uncertainties. As a consequence, scientific production is likely to be more concentrated in the scientifically most advanced countries if fields require high investments in basic research. This holds both for systemic and cumulative long-term risks, such as climate change and biodiversity loss.

Apparently, scientific interest in distant localities is not always well documented by co-authorships. Dahdouh-Guebas et al. (2003) analyzed research on least developed countries (operationalized as publications which mention at least one of the 48 least developed countries in the title) and found that 69 % of this research is published by authors from industrialised countries without including local research institutes. The authors attribute this to a "spirit of neo-colonial science" (pp. 334, 340). It is noteworthy that the LDC sub-sample amounts to less than 0.2 % of the basic set of publications in the database Current Content (1999-2000).

3.4.3 Hypotheses

Hypothesis (1): summarising the argument in section 3.4.2 with regard to the effect of spatial problem structures, we hypothesise that systemic GEC generates a higher degree of mutual task dependence among scientists than cumulative GEC, resulting in higher international collaboration frequencies (**INI**). This hypothesis can be specified further by assuming that the portion of systemic GEC research is higher in MAS than in Oceanography, leading to the following hypothesis:

1. $\textbf{INI}\text{ MAS} > \textbf{INI}\text{ Oceanography} > \begin{cases}\textbf{INI}\text{ Ecology}\\ \textbf{INI}\text{ Water Resources}\end{cases}$

Hypothesis (2): the fields MAS, Oceanography and Ecology contain a higher share of fundamental research than Water Resources, leading to the expectation that the former show higher concentrations of publication output among the scientifically most advanced countries. Furthermore, the initial investments in technology that are required to establish competitive research are typically larger in the two systemic fields compared to Ecology and Water Resources, constituting a higher entry threshold to the former fields.

If output concentration (**OC**) is defined as the output share of the 20 largest scientific producing countries (as a group), the following hypothesis can be formulated:

2. $\left.\begin{array}{l}\textbf{OC}\text{ MAS}\\ \textbf{OC}\text{ Oceanography}\end{array}\right\} > \textbf{OC}\text{ Ecology} > \textbf{OC}\text{ Water Resources}$

Hypothesis (3): although levels of scientific capacity are heterogeneous, developing, emerging and transition countries (DET countries) generally face important tasks of R&D capacity development (cf. Sagasti, 2004: 123ff.) Applied problems related to water resources are likely to receive more attention in DET countries than systemic or other long-term environmental risks associated with high scientific uncertainties. Participation of DET countries in international collaboration is measured as the ratio of international publications with authors from DET countries in relation to all international publications in a field (**DET ratio**). The hypothesis is:

3. $\textbf{DET ratio}\text{ Water Resources} > \textbf{DET ratio} \begin{cases}\text{MAS}\\ \text{Oceanography}\\ \text{Ecology}\end{cases}$

3.4.4 Methods

The hypotheses are investigated in three steps, measuring (a) share of international publications, (b) output concentration, and (c) ratio of international publications with DET countries for two fields of systemic GEC (MAS, Oceanography) and two fields of cumulative GEC (Ecology, Water Resources).

Publication output was searched in SCI expanded for the period of 2002-2003. The software VantagePoint is used to construct field and country databases. Output concentration is measured for the group of the top twenty countries in terms of output size. In order to ensure that scientific size is accounted for independently of that country's propensity for international collaboration, fractional assignments of articles to countries are used to determine output ranks (National Science Board 2004: A5-35).[17] All other computations in this paper assign publications to countries on a whole count basis.

Internationalization is compared on the level of entire fields and for individual countries, as it is well-known fact that countries' propensity for international collaboration differs significantly (Glänzel/Schubert 2004). The relative internationalization index (**RI**) measures how much a country collaborates internationally in an EES field relative to that same country's internationalization across the total database. **RI** is defined as:

RI = 100 tanh ln [(INI kj) / (INI k sci)],

where INI kj is country k's share of international publications in field j, and INI k sci is that same country's share of international publications in the database SCI+SSCI. The hyperbolic index is symmetrical and bounded to ± 100 (cf. Grupp 1998: 158).

In order to assess the relative importance of collaborations with countries that are still more peripheral to the global science system, we define the umbrella category of "developing, emerging and transition countries" (DET). This group includes all countries except USA, Canada, Japan, EU-15, Iceland, Switzerland, Norway, Israel, Australia, New Zealand and Russia. The importance of collaborations with DET countries is measured by international publications that include author affiliations from at least one of

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[17] 20 countries with largest output in 2001 in descending order: USA, Japan, United Kingdom, Germany, France, Canada, Italy, China, Russia, Spain, Australia, Netherlands, India, South Korea, Sweden, Switzerland, Taiwan, Brazil, Israel, Belgium.

these countries. The participation of DET countries in scientific collaboration is measured by the ratio of international publications that include author affiliations from DET countries by all international publications in that field (DET ratio).

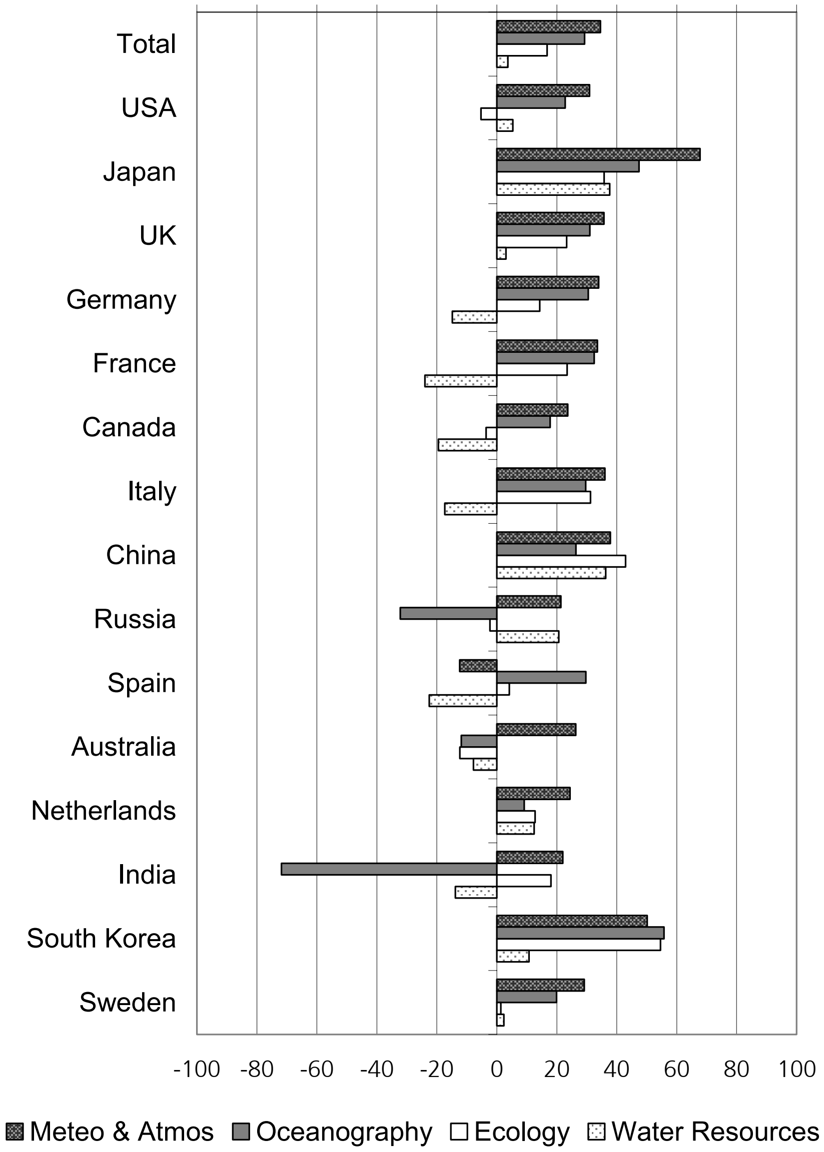
3.4.5 Results

International collaboration. Consistent with hypothesis (1), we find that internationalization is significantly more developed in systemic GEC fields than in cumulative GEC fields. As expected, INI MAS is higher than INI Oceanography (25.8 % and 24.3 %, respectively). INI Ecology (21.3 %) is still considerably above, and INI Water Resources (18.7 %) close to database average (18.0 %). On the country level, the systemic fields are characterised by high degrees of relative internationalization. RI indicates how much a country collaborates internationally in a given field relative to the country's internationalization in all fields of the database (figure 8).

In MAS, all 15 countries have very high RI values, with the exception of Spain (RI = -12.4). By far the highest RI are attained by Japan (67.8) and South Korea (50.2), followed by China, Italy, United Kingdom, Germany and France, (between 37.9-33.6). A similar pattern is observed in Oceanography, although on a slightly lower level, again led by South Korea (55.7) and Japan (47.4). In Oceanography, three countries show interesting deviations from the average pattern of high RI: India (-71.8), Russia (-32.2) and Australia (-11.9). In all three cases, this is due to strong domestic journals (see below).

By comparison with the systemic fields, RI is on average lower in the fields of Ecology and Water Resources and more variable across countries. Although Ecology is more internationalized than Water Resources, similar RI levels of both fields are observed for Japan, China and the Netherlands. In a number of other countries, RI is more elevated in Ecology than in Water Resources, including the UK, Germany, France, Canada, Italy, Spain and India. The opposite pattern (higher RI for Water Resources than Ecology) is observed only for Russia and to some extent for the USA. Again, the highest RIs are attained by East-Asian nations, with South Korea leading in Ecology (RI = 54.6), Japan and China in Ecology and Water Resources (Japan 35.8 and 37.7; China 43.0 and 36.3 respectively). However, the three East-Asian countries have negative specialisations in Ecology, and the contribution of South Korea to this field remains small

Figure 8: Relative internationalization (RI) in four GEC fields



Source: SCI web of science, 2002-03

If a country holds a large share of the reference database, as in the case of the USA, its RI tends to deviate less from the database average compared to countries with smaller publication output.

in absolute terms. China is the only country in our sample that combines a strong internationalization in Water Resources with a comparatively strong orientation towards this field.

The influence of domestic journals was checked for all four fields. Domestic journals in English language are an important vehicle for oceanographers from India, Russia and China to communicate results to an international audience.[18] In the cases of Russia and Australia, this international communication strategy is also linked with strong national specialisations, pointing to the existence of important oceanographic communities in these countries. In MAS, national journals play a similar role for China and, to a lesser extent, for Australia and Japan. In the two cumulative fields, domestic journals generally have less influence, with the exception of a Russian journal in Ecology. A limited role of domestic journals is also observed in the cases of Canada and Australia in Ecology, and for France and Canada in Water Resources.

Output concentration. Consistent with hypothesis (2), scientific output is more concentrated in systemic GEC fields than in cumulative GEC fields (table 5). In the two systemic fields, more than 91 % of all publications carry author affiliations from the 20 largest producing countries. Output concentration in Ecology is close to and Water Resources considerably below the database average. Although output concentration is still high in the field of Water Resources, these aggregate values indicate more participation by countries that are smaller in terms of scientific output.

Table 5: Output concentration across GEC fields (% of articles)

2002-03	SCI	Meteo & Atmos	Oceano-graphy	Ecology	Water Resources
Top 20 countries*	86.8	92.7	91.3	86.2	81.8
USA	33.0	47.7	45.8	41.2	27.6
Japan	9.3	8.0	7.7	3.1	4.3
UK	8.1	9.5	10.3	11.1	8.0
Germany	8.3	11.0	9.6	5.7	5.8
France	5.8	7.5	8.5	5.6	6.7

Source: SCI via host STN. Country assignment on the basis of whole article counts

* The 20 countries with the largest scientific output are searched as a group to avoid double counts of intra-group international publications.

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[18] Domestic journals contain large portions of national output in a field but low shares of international publications, e.g. "Indian Journal of Marine Sciences" (49 % of Indian publications); "Oceanology" and "Izvestiya Atmospheric and Oceanic Physics" (74 % of Russion publications); "Marine and Freshwater Research" (24 % of the Australian publications); "Acta Oceanologica Sinica" (30 % of Chinese publications).

Collaboration with developing, emerging and transition countries. The differences in the degree of internationalization between systemic and cumulative fields are not reproduced in collaboration with DET countries (table 6). INI DET is highest in Water Resources (9.7 %) and lowest in Oceanography (7.6 %). However, the difference is much more striking if we consider the fraction of DET collaborations in all international collaborations. Consistent with hypothesis (3), it is evident that DET countries play a more important role in the internationalization of Water Resources than in the three other GEC fields: 49.8 % of all international publications in Water Resources include authorships from at least one DET country, as compared to 33.6 % in MAS, 38.6 % in Ecology and only 31.1 % in Oceanography. This finding supports the conclusion that motives related to technology transfer and capacity building are an important factor for international collaborations in Water Resources.

Table 6: International collaboration across GEC fields (%)

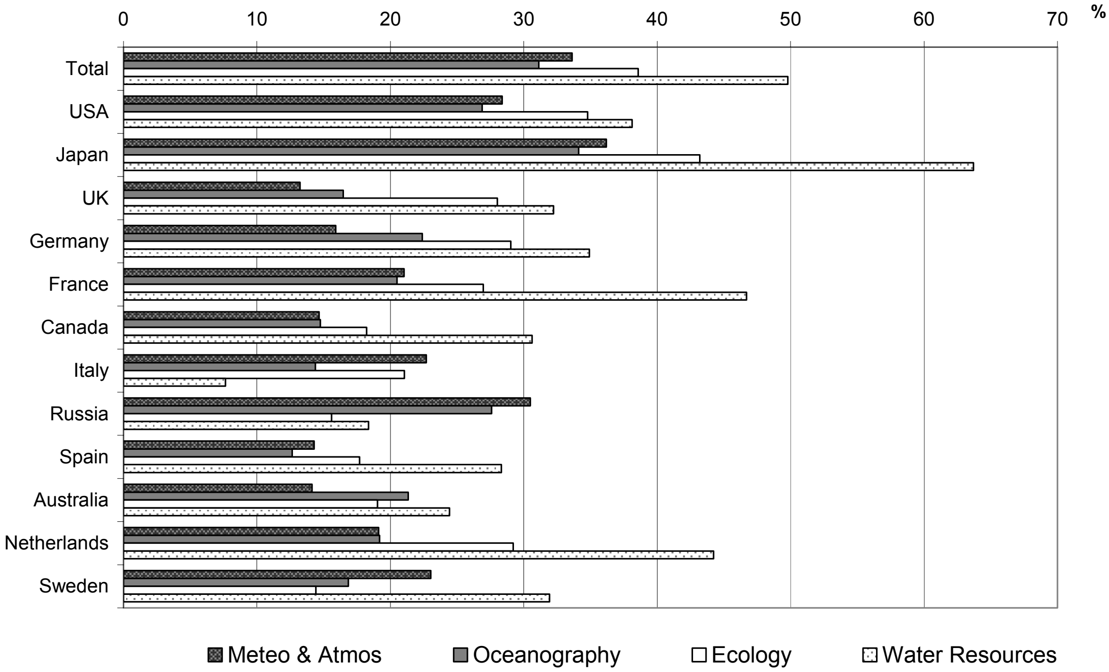
2002-03	Meteo & Atmos	Oceanography	Ecology	Water Resources
INI total (A)	25.8	24.3	21.3	18.7
INI DET (B)	8.7	7.6	8.2	9.3
DET ratio (B/A)	33.6	31.1	38.6	49.8

Source: SCI via web of science

On the country level, the strongest differences between DET ratios in Water Resources and other GEC fields are found in Japan, France, Netherlands, Canada, Spain, and Sweden. 63.7 % of Japan's international publications in this field also include authors from DET countries. Still, in absolute terms, the USA remains the largest collaborator of DET countries in Water Resources, with South Korea, China and Taiwan as its most frequent partners, followed by Brazil, Mexico, Turkey and India.

Apart from a country's attained level of scientific capacity, cultural and geographic ties shape the channels of DET collaboration: Japan's most prominent collaboration partner in Water Resources is China, followed by South Korea and Taiwan. France collaborates most frequently on water issues with authors from Mexico and Morocco, followed by Algeria, Brazil and Tunisia. Canada's most frequent partners are China, India and Mexico. Spain collaborates with Mexico, Brazil and Cuba; the Netherlands with China, followed by Egypt and India. Sweden's most frequent DET partners in Water Resources are China, the Czech Republic, India and Poland.

Figure 9: DET ratio in four GEC fields (% of international publications)



Source: SCI web of science, 2002-03

Large regions are barely included in global change science. Taking Africa as an example[19], we observe a striking difference between systemic and cumulative fields: MAS and Oceanography include authors from African countries in 6.6 % and 6.7 % of international publications, as against 17.5 % and 18.4 % in Ecology and Water Resources, respectively. However, these small numbers of African collaborations are very concentrated, with authors from South Africa in more than half of international publications across fields.

3.5 Conclusion

Nature-society interaction is becoming increasingly knowledge-intensive. As yet, bibliometric indicators are rarely used to monitor environment-related knowledge production and knowledge transfer, although this is common practice in other high-tech fields, such as nanotechnology (Heinze 2004; 2006). Our results confirm that linking biblio-

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[19] This definition of African countries excludes Arab states as a separate regional category.

metric data, sociological theory and insights in cognitive field structures advances our understanding of internationalization patterns in earth and environmental research.

International collaboration is a central feature of scientific work organization in the scientifically most advanced countries, but it also contributes to capacity building for DET countries. Few studies have investigated internationalization in environmental fields and their comparability is limited. Our findings demonstrate that different spatial problem structures of GEC can explain different levels of internationalization across EES fields. In particular, the high mutual task dependence generated by problems of systemic GEC leads to levels of internationalization that are matched by few other SCI fields. On the other hand, knowledge transfer and capacity building are important motives for international collaboration in application oriented fields, as shown by very high DET ratios in Water Resources. Output concentrations suggest that pressing environmental problems, e.g. water management issues, attract more scientific attention in DET countries than long-term environmental risks characterised by high scientific uncertainties. The present study of international co-authorships is complemented by an institutional analysis that compares the role and design of important international scientific collaboration programmes in systemic and cumulative GEC (Jappe 2005).

Science is at the core of our society's capabilities to improve eco-efficiency, to manage natural resources, to anticipate environmental risks, and to adapt to long-term global change in climate and ecosystems. Therefore, we suggest that STI research should examine environment-related knowledge production in a more comprehensive manner (cf. Cash et al. 2003). The study of international collaboration patterns is a small but important part of a larger endeavour to conceptualize and observe environment-related STI capacity development in scientifically advanced, emerging and developing countries.

Figure 10: Poster at the 9th International Conference on S&T Indicators, Leuven 2006

Explaining International Collaboration in Global Environmental Change Research

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The present geological age is called Anthropocene because humanity is a strong driving force for change in the Earth system. At the same time, nature-society interaction is becoming increasingly knowledge-intensive as social systems operate at the edges of ecological carrying capacity.

Humanity's planetary environment is large and heterogeneous, but scientific activity is concentrated in a limited number of industrialised countries. What does this strong disparity in the spatial distribution of environmental phenomena and scientific activity mean for international collaboration in Earth and environmental sciences? The bibliometric literature shows that some EES fields are among the most internationalised fields of science while in others internationalisation is below average, yet no consistent explanation of these findings has been offered.

Theoretical Explanation for Different Levels of Internationalisation across Fields:

- **Two types of cognitive problem structures** influence the social organisation of Earth and environmental sciences:

  Systemic GEC research treats global environmental systems, i.e. the climate system, geochemical life support systems or the total Earth system. The investigation of change in global systems *inherently depends on a global perspective*.

  Cumulative GEC research investigates changes that occur on local and regional scales but are globally so widespread that a significant fraction of the world's total areal or total natural resource is affected. This type of research *can be conducted independently at many places*. Examples for cumulative problems are biodiversity loss, soil degradation or water scarcity.

- **Mutual task dependence among scientists** (R. Whitley) is higher in systemic fields because synoptic observation of global systems requires big investments in observation systems, computing capacity, and international coordination, and because standardized datasets and numerical models enhance cognitive integration of research efforts worldwide (e.g. General Circulation Models).

  Systemic fields conduct long-term fundamental research; cumulative GEC fields include fundamental and applied research.

- **Hypothesis 1: Stronger mutual task dependence causes more frequent international collaborations in systemic GEC research** (comparison of INI total in Table 1).

- **Hypothesis 2: Participation of developing, emerging and transition (DET) countries in international collaboration is higher in applied research on local environmental resource management and engineering** (DET ratio in Table 1, Figure 2).

  Field Selection: *Meterology & Atmospheric Sciences* and *Oceanography* contain large portions of systemic GEC research, whereas *Ecology* and *Water Resources* contain very little. Ecology is predominantly basic research, Water Resources application oriented.

Main results are shown on the right. More findings are discussed in a forthcoming paper:

Jappe, A. (2006). Explaining International Collaboration in Global Environmental Change Research. *Scientometrics*. (forthcoming).

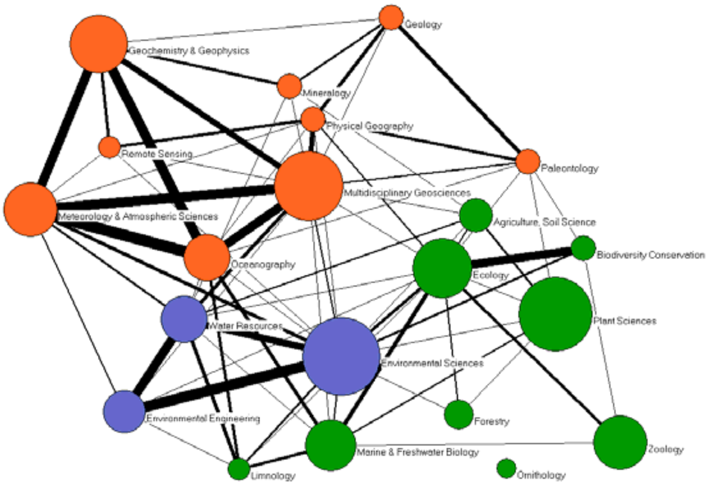


Figure 1: 21 Environmental Science Fields in the SCI

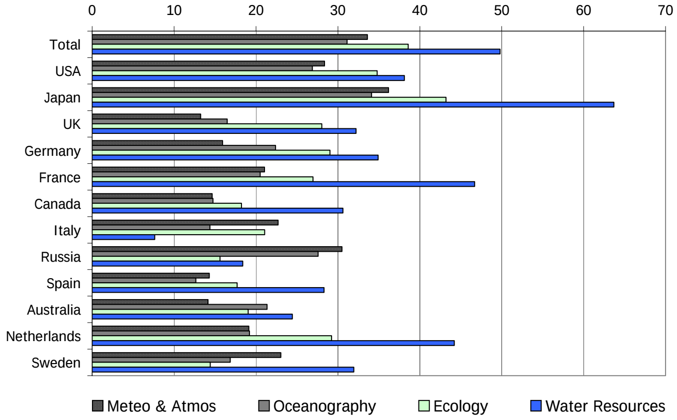
Research on: 🟧 Geosphere 🟩 Biosphere 🟦 Environmental Management & Engineering
SCI subject categories 2001-03, field size and overlap based on article counts

Table 1: International Collaboration in Four GEC Fields

Problem Type	Systemic GEC		Cumulative GEC	
2002-03	Meteo & Atmospheric	Oceano-graphy	Ecology	Water Resources
INI total (A)	25.8	24.3	21.3	18.7
INI DET (B)	8.7	7.6	8.2	9.3
DET ratio (B/A)	33.6	31.1	38.6	49.8

INI: Share of internationally co-authored papers; DET: group of developing, emerging, and transition countries; Source: SCI web of science.

Figure 2: Collaboration with Developing, Emerging, & Transition Countries as Share of International Publications (%)



Source: SCI web of science 2002-03

This research was carried out as part of a PhD project, Supervisor Prof. Dr. Peter Weingart, IWT University Bielefeld.

4 International collaboration for global environmental research. A comparison of IGBP and Unesco-IHP

An earlier version of this paper (Jappe, 2005) was presented at the Berlin Conference on the Human Dimensions of Global Environmental Change, "International Organisations and Global Environmental Governance", Berlin-Potsdam, 2-3 December 2005.

4.1 Introduction

The image of a small blue-green planet against the black background of space has become a cultural emblem for the globalization of relationships in a limited and fragile environment (Jasanoff 2001: 10). Yet the abilities to observe the environment are distributed extremely unequally on this globe: most environmental research and monitoring are hitherto carried out by advanced industrialized countries. This geographic concentration of scientific and technological capabilities is one of the main obstacles to the development of a global knowledge base on environmental changes worldwide.

This paper investigates international collaboration programmes as a form of organization that supports the development of global environmental knowledge. We compare two cases of international collaboration programmes, the International Geosphere-Biosphere Programme (IGBP) which is sponsored by the International Council for Science (ICSU) and the International Hydrological Programme (IHP) of the United Nations Educational, Scientific and Cultural Organization (Unesco). These cases represent different research goals and organizational formats: IGBP aims for international coordination in research on global change in the earth system, while IHP aims for scientific collaboration to enhance sustainable water management globally.

The present study has two objectives. Firstly, we take the two selected cases as historical examples for capacity development in environmental sciences and aim to understand their objectives and institutional design. Secondly, by means of a systematic case comparison, we seek to identify organizational factors of more general importance for the success of international collaboration initiatives in environmental sciences.

The International Geosphere-Biosphere Programme was selected because it is a clear-cut example of a tradition of scientific internationalism that is associated with the International Council for Science. This institutional tradition of large collaboration programmes leads from precursors in the late 19th century across the famous International Geophysical Year in mid-century up to contemporary programmes in global environmental change (GEC) research (Greenaway 1996). Since the mid-1980s, the initiative to build an IGBP contributed to the establishment of a new interdisciplinary research field, the investigation of interactive biological, physical and geochemical processes on the global scale (Mooney 1998).

The second case is the International Hydrological Programme which was selected because it originated in the same tradition of international collaboration programmes as IGBP but evolved along entirely different pathways – connected to the fact that it was institutionalized as a permanent Unesco-based activity in 1974. The International Hydrological Decade, a precursor to the IHP which lasted from 1965-1974, contributed to the international recognition of hydrology as a scientific discipline. Related to the sponsorship by Unesco, IHD and IHP always placed great emphasis on university education for students from developing countries. However, as an institution, IHP was not able to keep up with the subsequent growth of the discipline of hydrology. Today it appears as a rather small player among a variety of international water initiatives (Varady/Iles-Shih 2006). Yet IHP's focus on scientific collaboration remains a distinguishing trait in this field.

The present study identifies an important research gap, as neither the international collaboration programmes in the ICSU tradition nor the issue of capacity development for global environmental knowledge have been treated so far by scholars in sociology or social studies of science. Most of the literature on international collaboration programmes and the development of environmental science fields that we refer to has been written by historians of science (Doel 2003; Edwards 2001; Edwards 2004; Elzinga 1996; Golley 1993; Greenaway 1996; Haas/McCabe 2001; Hamblin 2005; Miller 2001; Oreskes/Doel 2003; Reuss 2003; Weart 2004; Weart 2005a; Weart 2005b), yet to our knowledge, the cases of IGBP or IHP have not yet been studied. Therefore, the literature on these cases comes mainly from scientists who were involved with either initiative, for IGBP: (Fleagle 1992; Kaye 2004; Malone 1986; Malone/Corell 1989; Mooney 1998; Rapley 1999; Steffen et al. 2001) and for IHP: (Batisse 1964; Batisse 2005; International Hydrological Programme (IHP) 1991; Nace 1964). In addition, grey literature on each programme has been analyzed.

In terms of theoretical concepts, we rely on Richard Whitley's theory of scientific work organization (2000) and on Niklas Luhmann's theory of the science system (1992). These authors draw a sophisticated picture of the social organization of science in general, yet they make no specific reference to environmental sciences, nor do they treat the topic of capacity for sustainable development. However, in the light of this framework it is clear that the organization of large scientific collaboration programmes is no trivial exercise. Decisions to collaborate are for the most part taken by individual scientists, not on the level of research organizations (Stichweh 1999), so that the number of potential partners is high and individual research priorities are likely to be heterogeneous. Besides, research funding is allocated by specialized national agencies which are foremost concerned with national policy processes. Thus, collaboration under a unifying international framework appears unlikely from the outset.

The cases are contrasted on two dimensions. With reference to Whitley, we investigate the relationship between cognitive structures and the social organization of scientific collaboration. We distinguish two types of global environmental change to characterize a basic difference in cognitive problem structures: environmental problems can be globally systemic (example of IGBP) or cumulatively global (example of IHP) (Turner et al. 1990). We link this geographical difference to Whitley's notion of mutual task dependence among scientists, a dimension of work organization that varies with the nature of a research task (2000). By comparing our two cases, we show that differences in the cognitive structure (systemic versus cumulative GEC) have an influence on the allegiance and participation to a programme on the part of scientists. This relationship can be explained by differences in the associated level of mutual task dependence.

The second dimension consists in the distinction between the science system and political system. As an institution, IGBP belongs to the science system, whereas IHP represents an institutional hybrid between science and international politics. We investigate the coupling of science and politics in both cases (Luhmann 1992; Weingart 2001) and analyze implications for scientific allegiance and participation.

By way of the individual case studies and by systematic comparison (Kelle/Kluge 1999), we investigate the implications of both dimensions for capacity development. We find that the design of IGBP is in several ways superior to IHP's in organizing scientific collaboration, but this successful model can not simply be transferred to environmental science fields with a very different problem structure. The history of the ICSU programmes suggests that large-scale collaboration and the cognitive integration of systemic GEC research are mutually reinforcing social and cognitive developments. A simple transfer of organizational structures to cumulative research fields such as biodiversity and human dimensions research apparently failed to generate broad allegiance from respective scientific communities. The main problem with IHP is the limited ability for programme growth that is a consequence of the intergovernmental administration. Yet IHP has been recently experimenting with a new approach for regional capacity building, an institutional network of regional water centres. This concept could be an interesting starting point for further comparative research in collaboration for global environmental knowledge.

Apart from the analysis of information from the scientific literature, grey literature, programme websites and official documents by Unesco and IHP, this study is based on twenty interviews with key participants of international programmes in the USA, Germany (IGBP und Global Water Systems Project) and France in 2004 and 2005 and during a three month stay at IHP secretariat, Paris in autumn 2005 (cf. annex on page 147). During this period we also attended sessions of the 33rd General Conference of Unesco and took part in an international scientific conference on the history of Unesco on the occasion of the organizations' 50th anniversary. An earlier version of this text (Jappe 2005) was presented to Mr. Szöllösi-Nagy, secretary of Unesco-IHP and was made public on the official IHP website in 2006.

The chapter is structured as follows: section 4.2 presents the case study of the International Geosphere-Biosphere Programme, section 4.3 the case study of the International Hydrological Programme. Each time we give a brief introduction to the history of the programme (4.2.1; 4.3.1), then we describe the organizational structure (4.2.2; 4.3.2). Subsequently, we discuss specific aspects of each programme with regard to the cognitive problem structure (4.2.3) and the institutional linkage of science and politics (4.3.3), and analyze the breadth of international participation to each programme (4.2.4; 4.3.4). Section 4.4 summarizes the findings of the case comparison and discusses implications for further research, while section 4.5 draws some general conclusions concerning the design of international collaboration programmes in global environmental research.

4.2 The global view of environmental change: the case of IGBP

4.2.1 History of global environmental change programmes

The International Geosphere-Biosphere Programme is part of an institutional tradition of scientific collaboration programmes (figure 11) that goes back to the International Geophysical Year in 1957-58 and to its precursors, the First and Second International Polar Years in 1882-83 and in 1932-33 (Millbrooke 1998). At the height of the Cold War, the IGY is the first incident of (nearly) globally coordinated research and a collaborative venture of unprecedented scope. The idea for a global study emerged in the early 1950s initially from research on the ionosphere, i.e. on layers of iones in the upper reaches of the atmosphere which are important for the transmission of radio signals. Eventually, the IGY included fourteen disciplinary areas. Approximately 60,000 scientists and technicians from 67 countries participated. Earth observation from space started with the launch of the satellite Sputnik I by the Soviet Union. For the first time, "world data centres" were created to collect and store observational data for long-term use (Greenaway 1996: 161).

The organization of the IGY was led by the International Council for Science (ICSU), a nongovernmental scientific organization with membership of international scientific unions (cf. Drori et al. 2003), such as the International Union of Geodesy and Geophysics (IUGG) or the International Union of Biological Sciences (IUBS), and national scientific members, in most cases national scientific academies. ICSU created a special committee, the "Comité Scientifique pour l'Année Géophysique" CSAGI which invited all interested scientific unions and national members to submit proposals for observation programmes (Greenaway 1996). The most important criterion in selecting research topics for the IGY was that problems require "concurrent synoptic observation at many points involving cooperative observations by many nations" (cited in Greenaway 1996: 153).

The scientific success of the IGY and the support by many governments inspired a number of subsequent collaboration efforts. In the aftermath, ICSU created three new committees for international collaboration on Antarctic, Oceanic and Space Research. The organizational model of the IGY was followed by large collaboration programmes in other disciplines, such as the International Years of the Quiet Sun (Greenaway 1996:

158), the International Biological Programme from 1964-74 (Golley 1993; Greenaway 1996: 172-176; Kwa 1987), and the International Hydrological Decade from 1965-74, which for the first time estimated the global water balance (Batisse 1964; Batisse 2005). In this way, a new tradition of scientific internationalism was founded. The IGY is widely held to mark "the beginning of the new view of the earth that characterised scientific cooperation in the second half of [the 20th] century" (Greenaway 1996: 156; see also Malone 1986).

In the following decades, the scientific view of the planet was transformed by the emerging concern over global environmental change (Fleagle 1992). From the scientific and technological interest in the ionosphere, the focus of collaboration moved to weather prediction, climate research, biogeochemical cycles and to the study of the total earth system. An intermediate step on this way was the Global Atmosphere Research Programme (GARP 1967-1980), jointly led by ICSU and the UN World Meteorological Organization (WMO). GARP aimed to strengthen meteorological services and research, with particular emphasis on the use of meteorological satellites. According to Greenaway, the GARP Global Experiment or Global Weather experiment 1978-79 was the largest experiment hitherto undertaken and "may be taken as the starting-point for the gradual improvement in weather forecasting" (1996: 188).

Subsequent to GARP, ICSU and WMO jointly established the World Climate Research Programme (WCRP) which became operational in 1980. The transition from GARP to WCRP marks the shift in focus from weather forecasting to the study of the global climate system. The main objectives of the WCRP were formulated in 1980, but they are still valid 25 years later:

> "The two overarching objectives of the WCRP are to develop the fundamental scientific understanding of the physical climate system and climate processes needed to determine to what extent climate can be predicted and the extent of human influence on climate (…) Today, the WCRP encompasses studies of the global atmosphere, oceans, sea- and land-ice, the biosphere and the land surface, which together constitute the Earth's climate system" (http://wcrp.wmo.int/About_Aims.html).

Soon after the establishment of the WCRP, a new initiative was started to take an even wider view by "uniting geophysics and global ecology" in a new earth system framework (Malone 1986: 9). The International Geophere-Biosphere Programme (IGBP) was designed to tackle the new interdisciplinary field of global life support systems:

"In the context of global change, the Earth System has come to mean the suite of interacting physical, chemical and biological global-scale cycles (often called biogeochemical cycles) and energy fluxes that provide the conditions necessary for life on the planet" (Steffen et al. 2004a).

The ICSU-led initiative was stimulated by the institutional reliance of WMO on a single disciplinary base which, according to Haas/McCabe "impaired its ability to assimilate information about new environmental risks" (2001: 340). The IGBP first became operational in 1990, and has started a new programme phase in 2003-05 (IGBP II). The organizational design of the IGBP is described in more detail below (4.2.2).

The scientific agenda of climate and earth system research was made possible through new technologies for observation and analysis, such as remote sensing and increasing computing power. Apart from analysis and modelling, an important objective of WCRP and IGBP is to produce new data on global system behaviour through large-scale experiments in different regions of the world. These in-depth investigations are closely linked to the enhancement of global observation systems (Kaye 2004; Lautenbacher 2006).

WCRP and IGBP follow a similar organizational model which was first implemented in GARP. Since the beginning of the 1990s, the successful model was also extended to social sciences and biodiversity research. The International Human Dimensions Programme on Global Environmental Change IHDP started in 1990 as Human Dimensions Programme HDP. "DIVERSITAS – an international programme in biodiversity science" first became operational in 1991. The four programmes WCRP, IGBP, IHDP and Diversitas constitute a family of research programmes because they organize scientific collaboration in similar ways and because they are all sponsored by ICSU, in partnership with various other nongovernmental scientific and intergovernmental organizations.[20] This relationship has been underlined through the formal establishment in 2001 of an "Earth System Science Partnership" (ESSP) with collaboration projects between the four programmes. Nevertheless, IHDP and Diversitas are still much smaller in terms of the number of associated scientists and research support than WCRP and IGBP.

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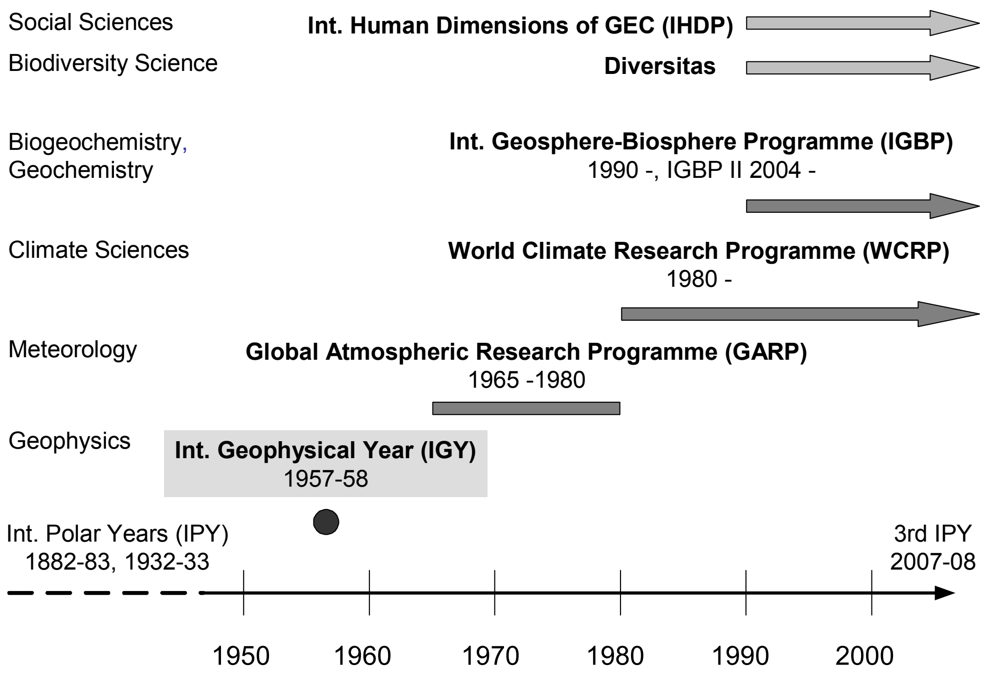
[20] WCRP is sponsored by WMO, Unesco IOC and ICSU; IGBP by ICSU; DIVERSITAS by IUBS; ICSU-SCOPE, Unesco, ICSU, and IUMS; IHDP by ISSC and ICSU.

Figure 11: International scientific programmes on global environmental change research – the ICSU tradition



Source: author

4.2.2 Organizational structure of the International Geosphere-Biosphere Programme

The basic idea of international collaboration in the ICSU tradition is that a large number of scientists, of many national and institutional affiliations, coordinate their work under one framework to achieve shared scientific goals. As the example of IGBP makes abundantly clear, multi-actor coordination in science is no simple task. Since the decision to collaborate is taken by individual scientists (Stichweh 1999), the core variable to describe a programme's capacity is the allegiance and support that it receives among the scientists in relevant intellectual fields (Whitley 2000).

Scientific allegiance is shorthand for the willingness of scientists to devote their time, wits and energy to a programme's objectives through carrying out research and, equally important, through coordinating their own research with the work of other scientists. Coordination is time-consuming and may have a distracting effect on the pursuit of new research venues that are judged most promising by the individual scientist. Therefore, coordination under a unifying framework is not to be taken for granted in the study of scientific work organization, nor should it be recommended in all cases, regardless of subject and research context.

The organizational scheme of the four GEC programmes in the ICSU tradition is similar, so that many points of this analysis are generalizable to all four programmes. IGBP is best described as an institutionalized network of scientists. It has been estimated that approximately 10,000 scientists participated in IGBP research during phase I (Steffen et al. 2004a: 305). In terms of sociological systems theory, the programme belongs to the functional system of science (Luhmann 1992). IGBP is sponsored by the nongovernmental ICSU, is committed to basic research and has no direct institutional linkages to national or international arenas of environmental politics. ICSU's sponsoring role chiefly consists in enablement and support of contacts into the scientific communities and organization of meetings (cf. Andresen/Agrawala 2002: 43). It also involves certain amounts of financial resources, mainly as seed money for the development of new programmes and projects, and for international meetings.

The planetary environment is framed in IGBP research as one global system which is composed of interactive physical, chemical and biological processes:

> "The objective of IGBP is to describe and understand the interactive physical, chemical and biological processes that regulate the total Earth system, the unique environment it provides for life, the changes that are occurring in that system, and the manner by which these changes are influenced by human action" (cited after Malone 1986: 8; Mooney 1998: 38).

The organizational challenge is thus not only to bring together scientists and resources from different countries, but to open up new interdisciplinary research to study the interaction between geosphere and biosphere (Rapley 1999). After successful completion of the first decade, IGBP started a new programme phase in 2003-05 (IGBP II).

IGBP II comprises nine "scientific core projects", sub-programmes which are the basic organizational sub-units. The core projects are designed as thematic building blocks within the overall programme framework. Figure 12 shows a simplified structure of IGBP II. IGBP scientific core projects investigate the major compartments of the earth (land, ocean, and atmosphere) and the interfaces between them. Cross-cutting themes in IGBP are the modelling of global systems and paleohistoric studies of past changes in the earth system (http://www.igbp.kva.se/).

The scientific objectives of each core project are described in a "science plan". A group of renowned scientists (planning or scoping committee) develops a proposal which represents the state of knowledge and defines key research questions for the following ten to fifteen years. During the preparation phase of a scientific core project, numerous consultations and workshops are held, so that a large number of scientists are given the opportunity to participate and to peer-review the proposed science plan.

IGBP has two levels of scientific leadership. The whole programme is led by a "scientific committee", a group of distinguished scientists appointed by the sponsoring organizations, i.e. the scientific unions, ICSU and partnering UN organizations. The task of the committee is to provide overall scientific guidance for the research, to develop the overall scientific plans, to oversee their implementation and to help disseminate the results. On the level of the scientific core projects there is a "scientific steering committee" which undertakes the detailed planning and implementation of the scientific core project. It is composed of 10-20 scientists from different countries.

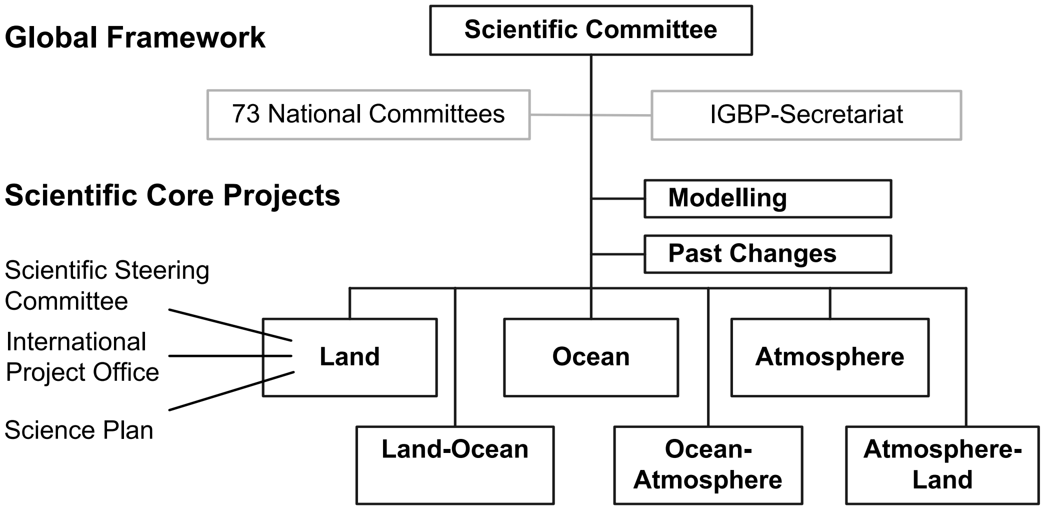
The organizational infrastructure of the IGBP scheme is decentralized. Besides the programme secretariat, each scientific core project has its own international project office which supports the steering committee, the implementation of the project and the publication of results with staff on a full-time basis. Due to this decentralized infrastructure, the organizational structure of the international GEC programmes has also been called "distributed megascience" (OECD megascience forum). International project offices are mostly financed by the respective host country, and in some cases through systems of national contributions.

There are two main ways in which nations allocate research funding to an international GEC programme. One is to support research activities in scientific core projects, the other is to provide funding for international project offices, scientific meetings and conferences, the so-called international "glue money" (IGFA 1997). Many scientific core projects do not have an overall budget at their disposal to implement their science plan. Rather, individual scientists and research groups approach their national funding agencies with research proposals that are approved by the core project's scientific steering committee. Another possibility which is increasingly sought is funding of European consortia by the European Union. In turn, the affiliation with a prestigious international

GEC programme can improve a scientist's eligibility for national or EU research funding and thus is an incentive for participation.

National Committees for IGBP (or GEC research more generally) exist in 73 countries. These committees are designed as an interface to GEC research at the national level and national S&T policy: "National IGBP or Global Change Committees assist in the national coordination of relevant studies, facilitate linkages between national and international global change research, and often assist in the mobilization of funds to support the central activities of IGBP".[21] In contrast, they are not conceived as a communication channel between science and national environmental policy or climate policy.

Figure 12: Organizational structure of IGBP II



Source: author

As a consequence of the scattered funding sources, it is difficult to determine the total amount of funding for IGBP. Resources scientists use for research under this or other international GEC programmes are often not explicitly specified for that purpose. The International Group of Funding Agencies for Global Change Research IGFA estimated the global total of R&D funding for national and international GEC research in 2001 to

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[21] www.diversitas-international.org/national.html#national; www.igbp.kva.se/cgi-bin/php/ frameset.php.; last accessed 14. Nov. 2005

be in the order of US $ two billion, excluding funding for satellite programmes (US $ 1,873 million from the countries represented in IGFA plus approximately 200 million from France and Japan). Assessments of resources that are directly connected to the international GEC programmes were undertaken twice so far, based on information requests to the funding agencies participating in IGFA. The first assessment estimated the total amount allocated to the international scientific core projects at US $ 513 million for 1995, which were allocated almost entirely to WCRP and IGBP core projects. The results of a second resource assessment in 2004 have not been published. The responses showed difficulties in making inter-country comparisons owing to many structural differences in the organization of GEC research and funding in the various countries (cf. IGFA 2004).

The network character and the fragmented funding sources restrict the viability of a hierarchic approach to programme integration. The achievement of coherence ultimately depends to a large degree on the personal effort and time that participating scientists are able and willing to invest in exchange and integrative work. The following quote from H. Mooney, who played a central role in IGBP I, summarizes this experience:

> "The reality of funding possibilities made IGBP a mix of bottom-up and top-down science. The IGBP planning process developed a community agreed-upon research agenda, based on a new research paradigm, and a structure to accomplish the required interdisciplinary research efforts. However, research funding, to a large extent had to come from the efforts of individual scientists captivated by the challenges and opportunities of a new kind of science. (…) funding for research for the IGBP is piecemeal coming mainly from national science programmes, most often not explicitly for one of the core projects. This is quite different than what happened with the IGY, or even the IBP, where funding was provided by governments specifically for these efforts. The more diffuse funding base for the IGBP has certainly been constraining but not totally limiting probably because of the dedication and conviction of the scientists involved. (…)" (Mooney 1998: 47f.)

Therefore, the most significant capital of this programme is the allegiance and support by scientists from the respective scientific communities. Input and feedback from a larger scientific community by means of consultations, scientific workshops and conferences are sought, especially during the planning phase of new scientific core projects, and for the review of achievements and the integration of results at the end of a programme phase. Chris Rapley, executive director of IGBP 1994-97 conveys the enthusiasm of one of these scientific meetings:

> "In my opinion, the greatest success of the IGBP has been its demonstrated capacity to assemble such international, interdisciplinary groups. It has attracted nearly two hundred of the world's

> top ranking scientists to carry out the ongoing planning and oversight of the programme, which now involves some ten thousand researchers and technical support staff from over one hundred nations (…). Last year, we brought all the Scientific Steering Committee members together for the first time, after nearly ten years; (…) We had Nobel Prize winners and Tyler Prize winners present, and the consensus view was that it was one of the most intellectually vibrant events that any of them had participated in, largely because the attendance list was like a "Who's who" of the bio- and geochemistry elements of Earth system science." (Rapley 1999).

IGBP by itself has no direct institutional linkage with the political system, apart from linkages with research policy through national committees. Yet a well-known interface in the surroundings of the IGBP is the Intergovernmental Panel on Climate Change (IPCC). In regular intervals, the IPCC assesses the scientific background, appraises potential impacts of climate change and options for adaptation and mitigation. The IPCC's fourth assessment report is published in 2007. As a research programme, IGBP contributes to the science that is assessed through IPCC, because IGBP is an interdisciplinary extension from physical climate research to climate-related biological and geochemical processes. IPCC as an institution is designed to manage the boundary between science and international politics (cf. Farrell/Jäger 2006). Through elaborate procedures a broad scientific review process is connected with intergovernmental negotiation on the summary for policy-makers. The development of the IPCC since its foundation in 1988 and its role for international climate policy are well documented in the literature (Agrawala 1998a; Agrawala 1998b; Haas/McCabe 2001; Shackley 1997; Siebenhüner 2006).

4.2.3 Mutual task dependence in the study of global systems

The organizational challenge of international GEC programmes is to coordinate scientific work and funding sources from many different countries under a common framework. IGBP responds to this challenge through a lean and distributed organizational format that leaves autonomy to the different scientific sub-programmes. It emphasizes cognitive over hierarchical modes of programme integration, mainly through scientific debate and peer review in the planning phase and in the synthesis of results, either on the project level or on the level of the whole programme. Yet the capacity of the IGBP scheme to coordinate the work of hundreds or even thousands of scientists from different countries cannot be understood solely in terms of the lean and flexible organizational blueprint.

In this section it is argued that the organizational model of IGBP is so powerful because this research area of GEC is characterized by a high level of mutual task dependence among scientists which is strongly influenced by a particular spatial extension of research problems. Following Turner et al. (1990), this type of spatial extension can be called "globally systemic":

> "In the first or systemic meaning, 'global' refers to the spatial scale of operation or functioning of a system. A physical system is global in this sense if its attributes at any locale can potentially affect its attributes anywhere else, or even alter the global state of the system. (…) Globally systemic changes need not be caused by global scale activity, only the physical impacts of the activity need to be global in scale, manifested through the systemic adjustments that follow". (Turner et al. 1990: 15f.)

The collaboration scheme of the international GEC was developed to investigate global systems, i.e. the climate system, biogeochemical cycles, global life support systems, and the total earth system. All fields that investigate GEC from a global systemic perspective depend on synoptic observations at the global scale, even though particular investigations are conducted on a broad range of spatial scales and may even deal with the sun and other planets.

The spatial extension of "global systemic" research problems has important implications for the cognitive structure and social organization in research fields, i.e. for the coordination and integration between research conducted at different geographic sites. These implications can best be understood by applying Richard Whitley's concept of "mutual task dependence" which he introduced for the analysis of scientific work organization. Whitley argues that in modern sciences as "systems of jointly controlled novelty production", researchers have to make new contributions to knowledge in order to acquire reputations from particular groups of colleagues. The more researchers have to use the "specific results, ideas, and procedures of fellow specialists in order to construct knowledge claims which are regarded as competent and useful contributions" in a given field, and the more they need to "co-ordinate task outcomes and demonstrate adherence to common competence standards", the more coherently and integrated this research is organized and conducted (Whitley 2000: 85-88).

In the light of Whitley's concept, systemic GEC research fields show remarkably strong mutual task dependence. Systemic fields show high levels of coordinated data collection and data standardization which are necessary to build and operate large-scale observation systems. They also demonstrate a strong cognitive integration of research findings in global theoretical frameworks and numerical models.

For example, there is already a long tradition of international cooperation to establish and enhance global observation systems which combine observations on the ground, by ships and buoys, airplanes and satellites. The oldest worldwide operational system for meteorology is the World Weather Watch/GOS, established in 1963 under the auspices of WMO. As Edwards notes, "behind the emerging consensus on climate change lie more than 150 years of slow, painful negotiations over global standards for measuring, recording, and communicating about the weather" (Edwards 2004: 827). Similarly comprehensive systems for observation of the oceanic and the terrestrial domain are still under construction today.

Yet mutual task dependence does not merely result from the direct cooperation in building operational observation systems, but also from the fact that global expert communities operate with highly standardized data products. International data centres serve the collection, storing and processing of data, ensuring open access to scientific information (Greenaway 1996). Due to the complex operations involved in the generation of global data sets, it has been argued that global data and global models are "no longer distinct entities, but parts of a single system for representing the world" (Weart 2005a).

Strong mutual task dependence also manifests itself in shared global frameworks, i.e. theories and numerical models. Atmospheric general circulation modelling (AGCM) is a prime example for task dependence through cognitive integration. GCMs are at the centre of research on climate change and are used to integrate observations and analytical contributions from diverse specialities (cf. history of AGCM in Elzinga 1996; Weart 2005a). Although observation and experiments are undertaken on a broad range of spatial scales, their ultimate purpose is to inform understanding of global system functioning. In turn, enhanced simulation of system behaviour is seen as prerequisite for the prediction of regional impacts. Model complexity and the requirements of computing power restrict the number of approaches that are used in parallel so that researchers in the AGCM field follow the development of a limited number of shared global frameworks (Edwards 2001: 58). Experiments that systematically compare the performance of different models are an additional element of both cognitive and social field integration.

The intertwined relationship between the spatial extension of problem structures and mutual task dependence in the social organization of researchers is also evident in a second, "global cumulative" type of GEC research field which can be defined as follows:

> In the second – the cumulative – sense, 'global' refers to the areal or substantive accumulation of localized change. A change is global in this sense if it occurs on a worldwide scale, or represents a significant fraction of the total environmental phenomenon or global resource. (…) If cumulative changes reach a global scale, it is typically as the consequence of worldwide or wide-spread human activity that may not be directly registered on the major geosphere-biosphere systems" (Turner et al. 1990: 15f.)

In contrast to global systemic GEC fields, environmental problems of the second type are related to specific regions or ecosystems that are global by accumulation, for example, issues of biodiversity, soil, or water management. Research in these regional problems can be conducted independently at many places even though the phenomenon may be globally widespread. Knowledge production on this type of problems is often focused on smaller spatial scales and is to a greater or lesser extent place-specific or "place-based" (Clark et al. 2004: 17). While theories and methods in place-based fields also contain generalizations that make them applicable in different contexts and allow the accumulation and progress of knowledge across sites, the mutual dependence of scientists at different places on each other's cognitive achievements remains weaker relative to systemic fields. Scientists in cumulative fields need to co-ordinate task outcomes and demonstrate adherence to common competence standards to a lesser degree than researchers in systemic fields. Lower mutual task dependence leads to a greater diversity of approaches and reduces the pressure for a standardization of data, methods and concepts.

The difference between systemic and cumulative GEC research fields was demonstrated in a bibliometric analysis of international research collaboration (chapter 3). Systemic research fields have been identified as having thicker international collaborative ties between peer scientists than cumulative fields. For instance, the field of meteorology & atmospheric sciences (as defined by the Science Citation Index) has an INI total of 25.8 whereas the INI score of the water resources field is 18.7 – a score which reflects the database average score for the INI total (table 6).

Furthermore, there is evidence for organizational problems of global research programmes in cumulative fields in comparison to systemic fields programmes. Although cumulative programmes, such as IHDP and DIVERSITAS, are almost identical to IGBP with regard to organizational design and structure, they had to be restructured and relaunched a few years after their start, and they have had persistent difficulties to attract funding for international collaboration from national funding agencies. What is even more important, there also appear to be great differences in the allegiance and support different international GEC programmes can claim among their respective scientific fields.

IHDP was first launched in 1990 as Human Dimensions Programme HDP by the International Social Science Council (ISSC). By the mid-1990s, the Scientific Council on Global Change of the German government reported that IHDP had not achieved advances comparable to IGBP (WBGU 1996: 29). Consequently, IHDP underwent major restructuring, including the movement of the project secretariat to Bonn. DIVERSITAS first started operating in 1991, but only a few years later the position of the executive director of the programme fell vacant due to insufficient funding. The programme was discontinued and formally re-launched in 2001-02, together with the celebration of an International Biodiversity Observation Year.

The meeting reports of the International Group of Funding Agencies for Global Change Research (IGFA) regularly document the difficult funding situation of IHDP and partly of DIVERSITAS. In the 2004 meeting the executive director of IHDP deplored that "there is currently a mismatch between the increasing demand for human dimensions research and institutional involvement of IHDP and the operational limitation (work force and finance) that must be reconciled if IHDP is to function optimally" (IGFA 2004: 28). Yet a severe deficiency in funding of IHDP was also stated in each of the preceding years since 1996, and the same applied to DIVERSITAS in the years 1998-2002 (IGFA reports 1996-2004).

Most importantly, international collaboration schemes in areas of cumulative global change have suffered from a lack of strong national scientific constituencies. Greenaway states that "although governments had high expectations of the social-science contribution, it proved difficult to bring HDP into operation, to some extent because ISSC had yet no tradition of major international research programmes, nor did it possess a strong constituency of national scientific members" (IGFA 2004: 28). Today this view is repeated among major GEC funding agencies, concluding that among the causes for the persistent funding deficiency one finds "the importance for IHDP to build national constituencies of scientists who can channel the scientific interests of IHDP into relevant national funding bodies" (IGFA 2003: 16).

One of the important consequences of place-based problem structures is that synoptic assessments of environmental conditions on large regional or global scales are especially demanding in cumulative fields, both methodologically and from the organizational point of view. Models and satellite remote-sensing can substitute for in-situ data to a lesser extent than in systemic GEC research. For this reason, global assessments are often compilations of existing knowledge complemented by original research at carefully selected places (e.g. Millennium Ecosystem Assessment).

4.2.4 International participation

The scientific and technological capacity to investigate global systems has made enormous advances since the establishment of the WCRP in 1980. Yet who contributes to the international GEC programmes? At the beginning of the 21st century, scientific capacity is still heavily concentrated in a limited number of industrialized countries, as indicated by national shares of peer-reviewed scientific publications (national publication shares). In 2003, the triad of the USA, EU-15 and Japan alone account for 70.3 % of publications in the ISI databases Science Citation Index (SCI) and Social Sciences Citation Index (SSCI). Many developing countries still lack the scientific and financial resources to contribute significantly to long-term fundamental research.

To measure participation in the international GEC programmes, we analyzed the national affiliations of their scientific leadership. In 2006, the four GEC programmes comprise a total of 20 scientific core projects (IGBP: 9) each led by a scientific steering committee (SSC), involving in total 266 scientists from 41 countries (IGBP: 145 scientists). We also wanted to know if national representation in the GEC programmes mirrors the overall scientific capacity of individual countries. Therefore we compared national shares in the scientific steering committees to national publication shares in the SCI/SSCI database.

The findings of the participation analysis are shown in table 7. One third of all SSC members have institutional affiliations in the USA or the United Kingdom, followed by memberships from Japan, France, Germany and the Netherlands. Relatively strong SSC representations are also shown by a group of rapidly industrializing countries, including China, India, South Africa, Chile, Brazil, Argentina, and Mexico. Participation of this group is also strong in IGBP. A dozen SSC members come from developing countries with very low scientific capacity (<1 ‰ of SCI/SSCI output), including countries in Africa (Ghana, Kenya, Ethiopia, Senegal), South America (Colombia, Costa Rica), and Asia (Indonesia, Philippines, Sri Lanka).

A comparison with national SCI/SSCI shares shows that scientifically advanced countries differ in their propensity for engagement in international programmes: some of them contribute more SSC scientists than might be expected from their scientific size in the SCI/SSCI, in particular Norway, New Zealand, Denmark, the Netherlands, and Australia. The representation of these countries in GEC programmes mirrors strong national specializations in earth and environmental sciences. In interviews conducted by the author, scientists mentioned that the opportunities for collaboration through GEC programmes are especially valued by these scientifically medium-sized countries. Yet other industrialized countries remain comparatively disengaged, such as Spain, Italy, Israel, and Austria. Furthermore, there is a conspicuous lack of SSC members from eastern European countries. Russia is engaged with only five SSC members, three in WCRP and two in IGBP. Poland, Czech Republic, Hungary, and Ukraine have publication shares of SCI/SSCI ranging from 1 % to 0.3 % respectively but are missing from GEC programmes.

Table 7: Does participation in scientific steering committees (SSC) match national shares of publication output?

SSC members per country	Countries	SSC members Σ country group	SSC members %	SSC members cumu-lated %	country output SCI/SSCI %	country output SCI/SSCI cumu-lated %
64	USA	68	25.6	25.6	30.2	30.2
24	UK	23	8.6	34.2	6.9	37.1
10-20	Japan, China, France, Germany, the Netherlands,	70	26.3	60.5	25.6	62.8
5-9	Australia, Canada, India, Norway, South Africa, Chile, Brazil, Russia	55	20.7	81.2	12.2	74.9
2-4	Argentina, Denmark, Italy, Mexico, New Zealand, Sweden, Switzerland, Belgium, Colombia, Finland, Ghana, Greece, Kenya, Singapore	38	14.3	95.5	11.2	86.1
1	Austria, Costa Rica, Ethiopia, Indonesia, Israel, Philippines, Portugal, RoC Taiwan, Senegal, Spain, Sri Lanka, Thailand	12	4.5	100.0	6.1	92.2
Total	41 countries	266	100.0		92.2	

Source: programme websites for SSC membership (2006); NSB (2006) for SCI/SSCI.

Participation in the scientific leadership of the four GEC programmes demonstrates a basic dilemma of global change research. While global coverage and the broadest possible participation are desired in principle, advanced levels of scientific capability are needed for effective contributions to this rapidly developing research branch.

4.3 Science for regional water management: the case of IHP

4.3.1 History of the International Hydrological Programme

Among the specialized UN agencies, a variety of programmes involve data collection and assessment of environmental conditions, but few are dedicated to scientific collaboration as their main purpose. The International Hydrological Programme (IHP) is one of these exceptions. It has been chosen for comparison because it originated from similar roots as the international GEC programmes. Invigorated by the success of the

IGY and in parallel with other international science programmes reaching across the Iron Curtain, hydrologists set up an International Hydrological Decade (IHD) from 1965-1974, led by Unesco and conducted in cooperation with other UN agencies. After the end of the hydrological decade, the IHP was founded (Batisse 2005).

In terms of its scientific objectives and its realization as a large-scale coordinated effort, the IHD was similar to other programmes in the ICSU tradition (section 4.2.1). One of IHD's principal scientific outputs was a reliable estimation of the global water balance. Prior to the IHD, estimations of the total size of the world's freshwater resources had differed widely. To this end, hydrological monitoring networks had to be created in a large number of countries and instruments and methods for data collection had to be standardized (Batisse 1964). Another major objective was to advance the establishment and recognition of hydrology as a scientific discipline. From the beginning, IHD/ IHP placed a strong emphasis on education, particularly at the postgraduate level. During the IHD, approximately 800 hydrologists were trained. An emphasis on education was facilitated by the sponsorship of Unesco.

According to R. L. Nace, at the time responsible for hydrogeological research at the US Geological Survey and an initiator of the IHD,

> "a major purpose of the International Hydrological Decade is to gain worldwide realization that a science of hydrology exists, that teaching, training and research must be expanded enormously, and that many and varied career opportunities exist for hydrologists" (Nace 1964: 414).

This objective brought allegiance and enthusiasm from scientists and engineers of different backgrounds working on water issues (interview by the author).

After the end of this decade of hydrological research, international collaboration was put on a more permanent basis through the creation of the International Hydrological Programme (IHP), and the secretariat was incorporated in Unesco (Batisse 2005). In this way, IHP has become an institutional hybrid between scientific and intergovernmental forms of collaboration and taken a different development path than the ICSU GEC programmes.

The IHP is structured in successive five-year periods and has been in continual operation for over 30 years. IHP activities focus on scientific collaboration, capacity building and education in water-related topics. Scientific collaboration projects typically start on a regional scale and, depending on the region, there is often no clear separation of research and capacity building objectives. A recent example is the FRIEND regional hydrology programme which focuses on the exchange of data, knowledge and techniques to improve understanding of hydrological variability and similarity across different river basins.

Since the 1960s, the development of postgraduate study programmes has been part of the IHD/IHP activities, including the creation of Unesco chairs in water resources at universities. In 2003 the Dutch government dedicated a former Dutch institution, the Institute for Water Education IHE in Delft, to become an integral part of Unesco. This institute has been working with developing countries for almost 50 years and is now the most important means of water education within Unesco, while the Dutch government continues to provide most of the institutional funding and fellowships (IHP IC-XVI-6).

4.3.2 Organizational structure of the International Hydrological Programme

IHP's main objective is to advance member states' capacities in hydrological research and water resources management. According to the mission statement,

> "IHP is a vehicle through which Member States can upgrade their knowledge of the water cycle and thereby increase their capacity to better manage and develop their water resources (…)".

This statement clearly states the hybrid nature of IHP, since the scientific and technical advances are explicitly framed as capacities owned by individual nations. Whereas IGBP's objective is to advance fundamental scientific understanding with scientific communities as their primary audience, IHP's mission comprises both: universal progress of understanding and technology, but also progress in relation to the existing level of water management capacity in each country.

Whereas the IGBP programme is an institutionalized network of scientists with a science-driven agenda, the formal structure of IHP centres on the collaboration of states. Consequently, a continuous operational challenge for IHP is to keep its intergovernmental governance linked with scientific collaboration activities. The main structural components of IHP are National Committees (NCs) and an international headquarter at UNESCO in Paris (figure 13). NCs are IHP's formal interfaces with national governments and at the same time with national scientific and professional communities:

> "The composition of a National Committee may vary from country to country, however, the IHP Intergovernmental Council recommends that the composition include public agencies in hydrology and water resources, private individuals, relevant university faculties and departments, research institutes, consulting agencies, professional and learned societies", (www.unesco.org/ihp/structure.shtml, last accessed 19.9.05).

NCs are more important in IHP than their respective counterparts in IGBP because they are more directly involved in the implementation of IHP. IHP maintains that "the efficiency of National Committees clearly determines the overall efficiency of the programme" (IHP Bur-XXXV-3: 6).

The programme headquarter is built of hierarchical layers of decision-making. The intergovernmental mechanism of the Unesco General Conference is situated at the top. It convenes every two years and has to approve the strategy, programme lines and budget of the whole organization. At the programme level, IHP is directed by another body of intergovernmental representatives, the IHP Intergovernmental Council, which is a subsidiary organ of the General Conference. Having its own intergovernmental body provides IHP with a high degree of autonomy and almost the status of an international organization. Formally, the IHP Intergovernmental Council has "overall governing responsibility for planning, defining priorities and supervising the execution of the IHP". Regional representation is an important criterion for the election, but the representatives usually have a scientific background related to hydrology.

The Intergovernmental Council convenes in plenary session biennially. In between these plenary sessions, operational work is coordinated by the Bureau of the Intergovernmental Council with support of the IHP secretariat. The IHP Secretariat has to coordinate the interests and proposals of member states and other international organizations wishing to collaborate through IHP. To facilitate contact with national committees and project implementation, IHP has a small number of staff in Unesco regional offices and can use the infrastructure of Unesco field offices which exist in a large number of countries.[22] In practice, professionals at the secretariat have a central role to play in defining directions of the programme. In that way, a tension is built into the structure between the formal responsibility assigned to the IHP Intergovernmental Council (government representatives) and the scientific leadership at the operational level by the secretariat (interviews conducted by the author).

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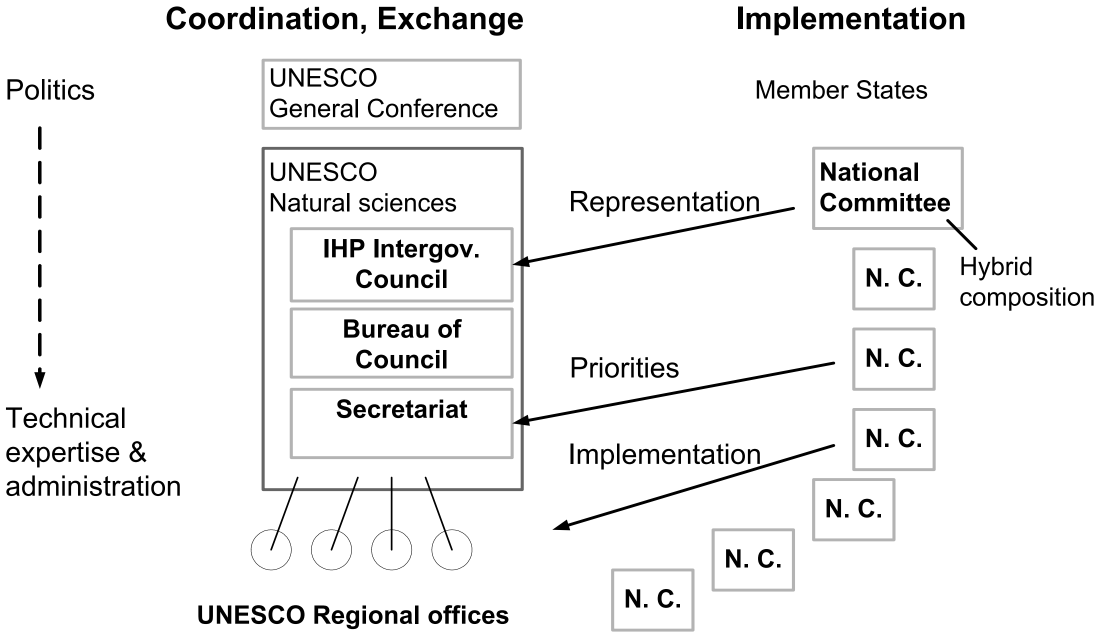
[22] Regional hydrologists are located at Unesco offices in Cairo, Jakarta, Montevideo, Nairobi, New Delhi and Venice.

Figure 13: Organizational Structure of IHP



Source: author

By comparison with the IGBP scheme, the programme is less decisively geared towards the priorities of scientific disciplines. For example, IHP's strategy is not exposed to a broad peer-review at an open scientific conference. IHP is owned by member states and has to accommodate their priorities and interests in scientific and technical topics. The negotiation of thematic priorities is done through the preparation of a plan for an IHP phase of six years duration. The development of this plan involves an extended communication process between national committees and the secretariat. IHP phase planning commences with a technical task force that is in charge of drafting a concept note outlining a proposed approach. The task force seeks proposals, comments and revisions from the national committees in several iterations in order to take the needs and interests of member states into account. The Intergovernmental Council approves a draft and in a later session the final version of the plan. The planning document describes a broad umbrella of themes in water research and management, and a list of priorities under each theme. More detailed planning decisions are involved in the biennial allocation of the Unesco IHP budget.

As with many types of hybrid organizations, the successful coupling of spheres (in this case science and intergovernmental politics) depends on people who are capable of fulfilling multiple roles. The IHP secretariat has to combine the role of diplomats and scientific professionals. As a result of its hybrid design, IHP strongly depends on individual gatekeepers within the Unesco headquarters, field offices and the national committees to keep up front of scientific developments. These gatekeepers are people who ideally have the personal capability, including the personal contact networks, to bridge science and bureaucracy. The importance of this personal capability is elevated by the low job mobility of professional staff at headquarters as a result of their status as international civil servants.[23] Furthermore, staff recruiting is required to represent different world regions. At the international level, the programme cooperates with the International Association of Hydrological Sciences (IAHS), the International Association of Hydrogeologists (IAH), and the International Atomic Energy Association (IAEA), among others.

4.3.3 Constraints to programme growth

Besides the coupling of science and intergovernmental relations, the other major operational challenge of the hybrid structure is programme growth. In response to the needs of member states and due to its orientation towards societal benefits of scientific achievements, IHP's thematic agenda has displayed a remarkable thematic broadening over the successive programme phases. Since the 1960s, the scope of issues was extended from the hydrologic research-driven IHD and IHP phase I, to the more practical goal of integrating science and rational management of water resources (phase II and III), to a stronger inclusion of environmental issues and ecosystem management (phase IV and V), while more recently an increased emphasis is placed on water and social issues (phase VI and VII).

A broader remit allows IHP to accommodate almost any upcoming topic or need of member states in the area of water resources management. Yet the thematic broadening tendency has not been accompanied by a strong growth of staff or resources, as might be expected if all these thematic areas were to be covered. The fact that IHP's

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[23] Recently, a policy of staff rotation between Unesco headquarter and field offices was introduced as part of an organizational reform (UNESCO 32 C-32:11).

infrastructure is financed as part of the Unesco regular budget secures organizational continuity over time, but at the same time severely restricts the programme's growth potential.

Unesco's regular budget covers costs for staff at headquarters and in the regional field offices and costs for activities. Activities include studies and research, conferences and meetings, publications, training courses, seminars and workshops, and technical and advisory services (UNESCO 32 C-5Appendix III: 316). IHP is not equipped to fund the implementation of research projects or capacity building in member states. Apart from limited amounts for travel, workshops, or publications, implementation has to be borne by member states or other donor agencies. Member states also cover the costs of representatives to IHP governance bodies (except for the IHP Bureau). Since there is no central budget for programme implementation, accounts of the total costs of national and regional activities tied to IHP are lacking, similar to the situation in the case of IGBP.

IHP can only increase the volume of its regular budget if Unesco's regular budget grows as a whole or if the programme's share in this budget increases. Under the Director General K. Matsuura, "water and associated ecosystems" have been assigned a principal priority within Unesco (UNESCO 31C-4: 32). After a long period of stagnation and relative decline of IHP's size, this prioritization led to an increase of the budget for IHP activities (excluding personnel) from US $ 2.76 million in the biennium 2000-01, to $ 8.91 million in 2004-05 and projected as $ 8.80 million in 2006-07 (figures from IHP IC-XVI-Inf. 6 and Unesco 33 C-5 Rev Annex I). IHP has currently 10 professional staff at the central headquarter and six at regional offices.

Beyond its regular budget, Unesco administers extra-budgetary funds contributed by member states, other UN specialized agencies, or international donors for particular purposes. Extra-budgetary funds account for a growing portion of Unesco's overall budget.[24] As for IHP, extra-budgetary resources amounted to $ 3.78 million in the biennium 2004-05, or 42 % of the regular budget for activities (IHP IC-XVI-Inf.3: 1). While extra-budgetary funding is a viable option to increase the volume of programme activi-

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[24] In the biennium 2006-07, UNESCO's regular budget is projected at a volume of US $ 610 million, plus $ 395 million extra-budgetary funds (UNESCO 33 C-5 Rev.Appendix I: 32).

ties, this growth option is practically limited by the fact that regular staff is required to direct and administer the additional projects.

> "With the large increase in extra-budgetary funding in recent years, ensuring the necessary administrative support becomes more critical. The administrative load cannot be handled by the current regular programme staff of the Division of Water Sciences (whose function is not anyway to tend to this type of requirements). The capacity of the Science Sector administration also seems to be reaching its limit. New mechanisms by which the extra-budgetary funding itself can be used effectively to provide this kind of support within the administrative framework of UNESCO must be found"; (IHP IC-XVI-Inf.11: 3).

By comparison with the bureaucratic intergovernmental infrastructure of IHP, the IGBP scheme can accommodate programme growth much more elegantly through the establishment of new scientific core projects with their own decentralized project office. By way of assigning temporary project leadership, IGBP can rely to a large extent on the employees and infrastructure of universities and research organizations.

Another growth restraining factor for Unesco-IHP is the fragmentation of water-related competencies among UN specialized agencies (see also Varady/Iles-Shih 2006). Recently, an inter-agency mechanism was initiated as a follow-up of the water-related decisions of the World Summit on Sustainable Development and the water-related Millennium Development Goals (IHP IC-XVI-Inf.17). The simple fact that 24 UN agencies and other bodies participate in this "UN Water" inter-agency mechanism is indicative of the present degree of fragmentation of water related action and the associated potential for overlap and competition within the UN family.

4.3.4 International participation

Since the development of national scientific capacity figures prominently in IHP's objectives, one might expect that participation in IHP to be broader and more diverse compared to the international GEC programmes. Yet only limited data are available to document this case. Global coverage in IHP means that each country is represented by a national committee. The national committee (NC) is designed as an interface between knowledge and decision-making in national water management. The vision of the IHP secretariat is to upgrade NCs "up to a level in which they have clear links with the decision-making apparatus of each country" (interview conducted by the author).

The IHP website lists 164 countries with an IHP NC or at least a national contact person (focal point). There is no regular record of participation in IHP In 2002-03, an evaluation of IHP phase V was conducted by a team of external evaluators. This evaluation concludes that many NCs are ineffective (IHP 2003: 5, 38). However, the evaluation did not ask NCs for explicit information on their activities or their composition. For the period of 2000-02, NCs from 42 countries submitted a voluntary report on their activities. Many of the documented activities in lesser developed countries relate to international conferences, workshops, publications and training courses. It is noteworthy that these reports often fail to make a clear distinction between scientific projects that are effectively related to IHP and other national research activities in hydrology.

The emerging picture is that IHP has some strong and many weak NCs (cf. IHP IC-XVI-10 Annex II: 4), depending on the scientific and political interest in IHP in individual countries and their scientific capacity. Options to activate and enhance NCs are a recurring topic at the IHP Intergovernmental Council. This debate shows that the role of national committees in hydrological collaboration has become ambiguous. Representatives from scientifically advanced countries, especially in Europe, emphasize the coordination of scientific work and the standardization of data and methods. Yet research collaboration between scientifically advanced countries does not depend on the involvement of national water policy which is sought by Unesco-IHP. On the other hand, representatives from developing countries emphasize the objective of regional capacity building. They argue for a decentralized administration of Unesco-IHP through the establishment of regional IHP Intergovernmental Councils (IHP IC-XVI-10 Annex II: 3). According to this argument, regionalization of IHP governance would increase the commitment and facilitate access for participants in developing countries.

The present state of this debate is a system of regular regional meetings to foster regional cooperation without changes in the formal organizational structure. Regional cooperation is reported to have successfully strengthened IHP participation in Latin America, the Arab states and south east Asia, while funding problems prevented regional meetings in Africa (IHP IC-XVI-10 Annex II: 4).

The question of enhanced participation in Unesco-IHP cannot be resolved without tackling the constraints to programme growth. Independent of the question of regionalization, a higher level of activity by a larger number of participants inevitably requires a larger number of people involved in programme coordination and support. This could be accomplished either by increasing the number of professional staff at the programme secretariat – which is very expensive – or by developing a more flexible organizational infrastructure. This organizational infrastructure should support the IHP objective of regional capacity development which is very different from the organization of global systems research, as argued in section 4.2.3.

In recent years, IHP started to build a network of regional water centres (IHP/IC-XVI/6 : 2; IHP/IC-XVI/7). Although this strategy is still in its infancy, it is an interesting organizational innovation, as explained below (4.4.3). The principal difference consists in that collaboration is established on the level of organizations. Regional centres are research and education institutions financed by national governments and affiliated with IHP through the assignment of the legal status of "centre under the auspices of Unesco". National governments show a growing increasing interest in this affiliation, since membership in this network can convey prestige to a national science institution and can facilitate access to international expert communities. Compared with collaboration under IHP in its present form, the main advantage consists in the decentralized organization and long-term support for local capacity development. This new approach could help to significantly expand IHP's reach and associated expertise.

4.4 Discussion

In the preceding sections we analyzed the cases of IGBP and IHP individually. In this section we discuss the results of this comparison and present questions for further research.

4.4.1 Findings of the structural comparison

The most crucial asset in building an international scientific programme is allegiance from scientific communities. In order for a programme to obtain strong scientific allegiance, it must hold the promise of scientific progress and associated benefits for scientific careers. We call these incentives "scientific rationales" for collaboration. In our case studies, strong scientific rationales are indicated by an ambitious science-driven research agenda, a strong role of peer review, and scientific leadership of programme activities. The comparison of these variables shows that scientific rationales play a more important role for IGBP than for IHP. Relatedly, IGBP's formal structure is superior for organizing scientific collaboration in several respects.

IGBP stands for a strong and ambitious research agenda. It set out to develop a new perspective that embraces the earth system as a whole (Malone 1986; Malone/Corell 1989). The goal to investigate the interacting global biogeochemical cycles gives a common framework to all its scientific sub-programmes (the scientific core projects) and there has been a synthesis phase to integrate results at the end of IGBP phase I (Steffen et al. 2004a). In contrast, IHP no longer pursues an overarching research objective. Whereas the earlier International Hydrological Decade set out to estimate the global water balance, today IHP has no central research framework, but promotes collaboration activities in different regions on a broad range of water-related topics.

The significance of scientific rationales is also indicated by peer review and scientific leadership. IGBP emphasizes that a large number of scientists contribute to the development of its science plans through open scientific meetings or conferences. By contrast, the six-year plan for an IHP phase is the result of the coordination between the IHP national committees, but the IHP secretariat does not systematically consult the opinion of international experts from different subfields. Research in IGBP is led by ca. 150 scientists from different disciplines and these mandates are confined to a period of six years, increasing the number of participants over time. By contrast, IHP is led by a small secretariat of permanent staff who are expected to personally combine the roles of scientist and diplomat in a UN bureacracy.

IGBP's structure offers several important advantages. IGBP establishes direct links between scientists from different countries through the implementation of a scientific core project. This project-based organizational format provides a clear definition of the purpose and scope of collaborative activities. In contrast, IHP's basic organizational unit are permanent national committees which include participants from science, government officials and engineering professions. Thus, if taken literally, IHP's formal structure would require scientists to address their national committee before establishing collaboration projects with scientists from other countries. In an increasingly globalized work environment, this step may often prove unnecessary, especially when respective national committees are not very active.

Further, IGBP's administration is lean in that it offers few full-time positions for international coordination. Instead IGBP relies on voluntary work by distinguished scientists who continue to be employed by universities and public research organizations. In this way, the costs for central coordination are kept to a minimum and there is much flexibility to engage in new collaborative activities. Consequently, the IGBP-programme type places few structural constraints on programme growth. By contrast, IHP's centralized bureaucratic organization restricts programme growth. Although governments can donate extra-budgetary funds for programme activities, all additional funds have to be managed through a fixed number of Unesco staff at the secretariat or the regional offices.

While there are no direct measures of how many scientists participate overall in each of the two programmes, the results of our participation analysis indicate limitations of scientific allegiance in IHP. The evaluation of IHP phase V concluded that many IHP national committees are inactive, even among scientifically advanced countries, and found little evidence for the scientific impact of IHP on current developments in hydrology.

The main advantage of IHP consists in the good reputation that Unesco enjoys in many developing countries. In countries which lack established scientific communities, official channels through government can help foreign scientists to identify suitable collaboration partners and to obtain permission for field work. Formal intergovernmental relations are also important in cases where public access to national hydrological information is limited. With regard to capacity building for regional water management, the most important asset is Unesco IHE in Delft, the Netherlands, which offers graduate and professional training for students from developing countries. Through its long-standing emphasis on hydrological education, IHP has been able to develop an extended contact network with experts from many developing countries.

4.4.2 Limited transferability of the IGBP model

The case comparison shows that the organization of scientific collaboration in IGBP is in many ways superior to IHP's, but it also suggests that this successful model can not simply be copied and transferred to other environmental science fields with a different problem structure. We have argued that the organizational model of IGBP proves so powerful because research on global systems is characterized by a high degree of mutual task dependence. Research on systemic GEC needs global observation systems, often uses highly standardized data products and seeks to integrate findings in complex global models.

The history of the ICSU programmes suggests that large-scale collaborative organization and the cognitive integration of systemic GEC research are mutually reinforcing social and cognitive developments. Sustained efforts at international cooperation are required in order to establish new global observation systems – but once these systems are built, the resulting data assume the function of an internationally shared frame of reference – significantly reducing transaction costs and thus facilitating future collaboration activities.

A simple transfer of organizational structures to cumulative research fields such as biodiversity and human dimensions research failed to induce scientific collaboration of comparable scales. The ICSU programmes Diversitas and IHDP demonstrate that the same organizational scheme which is so successful in WCRP and IGBP can also be used in cumulative fields to build specialized international networks and to develop new research topics - but so far Diversitas and IHDP experienced much more difficulty in obtaining participation and support among scientists and funding agencies.

The establishment of big international collaboration programmes should also be viewed in the context of international relations. The relationship between science and international politics is complex and, in the case of the contemporary programmes WCRP and IGBP, has not yet been scrutinized by historians of science. Doubtless the negotiations in the emerging field of international climate policy, which commenced in the mid-1980s (Agrawala 1998a; Agrawala 1998b; Haas/McCabe 2001), played an important role for the provision of research funding. Besides, in the 1990s it was a political strategy in the US, but not only there, to delay decisive action against anthropogenic climate change by emphasizing scientific uncertainty and the ensuing need for further research (Weart 2004).

In recent years some excellent studies on the history of the IGY have been published, the event which founded the institutional tradition of the GEC programmes (Doel 2003; Elzinga 1993; Hamblin 2005). According to these studies, the context of Cold War competition between the superpowers US and USSR constituted a singular opportunity structure for the discipline of geophysics and related science fields:

> The rapid rise of military funding for the earth sciences in the US after 1945 quickly elevated such fields as oceanography, atmospheric science, terrestrial magnetism, solid earth physics, and ionospheric studies, making them second only to physics in levels of support" (Doel 2003: 636).

During the planning and implementation of the IGY, purely scientific aims and aims of national security policy frequently became amalgamated. According to Doel, the IGY was intimately connected with the national security aims of the leading nations involved in the effort (Doel 2003: 647). While the IGY was accompanied by a strong rhetoric of easing tensions and fostering peace through scientific collaboration, its actual effects upon the climate between the superpowers appear more equivocal in hindsight, especially in connection with the launch of Sputnik I (Hamblin 2005).

Later collaboration programmes of the 1960s and 1970s, e.g. the International Hydrological Decade (own investigation) or the International Biological Programme (Golley 1993; Kwa 1987) never met with comparable interest from foreign and national security policies. The aims of these and other initiatives of the time (cf. Hamblin 2005) were framed more in terms of development policy objectives and rational use of natural resources. For contemporary GEC-programmes, the influence of international relations has not yet been investigated.

The view that the Cold War constituted an important opportunity structure for geophysics is not equivalent to reducing the scientific success story of the IGY to the security interests of the contributing nation states. This particular achievement of scientific organization can neither be separated from nor reduced to the political support that it received – rather, the political support was obtained by scientists who capitalized on this opportunity to develop their own research fields. The notion of scientific actor coalitions that are capable of seizing upon political opportunity structures is similar to the concept of structural capabilities discussed in chapter 2.

4.4.3 Capacity building and global diffusion of environmental knowledge

International collaboration programmes are built to enhance knowledge of the global environment. Capacity building has two different meanings in this context. Science-driven programmes such as IGBP and WCRP seek to advance the frontiers of knowledge and to answer questions which have never been addressed before. This can be understood as scientific capacity development in a universal sense, and is well illustrated through the progress which has been achieved since the mid-1980s in understanding and predicting the behaviour of the earth's climate system.

The question of environmental knowledge needs to be understood also in the sense of the global diffusion of knowledge and abilities, since most intervention and purposeful action take place on regional to local scales with locally available means. Due to the heterogeneity of environmental conditions, the worldwide diffusion of environmental knowledge does not merely entail the multiplied application of proven approaches, but instead requires creative adaptation and the integration with local practices and indigenous knowledge (cf. Clark et al. 2004). Hydrology and water management are good illustrations of this heterogeneity in local conditions. Therefore, the enhancement of global environmental knowledge should be understood to encompass both – scientific progress in the universal sense but also a strong emphasis on regional scientific capacity building.

In our view, future research in the organization of international collaboration should concentrate on the topic of scientific capacity enhancement in emerging economies and developing countries. The case of IHP suggests an interesting starting point for further research, namely the concept of a network of regional research centres (IHP IC-XVI-6; IHP IC-XVI-7). The basic idea of this network consists in a combination of three elements:

1. Regional capacity development is fostered on the ground by permanent research and education institutes (regional centres). In this way, the need for continuity and long-term thinking in capacity development is acknowledged. In the case of IHP, the regional water centres are financially supported by national governments and have an institutional affiliation with Unesco. This affiliation is obtained via a formal application process.

2. Regional centres belong to a partnership network of comparable institutions worldwide, i.e. from developed and developing countries. The mandate of this international network is to support regional centres in establishing international scientific contacts and in gaining access to new scientific and technological developments. In this way, the institutional membership supports the research activities and training of scientists locally. As in the case of IHP, sponsorship of the network by an international or UN organization can help to enhance the political prestige of network membership.
3. In the case of IHP, an international institution is part of the network which specializes in the university education of students from developing countries (Unesco IHE, Delft).

The development of the Unesco network of regional water centres is still in its infancy. However, it contains the seed of a promising strategy which is notably different from the original approach of collaboration under IHP. A network of regional centres does not need a shared global research agenda – since research objectives should be responsive to local conditions. Instead, the network pursues a strategy of global knowledge diffusion and training. Similar to the organizational structure of IHP, the institutional network should have the permanent support of an international secretariat with formal links to national governments. Similar to IGBP, the organizational structure of such a network is decentralized, and thus flexible with regard to the inclusion of new regional centres and programme growth.

The potential of such institutional network strategies could be investigated through a survey of different existing approaches. Another, more well-known example is the Consultative Group on International Agricultural Research (CGIAR) which supports fifteen international agricultural research centres, among them the International Water Management Institute which is based mainly in African and Asian countries (World Bank 2004). Since international networks of regional centres might be applicable to many fields of environmental science and technology, much could be learned from a systematic overview and evaluation of existing experiences, especially if such evaluations trace the development of different regional centres over time.

4.5 Conclusion

In this study we compared the organization of international collaboration programmes in two very different cases. IGBP is part of the ICSU tradition of international big-science programmes on global environmental change. Together with the World Climate Research Programme, it stands for an enormous build-up of capacity which was achieved in global climate and earth system science over the past 30 years. The main function of this type of programme is to coordinate the efforts of scientists and leading research institutions from developed countries in order to create synergies and to enable investigations of natural systems on the global scale. IHP treats one of the most pressing environmental problems globally, that is sustainable water management. Institutionally, the Unesco programme is a hybrid between science and politics and it engages primarily in the enhancement of regional scientific and technical capacity.

To date, one of the main obstacles to the creation of environmental knowledge – globally and worldwide – consists in the extreme disparity between the spatial concentration of research capacity in developed countries on one side and the global spread of environmental changes and driving factors on the other. What lessons can be drawn from the present study for the organization of multilateral cooperation endeavours, especially when the environmental problem of interest is global in the cumulative sense?

1. The most important dimension of organizational capacity is the allegiance of scientists from one or several research fields to a programme's overarching objectives. This allegiance is manifested most notably in direct participation and in the perceived relevance of a programme's objectives and outcomes for the advancement of their own field of research.
2. Strong mutual task dependence in a research field enhances incentives for scientists to coordinate their own research with the aims and methods of others. Therefore, if mutual task dependence is high, the likelihood increases that superordinate programme objectives or master plans will meet with broad support from an intellectual field. This proposition is well illustrated by research topics in systemic GEC programmes.
3. Independent of whether or not a programme aims for a strong cognitive integration of its component parts, the example of IGBP shows that a decentralized organizational structure has important advantages. Perhaps most significantly, the

design should allow different national funding sources to be incorporated, not only in the funding of research but also in the funding of administrative tasks. This point is illustrated by IGBP's decentralized project offices, which provide the flexibility and capacity for organizational growth that is lacking in IHP.

4. If the organization of scientific collaboration is coupled too closely with objectives and institutions that are external to the narrow pursuit of science, e.g. development policy objectives, it is likely that scientific allegiance will decline as a result. A simple reason is that the relationship between the expenses of engaging in collaboration (e.g. increasing time needed for meetings and administrative procedures) and the expected scientific outcome is likely to deteriorate, making collaboration less rewarding from the scientists' point of view. This is illustrated by the hybrid design of IHP, but also by other examples discussed by Hamblin (2005). Instead of too narrow organizational coupling, a careful management of boundaries between science and policy is advisable (Cash et al. 2003; Farrell/Jäger 2006; Guston 1999). This may involve the establishment of separate organizations designed to institutionalize communication across boundaries (Guston 2001). A salient example for institutional boundary management is the Intergovernmental Panel on Climate Change.

5. One of the largest obstacles to the development of large international collaboration programmes in cumulatively-global fields, such as hydrology, is a far-reaching institutional separation of development policy and support for public research in many developed countries (cf. IGFA 2005; IGFA/ICSU 2005). This is an important area for further institutionalist research in sociology of science (cf. Schimank 1995). For example, we currently lack a survey and comparative evaluation of institutions for collaboration that are evolving in various fields of environmental research.

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Annex: List of interview partners

Prof. Robert Varady
Hydrologist, Deputy Director and Director of Environmental Programmes
Udall Center for Studies in Public Policy, University of Arizona, Tucson
1. interview: 22. 4. 2004, location: Fraunhofer ISI, Karlsruhe, Germany
2. interview: 31. 8. 2005, location: IHP secretariat at Unesco, Paris

Prof. Peter Vitousek
Ecologist, Stanford University
Date: 11. 5. 2004, location: Stanford University, Palo Alto, California

Prof. Stephen H. Schneider
Climatologist, Stanford University
Date: 12. 5. 2004, location: Stanford University, Palo Alto, California

Prof. David L. Freyberg
Hydrologist, Stanford University
Date: 14. 5. 2004, location: Stanford University, Palo Alto, California

Prof. Harold Mooney
Co-Chair Assessment Panel, Millenium Ecosystem Assessment (MA)
Former Member Scientific Steering Committee IGBP I
Date: 17. 5. 2004, location: Stanford University, Palo Alto, California

Christopher B. Field
Director, Department of Global Ecology
Member of ICSU-Scientific Committee on Problems of the Environment (SCOPE)
Carnegie Institution of Washington, Stanford, California
Date: 19. 5. 2004, location: Carnegie Institution of Washington, Stanford, California

Prof. Dr. Roberto Sanchez-Rodriguez
Member of the IHDP Scientific Steering Committee; University of Riverside
Date: 1. 6. 2004, location: University of Riverside, Riverside, California

Prof. Dr. Claudia Pahl-Wostl
Member of the GWSP Scientific Steering Committee
Institute of Environmental Systems Research, University of Osnabrück
Date: 20. 7. 2004, location: University of Osnabrück, Germany

Dr. Eric Craswell, Executive Officer
Global Water Systems Project, International Project Office at the
Center for Development Research (ZEF), University of Bonn
Date: 28. 7. 2004, location: GWSP International Project Office, Bonn, Germany

Dr. Holger Hoff
Member of the GWSP Scientific Steering Committee, University of Potsdam
Date: August 2005, location: Potsdam Institute for Climate Impact Research, Potsdam

Mr. Alexander Otte
International Hydrological Programme, Division of Water Sciences, Unesco
Date: 23. 8. 2004, location: IHP secretariat at Unesco, Paris

Prof. Dr. András Szöllösi-Nagy
Secretary of International Hydrological Programme
Division of Water Sciences, Unesco
1. interview: 23. 8. 2004, location: IHP secretariat at Unesco, Paris
2. interview: 24. 11. 2005, location: IHP secretariat at Unesco, Paris

Mr. José Alberto Tejada-Guibert
Deputy Secretary of the IHP
International Hydrological Programme, Division of Water Sciences, Unesco
Date: 23. 8. 2004, location: IHP secretariat at Unesco, Paris

Dr. Mike Bonell
Chief of Section: Hydrological Processes and Climate; Division of Water Sciences
1. interview: 23. 8. 2004, location: IHP secretariat at Unesco, Paris
2. interview: 23. 11. 2004, location: IHP secretariat at Unesco, Paris

Ms. Cornelia Hauke,
Programme Specialist Word Water Assessment Programme, Unesco
Date: 4. 10. 2005, location: Unesco, Paris

Ms. Alice Aureli
Programme Specialist International Hydrological Programme,
Division of Water Sciences, Unesco
Date: 9. 11. 2005, location: IHP secretariat at Unesco, Paris

Dr. Sorin Dumitrescu
Former secretary of International Hydrological Programme
Division of Water Sciences, Unesco
1. interview: 10. 11. 2005, location: Unesco, Paris
2. interview: 24. 11. 2005, location: Unesco, Paris