Sustainability Science for Strong Sustainability

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Executive Summary

Research over the last two decades has shown that the human influence on global life support systems has reached a magnitude unprecedented in human history. To document this **global sustainability**[1] crisis**, scientists working across disciplines and contexts have produced global peer reviewed assessments. A well-known example is the assessment on climate change by the International Panel on Climate Change (IPCC), but similar globally recognized assessments have been conducted in many other fields as well. Some of the most salient facts on the crisis reported in these assessments are:

- ***Ecosystem degradation***: 60 per cent of the ecosystems upon which human societies depend for survival are degraded (Millennium Ecosystem Assessment, 2005).
- ***Global warming***: if average temperature increases by 2°C or more this is going to lead to major ecological and socio-economic changes, most of them for the worse, and the world's poor will experience the most destructive consequences (International Panel on Climate Change , 2007). Current predictions for the 21st century are an increase in temperatures between 1.8 and 4°C, respectively for the most optimistic and most pessimistic scenario envisioned in the 2007 IPCC report (all temperatures for 2090-2099 relative to 1980-1999).
- ***Oil peak***: the *2008 World Energy Outlook* published by the International Energy Agency declared the "end of cheap oil". Oil prices are going to rise and sustainable alternatives must be found sooner rather than later, as oil accounts for over 60 per cent of the global economy's needs.
- ***Inequality***: 20 per cent of the global population account for 86 per cent of total private consumption expenditure, whereas the poorest 20 per cent account for 1,3 per cent (United Nations Development Program, 1998). Inequality of incomes was higher in most OECD countries in the mid-2000s than in the mid1980s and the past 5 years saw growing poverty and inequality in two-thirds of OECD countries (OECD, 2011).
- ***Urban poverty***: nearly 1 billion of the 6 billion people who live on the planet live in slums, or, put differently, one-third of the world's total urban population (United Nations Centre for Human Settlements, 2003).

The picture that emerges from these assessments is that of a highly unequal urbanised world, depending on rapidly degrading ecosystems, with looming threats triggered by climate change and food insecurities. However, at the very moment that humanity is facing these major global crises of an economic, environmental and social nature, and that both policy makers and civil society are calling for a shift in the functioning of our societies, modern science seems incapable of providing operational solutions for overcoming these current crises. In this context, both Noble prize laureates, such as Elinor Ostrom (2007) and Sir John Sulston (2003), and high-level science officials (see for example the Tallories declaration by the Association of University Leaders for a Sustainable Future and the MASIS report by the European Commission) have stressed the need of an **in depth transformation of the modes of organisation of scientific research** for governing the transition** to sustainable societies. Following recent scholarly contributions and policy reports, this envisioned new mode of organisation of scientific research is referred to as sustainability science in this report.

[1] Terms defined in the glossary are marked with a simple/double asterisk upon their first appearance in the text or upon their first appearance in the executive summary.

To substantiate these claims, scientists and practitioners who gathered in May 2009, at a major conference organized by the European Commission, DG Research, identified two major challenges for sustainability science. First, in dealing with sustainable development, scientists also have to address the need of a change in the core values and worldviews that drive individual actions and organisations, beyond formal descriptive-analytical** modelling of complex systems. Therefore, it is the responsibility of scientists to engage in new forms of collaboration with stakeholders and citizens, in the urgent search for an implementation of feasible options for substantive and decisive action. Second, there is a need to remove practical and institutional barriers for the development of the goal-seeking, iterative and integrative approaches needed to address the issues of sustainability. This will require organisational changes, but also changes in funding and evaluation of science.

In response to these needs, visionary leaders in science policy administrations and higher education institutions have set up **frontier science institutions for sustainability**, both at the level of strategic research and training programs and at the level of networks for broader capacity building. Well recognized examples which illustrate frontier research initiatives are the program at the *Graduate School of Frontier Sciences* at Tokyo University and the *Institute for Landscape Ecology and Botany* at the University of Greifswald. Both these institutions combine research into economics and ecology with a specific expertise in empirical social research and collaboration with sustainability stakeholders. In addition, these institutes have set up interdisciplinary international master programs combining training in environmental sciences, economics and sustainability ethics. Prominent examples that illustrate networks for capacity building in sustainability science are the Swiss Network for Transdisciplinary Research (td-net), at the Swiss Academies of Arts and Sciences, and the Alliance for Global Sustainability between four science and technology universities in the US, Japan and Switzerland. Transdisciplinary research is key to all these capacity building initiatives and is understood as basic or applied research into socially relevant problems, implemented through research collaborations between scientific and stakeholder expertise. The goal of these networks is to advance the mutual learning between inter- and transdisciplinary researchers and lecturers across thematic fields, languages and countries.

Nevertheless, in spite of the wide recognition of the path breaking contribution of these frontier science initiatives, the efforts of many sustainability science researchers and sustainability stakeholders are hampered in practice by the **structural constraints imposed by the current mode of organisation of the scientific research system**. Indeed, as documented in the report, serious obstacles arise from the lack of career incentives in interdisciplinary and transdisciplinary sustainability science in higher education institutions, the shortage of training opportunities in multi-method quantitative and qualitative case study research, and, most importantly, the dominance of mono-disciplinary peer review of research projects, individual researchers and of higher education institutions themselves. The effects of the latter can be illustrated with a recent study that published bibliometric research of the peer-reviewed articles with the word "sustainability", either in the title or the key-words, in the approximately 16 500 peer reviewed journals of the Scopus database that were published between 1996 and 2009. This study showed that, even in the articles that explicitly mention sustainability as a key-word, cross-referencing between the three pillars of sustainability science (environmental, social and economic) is rare, especially for the articles in the environmental science journals, with only around 25 per cent of these sustainability articles citing other articles from the social science journals and 10 per cent from economics journals. For the articles on "sustainability" topics in economics journals, cross-referencing is more frequent, but the overall proportion of articles on sustainability in the economics journals is much lower and overall marginal.

The reality of these institutional constraints contrasts with the need of **moving beyond the "value neutral" and "ivory tower" mode of organisation of research** for sustainability highlighted above. Nevertheless the conventional mode of research is still even more deeply entrenched in the research practices outside the community of sustainability scholars. To illustrate this, it suffices to analyse prominent economists' reactions to the 2008 financial crisis. These reactions, analysed in more depth in section 3.3. of the report, show two major strategies to keep mainstream economic analysis of the financial system within the remits of a highly abstract apparatus that is disconnected from empirical analysis of social and human behaviour. First, the recourse to abstract equilibrium or near-equilibrium modelling, in conjunction with the assumption of a uniform individual "representative agent", as the main respected methodology leads to a systematic marginalisation of the issue of systemic risks and instabilities in the financial system. A well-known example of this strategy is illustrated by the belief, originally shared by former Fed Chairman Alan Greenspan, that it suffices to introduce a sufficient number of appropriate derivative instruments to eliminate all uncertainty** from the market. The latter approach of a uniform economic agent using ever more sophisticated tools to correct the mathematical uncertainties of the system is in stark contrast to real-world social dynamics, based on interactions between heterogeneous economic agents which have different information sources, motives, knowledge and capabilities. The second strategy can be found in the beliefs expressly defended by prominent economic scholars (such as Robert Lucas, Nobel Prize laureate in economics) that situations of crisis are outside of the predictive power of economic sciences and cannot be dealt with scientifically within the discipline.

As shown through the analysis of successful contributions of **economic research** to sustainability, what is needed instead for sustainability research are **interdisciplinary practices combining economic research with analysis of social practices and an explicit discussion of the ethical orientations** that underline the modelling options. For instance, research on ecosystem services in the Millennium Ecosystem Assessment has successfully promoted a set of tools based on a combination of market creation for sustainable use of ecosystem products, with the building of local community organisations and science-based decision support systems. A successful application of these tools which illustrates this embedding of analysis of market processes in broader social practices is the Rio Platano Biosphere Reserve in Honduras. In this reserve, sustainability scientists have successfully supported communities to overcome the poverty driven degradation of shared ecosystems, by re-orienting the local economy towards non-timber forest products (such as cocoa, ornamental plants, medicines and oil), in the context of a community-based governance model. In a similar way, innovative modes of organisation of research that combine descriptive-analytical approaches of complex systems and the analysis of social practices have been proposed within post-keynesian macro-economics, ecological economics and Veblenian evolutionary economics. Because of the crucial role of economic thinking in policy making for sustainability, these approaches are analysed in depth in section 3 of this report, with the view to provide concrete ideas of the possible way forward in the transformation of the existing research practices

The analysis in this report of the concrete practices and the scholarly literature on the mode of organisation of sustainability science shows more generally the need to combine the descriptive-analytical approach of complex systems, developed for instance in economics and environmental sciences, with the analysis of and involvement in social practices and ethical debate. These requirements have been articulated in this report in terms of a **set of 3 basic conditions that have to be considered together for successfully addressing sustainability problems through sustainability research**:

- ***Interdisciplinarity*****: first, sustainability science has to adopt an interdisciplinary perspective that combines the descriptive-analytical approach of complex socio-ecological systems** with the analysis of social practices and transition pathways;
- ***Explicit discussion of strong sustainability ethics***: second, in so doing, sustainability science has to explicitly address how actors and decision makers in various problem situations can give concrete meaning to a strong sustainability ethics, which recognizes the intrinsic limits of the substitution of all natural life support systems by technological means or other forms of human-made capital. In particular, such discussions should clarify the situations in which a weak, intermediate or strong sustainability approach** is most relevant;
- ***Transdisciplinarity*****: third, because of the context specificity of both the solutions and the socially relevant ethical options, sustainability science has to combine inputs from scientific and extra-scientific stakeholder expertise in organizing scientific research.

As illustrated throughout the report, the failure to integrate these dimensions in the organization of research can have dramatic consequences for solving concrete sustainability problems. For instance, the failure to integrate the broader stakeholder perspectives in the management of the Everglades in Florida (US) leads to a dramatic miscalculation of the full causes of the degradation of the unique sea grass ecosystems. The latter resulted in one of the high costs ever to be paid in the US for ecosystem restoration, in particular for reversing the much deeper degradation that resulted from the miscalculation. In other cases, the failure to integrate an explicit discussion on sustainability ethics has led to neglect value-based conflicts in implementing proposed solutions, even in situations where there was initially a broad agreement on the need to factor in the intrinsic limits of the planets resources in economic development. A case in point is the transition approach to innovation in socio-technological systems: even though this approach has been predominantly used in a sustainable development context, the approach in itself does not have a conceptualization of sustainable development. This lacuna has led to increasing frustration and tensions for example in a major initiative on transition in Flanders, in the domain of waste and sustainable materials. In this initiative, the initial dominant ethical orientation in terms of reduction of waste materials has been overtaken in later stages of the research by a set of objectives focusing primarily on the creation of a market for the supply of waste as secondary products.

The interdisciplinary and transdisciplinary research practices in economic and environmental sciences analysed more specifically in this report show the importance of these three combined conditions for sustainability science. The general result from the analysis is the following: even though the experimentation with these conditions is still on-going, there is a broad consensus amongst sustainability scholars and senior science officials of the urgent need to move from the purely descriptive-analytical approach of complex system analysis to a transformative science approach. The latter combines the descriptive-analytical mode of research with an analysis of social practices of transition and a more in depth discussion of the ethical orientations that can be taken, within an overall recognition of the intrinsic limits of the earths’ living and natural resources. In addition, researchers in many other disciplines, such as political science, psychology, history, and sociology among others have experimented new modes of organisation of research for successfully addressing sustainability problems. The analysis in this report could certainly be extended to these other sciences, with the view to further learning from promising transdisciplinary sustainability approaches developed also elsewhere.

Finally, in implementing these research requirements for sustainability research, researchers in sustainability science face major institutional barriers, some of which were already highlighted above and which are analysed in more detail in section 4 of the report. More analysis is certainly needed to review and evaluate these barriers and to design the **institutional tools for capacity building** that can be put into place at various levels of policy intervention. However, the analysis of major successful initiatives, taken in other countries, already allows establishing a list of tools that have proven to be effective or that are in the process of being implemented. As shown in section 4, the following action points seem to be essential components of such an institutional capacity building policy:

Capacity building measures at higher education institutions

- Building of transdisciplinary research centres
- Creation of "bridging" research fellowships, between scientific and stakeholder expertise
- Establishment of transdisciplinary professorships

Tools within programmatic research funding at regional, national and EU level

- Requirement of transdisciplinary organisation of research
- Requirement of a strong sustainability ethics perspective
- Synergy grants to researchers for cross-institutional and multi-method sustainability research
- Cross-institutional competence centres for sustainability research

Support for new research networks

- Sharing best-practices and know-how for international networking
- Common transdisciplinary research infrastructure (journals, conferences, prices)
- Joint submission of larger research projects

Building new research institutions/platforms/panels

- Regional or national sustainability panels
- Organisation of stakeholder identification/submission of salient research questions
- Institute for advanced studies in sustainability research
- Advisory body on quality management procedures for transdisciplinary sustainability research

The implementation of these action points imply an in depth transformation of the current modes of organisation of research. Nevertheless, both the existing current incentive and reward system of disciplinary research, and the existing mode of university/industry collaboration geared towards the needs of industry, remain important and well-established social benefits of modern higher education institutions. However, they are clearly insufficient for implementing the type of multi-stakeholder collaborations required for solving complicated and interconnected sustainability issues. The aim of the envisioned tools therefore clearly is not to build a substitute to already well-established institutions of modern science that have proven otherwise productive. Rather the goal should be to build a new layer of interdisciplinary and transdisciplinary research on top of the existing research infrastructure, in order to tackle the unprecedented sustainability crisis that humanity is facing today. While there are no simple solutions to this challenge of an in depth transformation of existing modes of research, universities and funding agencies have repeatedly demonstrated their capacity to overcome the institutional and epistemological barriers discussed in this report, along the lines of the frontier science initiatives and networks illustrated above. Therefore, it seems worthwhile for the scholarly and policy communities to recognise these barriers and strive to lower them by providing greater institutional, organisational and financial support.

Introduction

Modern science is considered by many as one of the major drivers of the increase in human prosperity over the last three centuries (North, 2010; Mokyr, 2002). However, at the very moment that humanity fails to tackle major global crises of an economic, environmental and social nature, modern science seems incapable of providing operational solutions for overcoming these current crises. This failure of the project of modern science, as it was inherited from the enlightenment, has been analysed by many scholars in recent decades (Arendt, 1963; Latour, 1993; Funtowicz and Ravetz, 1993). In the context of these major challenges however, the debate on the role of science in society has gained a new momentum and **new path breaking transformative approaches to science have been developed over the last twenty years**. This report analyses the contribution of these approaches to managing the transition** of human societies to strong sustainability**, with a particular focus on environmental and economic sciences.

Scholars and practitioners who gathered in May 2009 at a major conference organized by the DG-Research in Europe to discuss the meaning of sustainable development for science identified **two major challenges for sustainability science** (Jaeger and Tàbara, 2011; Jaeger, 2011). **First**, in dealing with sustainable development, there is a need for transformations in the core values and worldviews that drive individual actions and organisations. Science can contribute to such changes, but only if the challenges are addressed in a collaborative, iterative and exploratory mode. Indeed, sustainable development issues are complex and require ethical judgement on the limits of the earths' resources and responsible choices between multiple stakeholder perspectives. It is the **responsibility of scientists to engage in new forms of collaboration with stakeholders and citizens**, in the urgent search for and implementation of feasible options for effective transition to sustainable societies.

Second, there is a need to **remove practical and institutional barriers** for the development of the goal-seeking, iterative and integrative approaches needed to address the complex issues of sustainability (Jaeger 2011, p. 201). This will require organisational changes, but also changes in the funding and evaluation of science. In particular, the funding and review mechanisms for proposals and projects in sustainability science must be designed in ways that reflect the basic interdisciplinary features of the emerging field. In addition, long-term funding will be required for research on coupled social-ecological systems, which require a continued learning process with stakeholders in open-ended policy experiments. Finally, there is a need for institutional support for training and capacity building for scholars who wish to engage in sustainability science, as sustainability science requires a distinct set of professional competences – facilitation skills, systems thinking, ethical reasoning and abilities to build strategic partnerships, amongst others – that are not currently sufficiently encouraged in academic training programs (Jaeger and Tàbara, 2011).

With the view to increasie our understanding of the core principles of sustainability science and to better address both the theoretical and organisational challenges, this report examines the following topics. **Section 1** addresses the question of why sustainability science is needed and how emerging research programs have attempted to address these needs, in spite of major institutional and practical hurdles. Based on this historical and institutional overview, **Section 2** analyses the common features of sustainability science that emerge from existing practice. A crucial issue in this context is to analyse how sustainability science can contribute to implement the normative vision of sustainable development since its initial formulation in the Brundtland report 25 years ago. However, sustainability scientists also have to address new challenges that have grown in importance since the Brundtland report, such as the governance of technological transitions in the field of energy and sustainable food systems and the systemic risks generated by globalized financial markets. **Section 3** reviews prominent sustainability science approaches that have been developed over the last two decades. Because of their important influence on policy making, this section focuses more specifically on interdisciplinary approaches in economics and environmental sciences, which have been developed to overcome the failures of Walrasian general equilibrium* thinking in economics and purely bio-physical approaches in environmental sciences. **Section 4**, finally, addresses the organizational and institutional challenges faced by universities and research policy officials when implementing the core organising principles and methodologies of sustainability science discussed in Sections 2 and 3.

Section 1: Why is sustainability science needed?

Research over the last two decades has shown that human influences on global life-support systems have reached a magnitude unprecedented in human history (Jerneck et al., 2010). On the one hand, pro-growth economic policies have encouraged rapid accumulation of consumption goods and technological innovations (Komiyama and Takeuchi, 2006; Orecchini et al., 2012), and resulted in increased human prosperity in many parts of the world, although in a globally disproportionate manner. As already stated in the Brundtland report 25 years ago: "Those looking for success and signs of hope can find many: infant mortality is falling; human life expectancy is increasing; the proportion of the world's adults who can read and write is climbing; the proportion of children starting school is rising; and global food production increases faster than the population grows" (WCED, 1987, p. 19). On the other hand, by depleting the world's stock of natural wealth on a global scale – often irreversibly – the prevailing, and predominant, economic and development models increasingly have detrimental impacts on the wellbeing of present generations, in particular leading to a broadening ecological crisis and ever widening social disparities. Concomitantly, these models present tremendous risks and challenges for future generations.

To document the most salient features of this global crisis, researchers throughout the world have engaged in vast enterprises of collaborative peer-reviewed research. The results of these mega-science projects for monitoring the multi-dimensional crisis have been most visible in the field of climate change research, in particular with the awarding of the Nobel peace prize in 2007 to the International Panel on Climate Change (IPCC). The latter assessment involved over 1000 scientists, from over 120 countries, and is entirely based on a process of peer-review amongst expert reporting on the latest findings from the various sub-fields of climate change research. Similar initiatives have been undertaken for monitoring the biodiversity crisis, natural resources depletion and global pollution amongst others. As a result of these initiatives, scientists working across disciplines and contexts produced a state of the art of major social and ecological indicators in globally significant reports. The most important of these are the following (Swilling and Annecke, 2012, pp. 27-28):

1. Ecosystem degradation: the United Nations (UN) *Millennium Ecosystem Assessment*, compiled by over 1300 scientists from 95 countries and released in 2005, has confirmed for the first time that **60 per cent of the ecosystems upon which human systems depend for their survival are degraded** (United Nations 2005).
2. Global Warming: the broadly accepted reports of the International Panel on Climate Change (IPCC) confirm that global warming is taking place due to release into the atmosphere of greenhouse gases caused by, among other things, the burning of fossil fuels. **If average temperature increases by 2°C or more this is going to lead to major ecological and socio-economic changes**, most of them for the worse, **and the world's poor will experience the most destructive consequences** (IPCC, 2007). Current predictions for the 21st century are an increase in global temperatures between 1.8 and 4°C, respectively for the most optimistic and most pessimistic scenario envisioned in the 2007 IPCC report (Synthesis report, p. 45; all temperatures for 2090-2099 relative to 1980-1999).
3. Oil Peak: the *2008 World Energy Outlook* published by the International Energy Agency declared the "**end of cheap oil**" (International Energy Agency 2008). Even the major oil

companies now agree that oil prices are going to rise and alternatives must be found sooner rather than later. **Oil accounts for over 60 per cent of the global economy's energy needs**.

4. Inequality: according to the UN *Human Development Report* for 1998, **20 per cent of the global population account for 86 per cent of total private consumption expenditure**, whereas the poorest 20 per cent account for 1,3 per cent (United Nations Development Program, 1998). In addition, inequality of incomes was higher in most OECD countries in the mid-2000s than in the mid1980s and the past 5 years saw **growing poverty and inequality in two-thirds of OECD countries** (OECD, 2011). Alternative, more complete indicators of inequality, integrating quality of life indicators and/or capabilities, show similar trends (see also the discussion in section 1.2 below).
5. Urban Poverty: according to the UN-HABITAT report entitled *The Challenge of Slums*, **nearly 1 billion of the 6 billion people who live on the planet live in slums** or, put differently, one-third of the world's total urban population (United Nations Centre for Human Settlements 2003).
6. Food insecurity: the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) (Watson *et al*., 2008) is the most thorough global assessment of the state of agricultural science and practice that has ever been conducted. According to this report, modern, industrial, chemical-intensive agriculture has caused significant ecological degradation which, in turn, will threaten food security in a world in which access to food is already highly unequal and demand fast outstripping supply. Significantly, this report confirmed that "**23 per cent of all used agricultural land is degraded to some degree**" (Watson *et al*., 2008: ch.1, p. 73).
7. Material flows: according to a 2011 report by the International Resource Panel (http://www.unep.org/resourcepanel), by 2005 the global economy depended on 500 exajoules of energy and 60 billion tonnes of primary resources (biomass, fossil fuels, metals, and industrial and construction minerals), an increase of 36 per cent since 1980 (Fischer-Kowalski and Swilling, 2011).

As stated by Swilling and Annecke (2012, p. 28), the above trends "combine to conjure up a picture of a highly unequal urbanised world dependent on rapidly degrading eco-system services, with looming threats triggered by climate change, high oil prices and food insecurities".

The situation is worrisome, in particular because most of the driving forces of environmental change such as economic growth, consumption levels in industrialized economies, the size of the world population, resource use and energy consumption continue to increase (Jaeger, 2011). For example, according to the latest forecast by the United Nations (2010), world population is projected to surpass 9 billion by 2050, from approximately 7 billion in late 2011. From a business or industrial perspective, this can be translated into billions of new consumers. Therefore population growth may offer room for market expansion, which could be considered as good news (Orecchini et al., 2012). However, the bad news is that the greater scarcity of resources, mounting economic pressure on the environment, and potentially worsening socio-economic conditions for larger parts of humanity, will necessarily influence the ability of those 9 billion to sustain present consumption lifestyles or to attain the standards of living enjoyed by the most developed and richest countries today (Orecchini et al., 2012). As a matter of fact, **over the next 40 years, demand for industrial materials in most sectors is expected to double or triple**. Projections of future energy use and emissions based on current technologies show that, without decisive action, these trends will continue (UNEP, 2011).

The Millennium Ecosystem Assessment provides an appropriate illustration of the interdependence between these driving forces of global change, the global sustainability crisis and its impact on human well-being. On the one hand, the Millennium Assessment has shown in its synthesis report that most of the ecosystem services are declining (Table 1.). More recently, a quantitative assessment of the threshold levels of critical global-scale processes, published in *Nature*, has shown that for nearly all the critical processes the observed values are close or already exceeding the critical thresholds (Table 1..). On the other hand, the evolution of these ecosystem services has a negative impact on physical, emotional and social well-being, leading to a call for change in governance and economic and social policy (see in particular section 3.2.3.a. and figure 3.1).

Table 1 : Global Status of Provisioning, Regulating, and Cultural Ecosystem services.

Source: Millennium Ecosystem Assessment Synthesis Report (MEA, 2005).

Service	Sub-category	Status	Notes
Provisioning Services			
Food	crops	↑	substantial production increase
	livestock	↑	substantial production increase
	capture fisheries	↓	declining production due to overharvest
	aquaculture	↑	substantial production increase
	wild foods	↓	declining production
Fiber	timber	+/–	forest loss in some regions, growth in others
	cotton, hemp, silk	+/–	declining production of some fibers, growth in others
	wood fuel	↓	declining production
Genetic resources		↓	lost through extinction and crop genetic resource loss
Biochemicals, natural medicines, pharmaceuticals		↓	lost through extinction, overharvest
Water	fresh water	↓	unsustainable use for drinking, industry, and irrigation; amount of hydro energy unchanged, but dams increase ability to use that energy
Regulating Services			
Air quality regulation		↓	decline in ability of atmosphere to cleanse itself
Climate regulation	global	↑	net source of carbon sequestration since mid-century
	regional and local	↓	preponderance of negative impacts
Water regulation		+/–	varies depending on ecosystem change and location
Erosion regulation		↓	increased soil degradation
Water purification and waste treatment		↓	declining water quality
Disease regulation		+/–	varies depending on ecosystem change
Pest regulation		↓	natural control degraded through pesticide use
Pollination		↓[a]	apparent global decline in abundance of pollinators
Natural hazard regulation		↓	loss of natural buffers (wetlands, mangroves)
Cultural Services			
Spiritual and religious values		↓	rapid decline in sacred groves and species
Aesthetic values		↓	decline in quantity and quality of natural lands
Recreation and ecotourism		+/–	more areas accessible but many degraded

Note: the "substantial production increase" in crops is achieved at the expense of a 5% annual increase in the application of chemical fertilizers; the "substantial production increase" in aquaculture is achieved at the expense of permanent damage to capture fisheries; the "substantial production increase" in livestock is achieved at the expense of degraded environment, increased use of antibiotics and hormones, use of chicken manure as feed and expanding feedlots industry (MEA, 2005).

This brief overview shows that, despite international agreements and action plans at all levels, there has been no success over the past few decades in reconciling human development with the environmental limits of the earth and in securing well-being for all people on this planet now and in the future (Jaeger, 2011). Indeed, we are faced with persistent problems of non-sustainability resulting from overexploitation of the planet's resources and from surpassing the threshold of its capacity to assimilate wastes. Transformative research is needed so that sustainable pathways can be explored and taken (Jaeger, 2011).

The following sections focus on three hard problems for transformative research that follow from this situation of non-sustainability and whose solution should be at the core of the principles of the emerging field of sustainable science: first, the problem of non-substitutability of natural capital by produced/technological capital; second, the problem of mounting inequalities and, third, the need to bridge the gap between science and society.

1.1. The challenge of decoupling growth from the exploitation of natural resources

During the two last centuries, the scale of human activities has grown exponentially. This growth has led to a situation where human social systems and the earths' ecological systems have become strongly coupled systems which have to be addressed in an integrated manner (Costanza et al., 1993). In particular, scientists and policy makers have recognized the need to acknowledge the biophysical constraints on the future possibilities of development of human societies. Such biophysical constraints include (1) the provision of raw materials for direct consumption and production, (2) the limits on the capacity for assimilation of waste products by the earth's ecosystems, (3) the maintenance of the provision of landscape, information and cultural services by ecosystems and (4) the maintenance of the provision of basic life-support functions that are prerequisites of all of the above (Ekins et al., 2003).

Sustainability in this context can be described as the "**maintenance of capital**" (Goodland and Daly, 1996). In case of economic sustainability it refers mainly to financial capital. For example, historically, at least as early as the Middle Ages, merchants wanted to know how much of their sales receipts could be consumed by their families without depleting the capital of their business (for example by using only the net profits, minus investment costs, for their private consumption). More recently, the concept of sustainability is increasingly used in the context of the ecological crisis, where the term **environmental sustainability** refers to the **maintenance of natural capital**.

Sustainable development aims at an equitable use of the different types of capital that are essential for the functioning of coupled social-ecological systems. In general the different types of capital can be subdivided in **natural capital** on the one hand and different forms of **human capital on** the other **(composed of cultural capital, institutional capital, social capital and technological/produced capital**). In this context, different approaches to sustainability have been proposed according to the possibility of substituting *natural* with *technological/produced* capital (technological artefacts and products of labour), ranging from ***weak sustainability*** (complete**

substitutability of natural by technological/produced capital) to different forms of ***strong*** **sustainability (limited or no substitutability of natural by technological/produced capital).**

Figure 1.1 illustrates the different degrees of substitutability between natural resources (R) and technological/ produced capital (K). Case (a) assumes full substitutability between natural resources and capital K, allowing a complete replacement of natural resources by capital K (weak sustainability). The second production function (b) corresponds to the existence of a limit on the substitution possibilities, with the recognition of a necessary minimum threshold of available natural resources in any production processes (represented by the minimum threshold levels r1, r2, r3 for each production function) (strong sustainability). The last graphic (c) represents a production function where no substitution is admitted (also a case of strong sustainability).

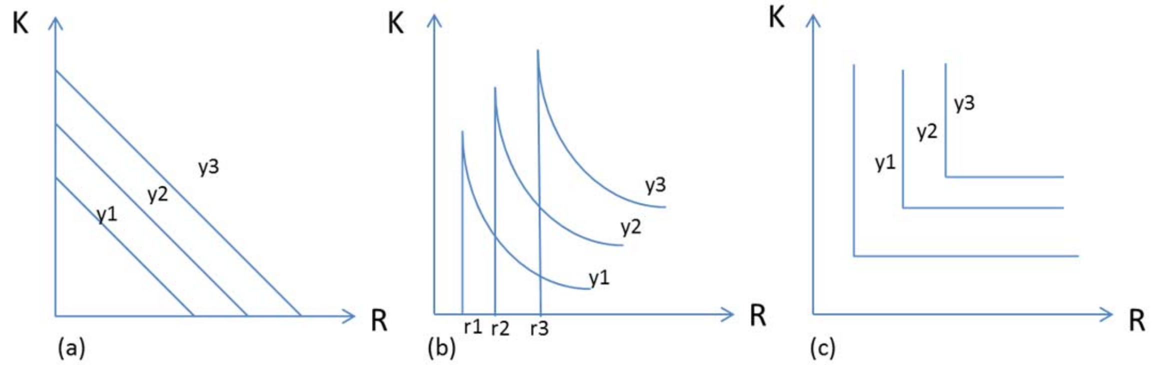

Figure 1.1: Different types of production functions

The three types of production functions link constant national income Y_i with technological/produced capital stock K (such as technology) and amount of natural capital R (such as non-renewable natural resources), under (a) full substitutability between K and R (= weak sustainability approach); (b) limited substitutability between K and R (= strong sustainability approach); and (c) no substitutability (= strong sustainability approach) (adapted from Common and Stagl, 2005 p. 220).

1.1.1. Weak sustainability compared to strong sustainability

The **weak sustainability approach** (Scenario (a) in Figure 1.1) extends the neoclassical model of economic development and considers non-renewable natural resources as one of the factors of production, seeking to "establish rules on how much natural resources to consume now and how much to invest in produced/technological capital to increase consumption later, when the non-renewable resources will be exhausted" (Dietz and Neumayer, 2007). This approach assumes that utility obtained from natural capital and technological/produced capital, is substitutable. For example, if individual utility is measured by individual monetary income, replacing wood products by plastic, or a natural flood plain by a concrete one, does not make any difference from a weak sustainable perspective if such substitution leads to an equivalent level of individual income (after taxation/after buying the consumption goods). In both these cases of substitution, neither the intrinsic limit of earths' resources, nor the value of certain natural resources for the appropriate functioning of basic ecosystems is taken into account. In fact, the weak sustainability model requires that either (a) natural resources are super-abundant, (b) the elasticity of substitution between natural and produced capital is greater than or equal to unity (that is: the marginal gain in utility is greater or equal than unity when substituting natural capital R by technological/produced capital K as input in the production process), or (c) technological progress can increase the productivity of the natural capital stock faster than that it is being depleted.

The weak substitutability approach leads to a development policy focused on the exploitation of natural resources in a way that allows a sustainable income stream from natural resources to be retained from new human capital investments, in spite of the depletion of the natural resources. This logic can be illustrated, for example, by the permanent process of compensation of loss of soil fertility, consequent to intensive agricultural practices, through increasing the recourse to mechanization, irrigation and fertilizers (Krishnan et al., 1995, p. 98). However, often the technological substitutes rely themselves on non-renewable natural resources (such as oil and fresh water in the case fertilizers and irrigation). In such cases, the weak sustainability approach clearly is only a blind belief in the promises of technological progress without real scientific support.

Conversely, the **strong sustainability approach** acknowledges that **not all the functions of natural capital can be replaced by produced/technological capital and that there are critical levels beyond which substitutability is no longer possible** (Daly and Farley, 2011). Situations of non-substitutability arise for example when critical thresholds are reached for the assimilation of waste products (such as greenhouse gasses in the atmosphere) or for the functionality of living systems (such as the collapse of a fishery's ecosystem). As Goodland and Daly (2011, p. 161) put it, complete substitutability would signify that a cooker can make a 1000-pound cake, using just the ingredients required for a 5-pound cake, "by stirring harder and baking longer in a bigger oven" (in figure 1.1.b., this would mean to produce income level y3 by using the same level of natural resources as income level y1, which is clearly not always possible, as y1 can be produced by using less resources than the critical threshold level r3).

In further developments of the strong sustainability approach, additional attention is drawn to the fact that those **critical levels for substitutability are extremely difficult to assess**. As argued initially by Holling (1973), under such conditions the weak sustainability approach should be replaced by a conception that focuses on preserving the functionality of living systems over time (resilience) and on maintaining each type of capital (natural, cultural, institutional, social and produced/technological) intact independently (Common and Stagl, 2005; Goodland and Daly, 1996). From a policy perspective, the criterion of strong sustainability has been used for example in the IPCC report. The IPCC's 450 ppm stabilisation target has been calculated based on a maximum tolerable increase of global temperatures of between 2 and 3°C. Beyond this temperature increase, the evolution of the climate would reach potentially threshold effects that cannot be compensated anymore by technological means.

Finally, scenario (c) in Figure 1.1. corresponds to a view where no substitution is permitted, that is no natural resource can ever be depleted. This view seems to be unnecessary as resilience is not necessarily achieved only through a static vision of nature, but can be achieved by a dynamic, but sustainable, co-evolution of nature and human societies. This scenario has been labelled by some as absurdly strong sustainability (Goodland and Daly, 1996). However, even though a universal application of scenario (c) can rightly be labelled absurd, this scenario still might be very relevant for some of the basic features that determine the health of critical ecosystem services on earth. In particular, this scenario could apply to situations where the exhaustion of natural resources or environmental degradation beyond a certain threshold would lead to so-called "tipping points" of irreversible damage to these basic services. One such case that has been recently documented in a review paper in *Nature* is the existence of planetary-scale tipping points, beyond which the earths ability to sustain us and other species would be threatened (Barnosky et al., 2012).

1.1.2. Beyond eco-efficiency: the challenge of absolute decoupling

The **weak sustainability approach**, currently dominating current mainstream economics, **is based on the assumption that economic growth can be decoupled from material throughput through decrease of natural resource use in production systems, in particular by technical innovation.** Such decoupling is supposed to cover both a decrease in consumption of non-renewable resources and a decrease of the production of waste products that have to be assimilated by the earth's ecosystems. In particular, the weak sustainability approach assumes that technological innovation, together with behavioural changes towards more sustainable consumption patterns, will ensure that continuing growth of consumption is compatible with a sufficient level of environmental protection. **But evidence of decoupling of economic growth from depletion of natural capital shows mixed results at best**. Granted, the last three decades have witnessed a marked increase in **relative decoupling, that is a decrease in use of natural capital per unit of economic output** (for example measured in terms of GDP), in part as a consequence of increased eco-efficiency (a more efficient use of resources or a reduction in pollution intensity per unit of economic output). Figure 1.2. presents the increasing levels of energy efficiency for five developed countries. In addition, carbon emission efficiency in developing nations, for the most part, steadily decreased during the 1990s. However, since 2000, these gains are likely to be totally offset by a new wave of use of inefficient carbon technologies in these developing nations (Jackson, 2009a, p. 49).

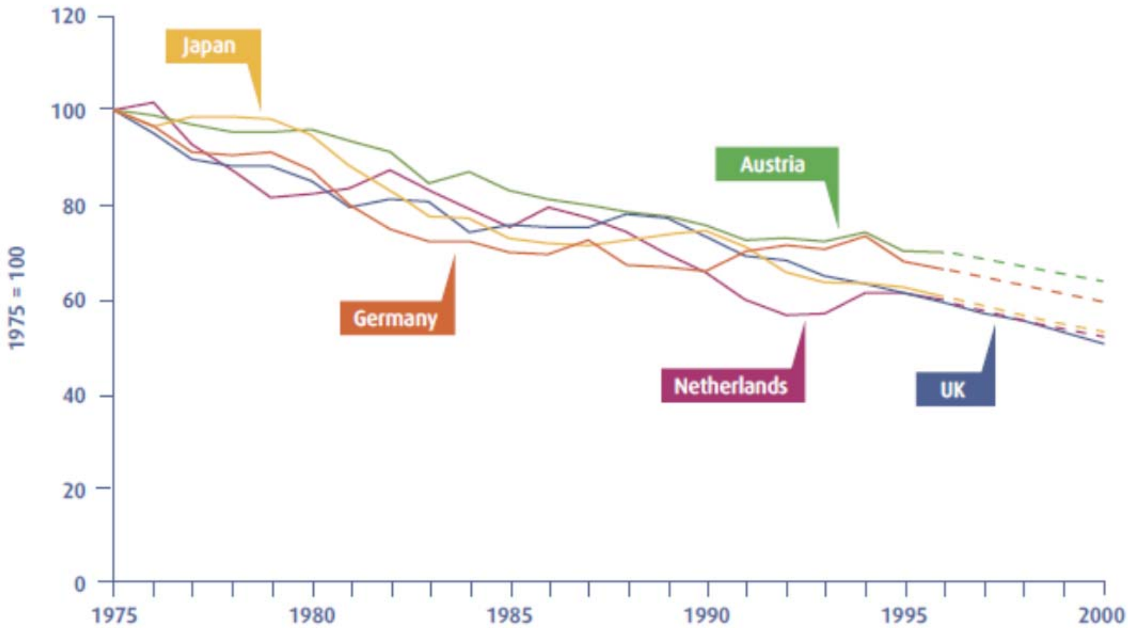

Figure 1.2: Relative decoupling in OECD countries 1975-2000

The relative decoupling is measured as direct material consumption (DMC) per unit of GDP, indexed to 1975 (Source: Jackson, 2009a, p. 49). Figure based on rough estimates – more accurate use of the statistical data however reveals similar trends for relative decoupling (see Laurent, 2011). The indicator that is used (DMC) measures the total amount of materials directly used in the economy, minus the materials that are exported. The DMC indicator does not include the outsourcing of "dirty" production/extraction to other countries. The use of the Total Material Consumption (TMC), which includes such outsourcing, would be more accurate, but is difficult to measure with the current data (Eurostat, 2001). The latter gives in any case a less optimistic scenario and would likely lead to the absence of relative decoupling, that is no decrease in TMC per unit of GDP (see Laurent, 2011).

Relative decoupling is certainly a necessary condition for ecological sustainability. But it is not a sufficient condition. First, even in relative terms, the global trend of increased efficiency hides significant differences between developed and developing countries. Second, **what matters for ecological sustainability is absolute decoupling, that is an absolute reduction of the increase of the use of natural resources**. However **relative decoupling has not lead to such *absolute decoupling*** on the global scale. Rather, global energy consumption in absolute terms has continued to increase in the period 1975-2000. For example, according to estimations of Tim Jackson, even though relative efficiency of energy use increased in the OECD, with overall energy efficiency gain of up to 50% in some countries, absolute energy consumption also increased or stayed at the same level in these countries (Jackson, 2009a, p.50; see figure 1.3). Other estimations indicate however the possibility to realise a certain level of absolute decoupling for certain countries in Europe. For example, according to the available data from the GIEC report, overall Green House Gas emission remained more or less stable in the EU over the period 1996-2007, while real GDP increased by 30% (Laurent, 2011). However, overall use of natural resources and accumulation of waste products resulting from EU consumption continued to increase over the same period, if one includes the environmental impact of the delocalisation of production sites for EU consumption products to non-EU countries. Therefore, the real impact of economic growth in EU on Green House Gas emission is much higher and the available evidence does not confirm the absolute decoupling, when measured by the Total Material Consumption in the EU (Laurent, 2011).

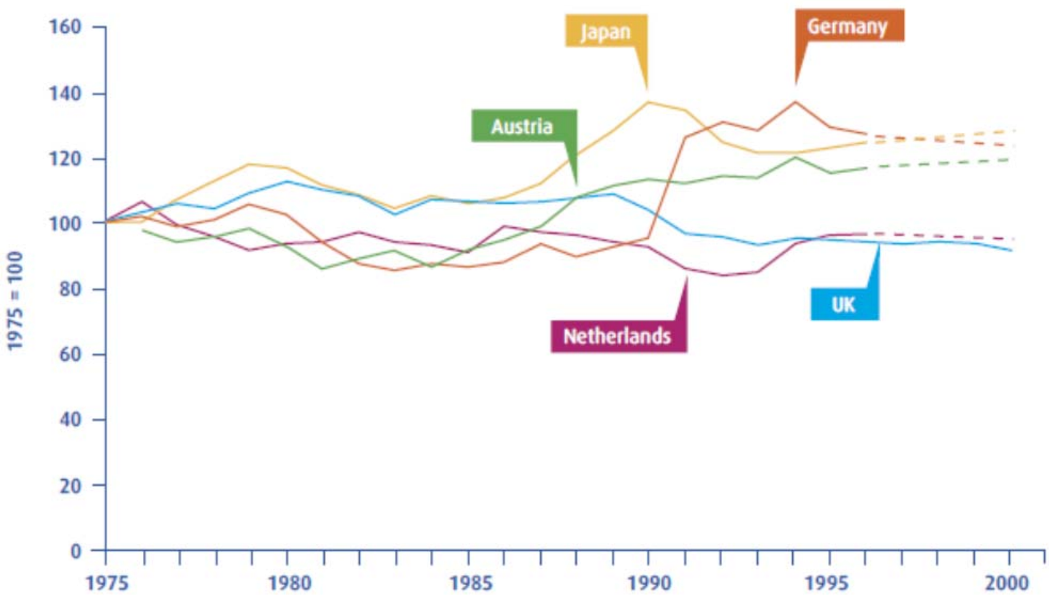

Figure 1.3: Direct Material Consumption (DMC) in some OECD Countries: 1975-2000

(Source: Jackson, 2009a, p. 50, source data from EIA, 2008). Figure based on rough estimates – more accurate use of the statistical data however reveals an absolute decoupling for European countries – as one of the few regions in the world – if one does not take into account the outsourcing of “dirty” production/extraction to other countries (Laurent, 2011). Using the Total Material Consumption (TMC) (see comment under figure 1.2) would again lead to no absolute decoupling, even for Europe (Laurent, 2011).

As a result of these trends, even if carbon emissions from fossil fuels have increased more slowly than the increase in economic activity, in 2007, they were still 80% higher than in 1970 and 40% higher than in 1990, the reference year of the Kyoto Protocol (IPCC, 2007, see also figure 1.4). This is especially alarming; knowing that to meet the IPCC's 450 ppm stabilisation target mentioned above, global carbon emissions would have to decrease by 50-85% by 2050.

For absolute decoupling to occur under the present market economy that is oriented towards growth in GDP, the rate of eco-efficiency improvement must be large enough annually to offset the combined impact of growth in population and growth in average income spent on new consumption goods (Weaver, 2011), whether from own production or from import. In addition the eco-efficiency gain must be "captured" and "dedicated" to reducing the absolute use of resources by the global economy, rather than being redeployed to support further material growth. Yet the market is structured and oriented in a way that ensures that gains in efficiency are dedicated to further growth through expanding consumer demand, without factoring in the intrinsic limits of this growth beyond the critical thresholds of natural capital.

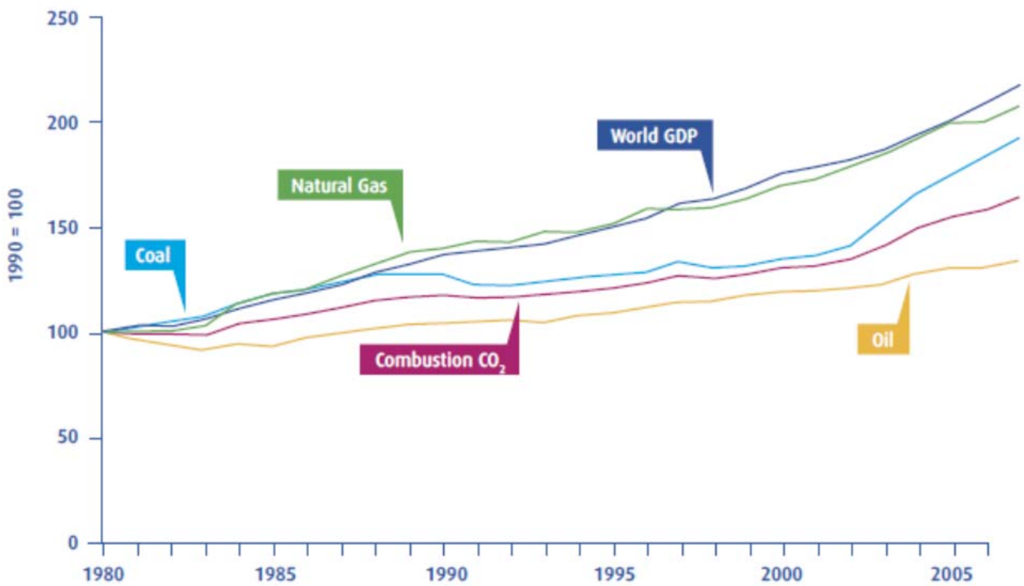

Figure 1.4: Trends in fossil fuel consumption and related CO2 emissions: 1980-2007

(Source: Jackson 2009a, p. 50)

Under present global market arrangements, investment in research and development to accelerate eco-efficiency is therefore unlikely to translate into absolute decoupling (Weaver, 2011). Moreover, energy efficiency gains can paradoxically also result in increases in energy use, or lead to less than expected environmental gains through the so-called rebound effect (Saunders, 1992). For example, a 5% improvement in vehicle fuel efficiency might result only in a 2% drop in fuel use, because the increased efficiency encourages drivers to go faster or further than before. Therefore, there is no reason (or credible evidence) to expect that appeals to conventional political and business logic based on improving eco-efficiency under the current development model will solve the problem of resource scarcity. This points to the need to go beyond the weak sustainability approach and to revise the broadly conventional role of scientific work in support of sustainable development, focused all too often only on undertaking research into resource substitution by technology, increasing energy productivity and reducing emissions of wastes and pollution (Saunders, 1992). These implications for scientific research, in an approach which recognises the need to focus on absolute decoupling, will be further discussed in Section 3.

1.2. The challenge of social equity for sustainable development

An uneven distribution of wealth worldwide has resulted from resource-extractive, industrial pro-growth development, as the limits to the earth's resources necessarily influence the ability of the estimated 7 billion human beings to benefit from this wealth. A World Bank survey of 1999 showed that the ratio between the average income of the top 5% in the world to the bottom 5% increased from 78 to 1 in 1988 to 114 to 1 in 1993 (Milanovic, 2002). New evidence on changes in poverty and income in the OECD countries shows a similar trend in the industrialised countries over the last 25 years. Inequality of incomes was higher in most OECD countries in the mid-2000s than in the mid-1980s and the past 5 years saw growing poverty and inequality in two-thirds of OECD countries (OECD, 2011). In particular, even traditionally low inequality countries, like Sweden and Denmark, are experiencing growing inequality. In Japan and Israel, the lower classes' average annual income actually fell. However, some countries bucked the trend: France, Spain and Greece (before the 2008 financial crisis) moved towards greater equality of incomes over the past 20 years, and both Mexico and the United Kingdom have seen a shrinking gap between rich and poor since 2000. This proves that there is nothing inevitable about the trend towards increased income inequality.

These statistics on equality are of course a very gross approximation and only indicate some trends that have to be further analysed. In particular, the use of income inequality as a measure of social inequality is of very poor relevance if we want to analyse the relationship between inequality and sustainable development. In this context, it is sufficient to recall that the social security safety nets vary from one country to another. As a result, a similar level of income inequality will have a different impact on human well-being in different countries. Therefore, as will be argued below, any useful comparison of levels of inequality should start from alternative indicators that integrate broader evaluations of human development, such as quality of life and/or capabilities (see section 3.3.1). However, in the present state of affairs, such alternative methodologies are still under development (Schiellerup et al., 2009). In any case, the call for using alternative methodologies only reinforces the point that social inequality is closely related to broader dimensions of human development.

Global and country inequality is also a central issue for reaching the transition towards strong sustainability. **First, the impacts of environmental decline are felt disproportionately by the poor in developing countries** (Srinivasan et al., 2008; WCED, 1987). Indeed, developed countries delay and relocate damaging effects, such as hazardous technologies and polluting industries (Andersson and Lindroth, 2001), to poorer nations while continuing to consume high volumes of material and energy from these same countries. In addition, rising poverty and unemployment have increased pressure on environmental resources as more people have been forced to rely more directly upon them. For instance, in many African countries, low quality-of-life, and lack of energy and livelihood choices have driven ecosystem decline and the migration of underprivileged and disenfranchised populations (Van der Leeuw et al., 2012). **Second**, although the challenges and scope of these impacts are less dramatic **in industrialised countries, similar patterns of higher impact of environmental degradation for vulnerable populations have been observed** there. For example, recent research into environmental justice in industrial countries has found that poor and minority neighbourhoods are more likely to contain commercial hazardous-waste facilities, sources of toxic pollutants, and sources of air and water pollution (Baland, Bardhan and Bowles, 2006; Ringquist, 2004; Boyce, 2007).

Disparities of wealth, and related disparities of power, influence not only how the pie of natural resources is sliced, but also the overall magnitude of the use of the natural resources (Baland, Bardhan and Bowles, 2006). The main reason is that, without social equity, a society cannot build a social base for conservation of its natural resources (Shiva, 2011). These resources are commons, and **it is only when society has organised a fair and equitable use of the ecosystem services provided by these resources that a common concern and action for these resources can be expected**. When social and power disparities are great, those at the top of the political and economic ladder can more easily pollute the air and water, and deplete the natural resource base, of those at the bottom, in particular because the elites in those countries have the ability to pay for avoiding the negative impact of resource degradation. When disparities are small, those on the bottom rungs of the shorter ladder are better able to defend themselves. A democratic distribution of power and equitable distribution of wealth, therefore, can help to protect the environment. Conversely, an oligarchic distribution of power and an inequitable distribution of wealth can exacerbate environmental degradation. A striking illustration of the latter is the massive export of tropical hardwoods in the Philippines during the Marcos regime in the 1960s and the 1970s. Those who benefited most from the logging industry were well-connected politicians and military officers; and those who suffered most from its consequences were poor people who lived in or near the forest.

In spite of the overall negative trends in relation to social equity, many actors at all scales have started to develop initiatives to address the joint problems of social inequality and environmental degradation. In particular, a combination of government economic incentive schemes, local community organisations and science-based decision support systems has proven to be a very effective tool in many situations around the world. For example, in the Rio Platano Biosphere Reserve in Honduras, communities have been able to overcome the poverty driven degradation of shared ecosystems, by agreeing upon alternative ways of exploiting them and re-orienting the local economy towards non-timber forest products (such as cocoa, ornamental plants, medicines and oil), based on the use of traditional knowledge and a community-based governance model (Weaver, 2011). In another case, in Flanders, Belgium, small-scale forest owners with few resources were able to self-organise forest groups in the mid-1990s to address the serious ecological degradation of the pine forests planted in the mining regions. These groups combined common ecological management of the forest and selling of fire wood, with the rebuilding of social capital and social learning around new sustainability challenges (Dedeurwaerdere, 2009).

The interdependence between environmental degradation, social equity and poverty has been highlighted in many reports and analyses, particularly since the end of the 1980s when it came to the foreground of the worlds' attention with the publication of the Brundtland report (WCED, 1987). Sustainability science, with its focus on complex social-ecological interactions and the participatory organisation of research, seems especially well placed to tackle these issues and help to design appropriate policy mechanisms. However, at present such approaches to social inequality are still very marginal (with some notable exceptions, for example the body of research presented by Baland, Bardhan and Bowles (2006)) and have received very little attention from mainstream projects on sustainable development. Traditional approaches all too often treat the external costs of environmental degradation as impersonal by-products of economic activities, without scrutinising the social dynamics that lead to the maintenance of these externalities in the first place. On the other hand, environmental policies can also lead to increasing social inequalities, when these policies are applied without due consideration of the social impacts. A case in point is the carbon emissions trading scheme in Europe, the cost of which is in large part paid by the consumers, through increasing energy prices. Better synergies with social policies, such as targeted support at vulnerable households or low-income group should be part of the appropriate policy mix in order to mitigate these social consequences. However, without a more fine-grained social, economic and ecological analysis of such synergies, and a broader involvement of the stakeholders in the elaboration of solutions, it is highly unlikely that the conventional policy tools of taxes, fines or market creation, based on the calculus of internalisation of environmental externalities into market prices, will be able to drive societies' transition towards a long-term sustainable development path.

1.3. Bridging the gap between science and society

Scientific and political interest in the degradation of the environmental commons grew throughout the 1970s largely in reaction to frightening news stories about sharp population declines in many species, acid rain and deforestation in the tropics. This interest appeared at a time when major environmental works such as *The Population Bomb* (Ehrlich, 1968), *The Limits to Growth* (Meadows et al., 1972) and Garrett Hardin's paper "The Tragedy of the Commons" (1968) were at the forefront of the academic and policy debates. These works all pointed to similar conclusions: that the global environment was threatened by what seem to be very fundamental attributes of the human being (Stern, 2011): for Ehrlich our desire to procreate; for Meadows, our tendency to endlessly expand the production and consumption of goods and services; and for Hardin our short sightedness and tendency to put ourselves first. These works inspired in turn a generation of environmental regulations, by which central governments sought to "command and control" human appetites, through the conventional policy tools of direct regulation, incentive politics and market creation. However, in spite of important and substantial progress in specific fields (such as combating acid rain and river pollution, and an increase in protected areas in industrialised countries), most of the policies were based on **overly simplified models and simple "cure-all" solutions**. As a result, there has been no overall transition to a more sustainable development path (Stern, 2011).

Hardin's vision in particular was very influential. His solution to the crisis was "mutually agreed upon coercion". However this involved a twofold oversimplification (Dietz et al., 2003): Hardin claimed that only two institutional arrangements – centralised government for some problems and further privatisation of property for the other problems – could sustain the commons in the long run; and he presumed that resource users were trapped in a commons dilemma, unable to create solutions. He missed the point that many social groups have struggled successfully against threats of resource degradation by developing and maintaining self-governing institutions in communities and social networks. Moreover, he assumed that only coercive rules or market incentives can be effective for governing the commons, and did not consider social norms or personal values in favour of common goods as valid drivers of sustainable governance frameworks. Although institutions based on local decentralised government or non-state collective action have not always succeeded, neither have Hardin's preferred alternatives of private or state ownership.

The main problem with these early initiatives is not that environmental regulation is inappropriate, but that it has been advocated as a "cure-all" solution or a panacea without envisaging a more interactive and participative process between scientists, policy makers and stakeholders. **Especially, in the 1980s and 1990s**, with the influential turn towards neo-liberal market deregulation under the Reagan administration in the USA, **market-based solutions have been treated as panaceas**. For example, it is astonishing that market-based tools (such as tradable marketable pollution permits in agriculture, carbon emission certificates under the Kyoto Protocol, and tradable permits for fishing in EU policy) continue to be presented as the optimal method for solving free-rider problems and for providing effective common-pool resource management (Pearce et al., 1989). Tradable market permits, like all institutional arrangements, have notable limitations (Dietz et al., 2003). They tend to leave those resources not specifically covered by trading rules (for example by-catch of fish species not covered by the permit) unprotected and to suffer when monitoring is difficult (for example under the Kyoto protocol, the question of whether geologically sequestered carbon will remain sequestered). Problems can also occur with the initial allocation of allowances, especially when historic users, who may be called on to change their behaviour most, have disproportionate power over allocation decisions or over local governments that fail to enforce their obligations to pay into the scheme (as happened with Arcelor-Mittal in Wallonia, Belgium). Similar panacea thinking has led to the promotion of governmental ownership in all situations (such as the idea that protected areas are the only solution to tackling biodiversity decline) or to portraying collaborative approaches through community participation as a “cure-all” (to the distress of researchers who work in the field) (Ostrom et al., 2007).

In spite of the fact that panacea thinking has led to poor environmental policy, it remains deeply embedded in the current scientific practice of giving expert advice to governments. This is especially true because of the dominance of the formal hypothetic-deductive epistemological model of the bio-physical sciences, leading to so-called value-neutral statements that can be readily used for policy advice, in spite of the many failures of this model to deal with complex coupled social-ecological systems, at multiple scales and in conditions of strong uncertainty**. Instead of adopting a simple class of formal models, for example through reducing individual behaviour to a simple model of self-interested utility maximisers, closer attention to the diversity of institutional histories and set of behavioural motivations is required (as has been advocated by sustainability scholars such as Ostrom (2007) and Young (2002) over the last twenty years). This will, however, in turn require the development of a more interdisciplinary, iterative and open-ended organisation of the interaction between science and policy makers, in close collaboration with stakeholders who can contribute to problem framing and on-going assessment and revision of proposed solutions.

Section 2: Principles of sustainability science

Over the past twenty years, an increasing number of researchers, practitioners and science policy officials have become engaged in sustainability science. This trend reflects the growing concerns amongst politicians, entrepreneurs and the public at large about the failure of science to provide operational solutions for addressing the sustainability challenges discussed above. More recently, the growing interest in sustainability science has been triggered by visible phenomena such as increasing oil and food prices, global warming and the continuing disappearance of species and biodiversity rich ecosystems. As many observers have mentioned, **sustainability science** is not however a scientific discipline by any usual definition (Rapport, 2007; Perrings, 2007). Rather it is a research field **characterised by a new form of collaboration amongst disciplines and between disciplines and sustainability stakeholders**. In a special issue of the Proceedings of the US National Academy of Science, Elinor Ostrom (2007) noted that, if sustainability science is to grow into a mature field of research, we must use the knowledge acquired in the separate disciplines of anthropology, biology, ecology, economics, environmental science, geography, history, law, political science, psychology and sociology to build and strengthen the diagnostic and analytical capabilities of the stakeholders who are directly confronted with practical sustainability problems (Ostrom et al., 2007).

The primary focus of sustainability science is to achieve the policy goal of sustainability, which encompasses ecological, economic, social, cultural, and governance dimensions (Patterson and Glavovic, 2012). It is both an interdisciplinary and a transdisciplinary field of research – combining scientific and non-scientific expertise (see Section 2.3 below) – that seeks to understand the complexities of coupled socio-ecological systems and develop practical solutions that promote ecological, economic and social sustainability.

Clearly sustainability science is still a relatively young field of research, with initially at least partly a different focus of research in Europe, Japan and the USA. As noted in the overview by Jaeger (2011), European practitioners have initially moved towards participatory, iterative processes with an implementation orientation, while Japan started with a technology-based approach and has only recently begun to pay more attention to the human dimensions, and the USA has prioritised interdisciplinary research on complex socio-ecological systems. However, despite these initial differences in approach, the discussions and projects in the scientific community over the past decades have clarified the common characteristics of sustainability science. In particular, recent discussions in the journals *Sustainability Science* and *Ecological Economics* characterise the agenda of the research field of sustainability science according to three core research dimensions (Wiek et al., 2012; Baumgaertner and Quaas, 2010):

(1) sustainability science has to address the question of how **coupled socio-ecological systems** have evolved (past), are currently functioning (present), and might further develop (future), in order to identify the key sustainability problems to be addressed;
(2) in the context of this understanding of the sustainability challenges, sustainability science has to specify what are the **ethical objectives of sustainability** to be attained by taking into account the intrinsic limits of the exploitation of the earths' resources and how coupled socio-ecological systems would function and look like in compliance with a variety of value-laden goals and objectives; and

(3) sustainability science has to **explore with stakeholders which transition pathways are viable** for coupled socio-ecological systems and what strategies can be adopted to find solutions to the sustainability problems.

As can be seen from these three core dimensions, sustainability science combines a descriptive-analytical perspective on coupled socio-ecological systems, a transformational agenda, within an explicitly ethical perspective on strong sustainability, and an engagement with stakeholders.** Because of this focus on a transformational agenda, and the aim of bridging the gap between science and society, some scholars have qualified sustainability science as an applied science (Clark and Dickson, 2003). However, such a perspective clearly misses the close interrelationships between the ethical perspective on sustainability, the need for innovative theoretical approaches to coupled socio-ecological systems and the transformational agenda, as can be seen in the need to rethink approaches both in political sciences, economics and psychology *inter alia* to address the sustainability issues (Brousseau et al., 2012a; Brousseau et al., 2012b). Moreover, as highlighted in the report of the MASIS expert group on "Challenging Futures of Science in Society", prepared for the Directorate General Research of the European Union (European Commission, 2009), such a combination of descriptive-analytical perspectives and contextual ethical and stakeholder dimensions is not unusual in scientific research. Indeed, as clearly stated, the contrast between basic and applied formal hypothetic-deductive scientific research on the one hand and relevant research (to specific context and value-laden goals and objectives) on the other hand is not a contrast of principles (European Commission, 2009, p. 12). The contrast has more to do with the institutional division of labour than with the nature of scientific research. The combination of scientifically grounded and socially relevant research occurs again and again in history and in present-day science (see Stokes, 1997; Rip, 1997). This combination is not present in all disciplines and scientific fields in the same way, but as can be seen from the current debate on sustainability, it is clearly a defining feature of sustainability science.

Institutionally, a good indicator of the increasing importance of such research programs combining conventional scientific excellence with social relevance is the spread of transdisciplinary research centres in various fields of research beyond sustainability science. The US Engineering Research Centres, the UK interdisciplinary research centres, and the Australian Collaborative Research Centres all started in the 1980s, and by now, such centres have been established throughout Europe (European Commission, 2009, p. 13). In the Netherlands, in the Scandinavian countries and in Germany (for example through the Fraunhofer Institute) large parts of public research funding are currently dedicated to such interdisciplinary and transdisciplinary research. Sustainability science is in that respect still a newcomer, but potentially this emerging field will become a very important member of the group of directly socially relevant research programs, given the challenges reviewed above.

2.1. Strong sustainability as the normative foundation of sustainability science

Sustainability has become part of the mainstream policy discourse over the last two decades. However, in practice, policy objectives related to sustainability are often very modest, especially because of the still widespread belief in the possibility of decoupling (in spite of the growing evidence against the possibility of a general decoupling of economic growth and the increasing use of natural resources, see section 1 above) and the tension with the dominant model of a consumption driven, low interest rate, economy. Therefore it is important **to go beyond lip-service to the notion of sustainability** and to specify its meaning as it emerges from the contemporary debates in environmental ethics and theories of justice.

2.1.1. Defining the ethics of strong sustainability

In general terms, sustainability aims at justice in the domain of socio-ecological relationships and in view of the long-term and inherently uncertain future, including both justice between humans of different generations (intergenerational justice) and justice between different humans of the same generation (intra-generational justice) (Baumgaertner and Quaas, 2010). These aspects are, for example, expressed in the widely accepted definition given by the Brundtland commission of the United Nations in 1987 (WCED, 1987, p. 43.):

> “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts: the concept of “needs”. In particular the essential needs of the worlds’ poor, to which overriding priority should be given; and the idea of limitations imposed by the state of technology and social organisation on the environment’s ability to meet present and future needs”.

However, this conventional definition of sustainability is still very abstract. Indeed, it only says that, from a long-term perspective on socio-ecological relationships, members of the present generation have “something” that other members of the present generation and members of future generations need, in order to satisfy their own needs, and that we therefore need to preserve in a satisfactory manner. But what is that “something”?

Some have argued that we need to transmit a certain level of economic welfare to future generations. Future generations should, in principle have a similar or even higher level of welfare than the present generation. However such a vision does not seem to be defensible (Claassen, 2011, p. 204). First, economic welfare does not necessarily lead to a better satisfaction of our aspirations in life or a more just society (see the discussions on GDP in Section 3.3.1 below). Second, even if “well-being” instead of welfare would be used as a measure of our aspirations in life, such well-being still cannot be transmitted directly to future generations. The well-being of future generations will be determined by circumstances that we cannot influence now. Third, future generations have their own moral autonomy and will make their own choices. A **better understanding of sustainability therefore is that we should aim to preserve the possibility of all present and future generations to make their own choices in their aspiration to an accomplished and just life.**

Irrespective of our particular understanding of intergenerational ethics, what needs to be transmitted cannot be fully captured in terms of current levels of capital. Preserving or extending the actual capabilities for self-determination of future persons is just as important (Sen, 1999). In a ‘capabilities approach’, well-being cannot be reduced to individual utility; it necessarily implies a reasoned judgment on what is valuable and worth achieving, as well as the *real* capability to act in order to achieve it.

The possibility of other members of the present generation, and of future generations, to acquire a certain level of autonomy of choice can be understood in terms of a combination of the two types of capital discussed in section 1.1.: natural capital and human capital (Claassen, 2011, p. 204). Human capital includes produced/technological capital, such as technological artefacts and products of labour, cultural capital, social capital and institutions. Natural capital includes both living and non-living natural resources, and the ecosystems and ecosystem services provided by these. As discussed above, current analysis show that **it is an illusion to believe that in transmitting the necessary level of human capital to future generations, technology will allow us to substitute all natural capital by one or another form of technological/produced capital, while preserving the same level of choice**. Therefore, to preserve the capability of the present and future generations to make their own choices, efforts have to be made to keep certain forms of natural capital intact. In short, there is the need to adopt a strong sustainability perspective for the natural resources that are critical to maintain these possibilities of choice in the short and long-term future.

2.1.2. The task of operationalizing the ethical framework

The current debate on sustainability clearly leads to a growing consensus amongst policy makers and scientists that preserving the capability of choice of present and future generations implies a duty to preserve certain critical forms of natural capital (Claassen, 2011). However, this does not allow policy makers and scientists to close the debate on the meaning of sustainability, nor will it lead them to adopt a single and uniform definition of the practical objectives to be agreed upon for reaching sustainability. Indeed, **the choice to invest in various elements of critical natural capital always also implies value-based choices, beyond the technical considerations of efficiency and technical constraints only**. In particular, the definition of the critical level of natural capital will depend both on the scientific understanding of the complex dynamics of coupled socio-ecological systems and on the broader social debate on value-laden goals and objectives. This complex interdependence between discussions on normative values and factual knowledge is one of the reasons why work in environmental ethics should be conducted in close dialogue with socio-economic analysis and the environmental sciences, amongst others. It also reinforces the argument made by most sustainability scholars that the three requirements of sustainability science (the better understanding of the ethical dimension, the complex systems' analysis of coupled socio-ecological systems and the transformational agenda) should be satisfied together. Therefore, **these questions for operationalizing strong sustainability should be considered as *research* questions and not just as implementation tasks for people outside sustainability science.**

In his discussion of sustainability, Rutger Claassen gives some interesting illustrations of contemporary debates which can illustrate this latter point, by using one possible technical measure of critical capital amongst others, which is the notion of an individual person's ecological footprint (Claassen, 2011). The ecological footprint measures all the resources that an individual uses (from fish and meat to paper and petrol) in terms of the hectares of biologically productive land and sea area necessary to supply these resources, and to assimilate associated waste. Using the model of the ecological footprint, it is possible to estimate how much of the earth (or how many planets Earth) it would take to support humanity, if everybody followed a given lifestyle. With the current world population, 1.8 hectare is available for each individual human being. At present, the average individual ecological footprint for the Belgian lifestyle is 8 ha, while the average footprint of the Chinese lifestyle is 2.2 hectares and the Indian lifestyle 0.9 hectares (National Footprint Accounts, 2012). Altogether, in the current situation, this leads to an average actual use of 2.7 hectares per human being for 2007, which is clearly an unsustainable situation. **In other words, in 2007, humanity's total ecological footprint was estimated at 1.5 Planets earth; that is, humanity uses ecological services 1.5 times as quickly as the planet can renew them**.

A **first ethical question** to be addressed, in the analysis of ecological footprint data, is to know **what species deserve to be included in the measure of present and future needs of natural capital**. The 1.8 hectare mentioned above is based only on the use of the planet for direct use by human beings. However, most sustainability scholars would argue for the need to include a certain level of natural capital for other species as well, in order to maintain a certain level of biological diversity on earth. Such an inclusion of other species also has a cost: in one study, Jones and Jacobs (2007) showed that, in such a modified scenario, the available hectares per person would decrease to 1.6 per person (from 1.8 in a human-needs only scenario). The question of the basis on which such a "gift" is justified is intensely debated. Some think that the anthropocentric ethics of the original ecological footprint analysis is unacceptable and that we need to adopt an eco-centric perspective, which also values nature also for its intrinsic worth (Sober 1986; Desjardins 2005). Others argue that human beings are dependent on the resilience of ecosystems – which is their capacity to regenerate after severe disturbances and shocks – and biodiversity is of crucial importance for such resilience. Therefore, there is no need to adopt an eco-centric perspective to include such indirect and long-term usefulness of biodiversity for human beings in the calculus of the ecological footprint. Still another position shows the importance of nature conservation as a component of cultural capital, as nature also has a sacred or an aesthetical value for various communities and individuals and therefore also plays an important role in their aspirations to a meaningful life.

A **second ethical question is how far we need to factor in the growth in consumption in developing and emerging economies**. Indeed, even if the ecological footprint in the rich countries needs to decrease, it seems fair to admit that the developing and emerging economies have the right to further develop and to increase their own ecological footprint from the current average of 0.5 to 1.5 hectare per person. Such a perspective leads to consider that the natural resources are a kind of common heritage, which should be equally shared amongst all. The latter position however leads to complex political questions. The calculus of the ecological footprint in Belgium, for example, also includes the use by an average Belgian lifestyle of hectares outside Belgian in developing countries to satisfy his own needs (such as hectares of rainforest cut down to produce soya for animal feed in Belgium), both in terms of the direct use of resources and of the assimilation of associated wastes. Therefore, the issue of the limits' on the earths' resources cannot be considered independently of issues of global equity in benefiting from these resources.

The ecological footprint indicator, as any indicator, has many shortcomings and needs to be considered together with other possible approaches to operationalizing the ethics of strong sustainability. However, what these ethical questions highlighted by Rutger Claassen (2011) show is the need to move beyond the technical and expert-based calculus of critical thresholds of natural capital only. Indeed, in operationalizing the ethics of strong sustainability, sustainability research also needs to address the various context specific value-laden goals and objectives that play a role in the practical definition of certain criteria of sustainability for a given community, city, geographical region or country. In short, to operationalize the ethical dimension of sustainability science there is a need to clarify the ethical debates on specific objectives for reaching sustainability in a given context, in combination with the building of common ground on general ethical frameworks and indicators. Typical tasks to be fulfilled in clarifying the ethical foundation of sustainability science and in contributing to effective policy are for example (see Baumgaertner and Quaas, 2010):

- the development of specific notions of efficiency and justice for socio-ecological systems, and the corresponding ethics that explicitly deals with the long-term future, which is inherently uncertain and, beyond that, to a significant extent, in principle unknowable;
- the clarification of the relationships among the different value-laden goals of various sustainability stakeholders and the identification of potential conflicts and trade-offs;
- the development of operational qualitative and quantitative indicators for the value-laden goals, and the determination of adequate targets and tolerable windows for the indicators for specific contexts.

2.2. An integrated perspective on socio-ecological systems

Several characteristics of persistent problems of unsustainability present serious challenges for scientific research. As Jaeger (2011) points out "for each of the different problems (climate change, land degradation, biodiversity loss, etc.) or problem sector (agriculture, energy, transport, etc.) the symptoms of unsustainability mask deeper underlying problems in our societal structures and institutions". Thus, as Rotmans et al. (2001) also stresses, these problems cannot be solved in isolation. According to their analyses, the complexity arises because of the multiple and interacting drivers of change (for example agriculture requires land, water and energy), the interactions within the earth system (for example between the atmosphere and the oceans or between climate and vegetation), the interactions between levels of scale, time delays in responses of ecosystems to external shocks and because of the massive complexities of human consumption and production systems. Further, an important feature of coupled socio-ecological system, which results from the complexity, is the presence of different types of uncertainty, ranging from simply technical-statistical, to methodological (choice of methods) and epistemological levels (irremediable uncertainty, irreducible lack of knowledge). **The complexities and uncertainties, together with the fact that there are multiple stakeholders, mean that normal scientific research projects are ill-equipped to deal with persistent problems of unsustainability**.

2.2.1. Navigating complex socio-ecological interactions

The multiple-scale and multi-facet features of sustainability problems clearly challenges the effectiveness of the analysis of socio-ecological systems. Arguably, the traditional scientific approach, which tends to build systems as aggregates of elements which, for the purposes of analysis, can ignore the integrated or emergent outcomes of their interconnection, is not appropriate for the field of sustainable development. However, as discussed above, most current scientific thinking about natural resources and sustainability is still driven by a "frontier economics" mentality, where bio-physical limits are axiomatically assumed not to exist, or, at least, are considered as not being particularly important. Further, all too often, the analysis leads to the proposition of optimal solutions instead of suggesting a set of tools for improved diagnostics and adaptive learning by actors and policy makers interacting and operating in complex socio-ecological systems.

Current science seems to work well for problems which are compartmentalised, but does not perform well in providing answers to problems that are systemic, interdependent, multi-scale (temporal and spatial) and multi-faceted (i.e. with economic, political and environmental facets). Indeed, **the presumption that scholars can generate simple, predictive models of coupled socio-ecological systems and deduce general solutions has led to a track record of repeated and often dramatic failures** (Ostrom et al., 2007). Higgs (1996, p. 247) for example outlines how efforts to turn the regulation of the Washington salmon fishery entirely over to the state government, a frequently recommended cure-all, generated "a legal and economic horror story" that reduced the productivity of the fishery to a small fraction of what it was at the turn of the 20th century. Bacho (2005) documents how the panacea of decentralisation, as implemented in a multi-ethnic district of Ghana, generated extensive ethnic conflict. Gelcich et al. (2006) report how imposing a blueprint co-management system on a traditional lottery system for managing a marine ecosystem weakened the level of trust in a community and intensified conflict. Von Weizsaecker, Young and Finger (2005) challenge the view that privatisation is always the best option for delivering public services and present 50 case studies on best-case and worst-case experience of efforts to privatise water, transport, and energy.

Advocates of cure-all or panaceas make two false assumptions (Ostrom et al., 2007): (i) all problems, whether they are different challenges within a single resource system or across a diverse set of resource systems, are similar enough to be represented by a small class of formal models; and (ii) the set of preferences, the possible roles of information, and individual perceptions and reactions are assumed to be the same as those found in developed Western market economies. To move beyond panaceas and build a solid field of sustainability science, a more fruitful approach is to recognise that complex systems cannot be separated into linear independent parts, but are only partially decomposable into their structure (Ostrom, 2007). Simon (2000, p. 753) describes nearly decomposable systems as being "arranged in levels, the elements at each lower level being subdivisions of the elements above … Multi-celled organisms are composed of organs, organs of tissues, tissues of cells". One consequence is the need to specify at what level and in what part of the system policies apply. Indeed, policies can be explored in one part of a system without imposing uniform solutions on the larger system that might lead to a large-scale collapse. Second, it is essential for scholars to recognise that combining variables, for instance A, B and C, can lead to a system with emergent properties that differ substantially from combining two of the original variables with a different one, say A, B, and D.

2.2.2. Building integrated frameworks of analysis

Sustainability scholars have developed a set of tools and practices to address the complex dynamic interaction between nature and society in an integrated way, without having recourse to the reductionist fallacies described above. For example, in the context of political science, Ostrom (2007) proposed an analytic framework for the comparative institutional analysis of coupled socio-ecological systems consisting of a resource system (for example a fishery, lake, grazing area), resource units generated by that system (for example fish, water, fodder), the users of that system and the governance system, where all these components and their interactions are bound by other related ecosystems and constrained by social, economic and political settings. Another important framework was proposed by Herman Daly in ecological economics (Daly, 2005). This framework is based on a nested hierarchical model in which the socio-economic system is a sub-system of the overall biophysical system. In addition Daly's framework emphasises the feedback loops amongst materials, energy resources, technology, information flows and production processes underlying economic activity.

Needless to say, there will never be one generic framework useful for all research agendas. However, an important point to underline is that each single discipline will have to revise and adapt its own basic framework principles in order to address the sustainability problems in an integrated way (as Ostrom and Daly started developing a new framework for complex systems analysis in political science and economics respectively).

Analysing the multiple processes occurring in complex, nested, socio-ecological systems is far more challenging than recommending a favourite cure-all solution. In a similar way to other strategic sciences such as medicine or engineering, **sustainability science aims to find diverse solutions to complex problem situations, based on initial diagnosis, deeper analysis, continuous monitoring of various indicators and systematic learning from failures**. The insistence of sustainability scholars on adopting a diagnostic and iterative approach for the study of the coupled dynamics between ecological and socio-ecological systems again emphasises that **sustainability science** is neither a purely descriptive-analytical science, nor is it a purely normative endeavour, but **an interactive and iterative learning process** that combines elements of both. It is what has been called “strategic science” (European Commission, 2009) or “relevant science” (Baumgaertner and Quaas, 2010, p. 447; see also the discussion above in the introduction to Section 2).

Taking an integrated view of socio-ecological systems, in which scarce resources are used over a long time and under conditions of uncertainty, leads to a set of specific and genuine sustainability science research questions, contributing to the core aim of achieving the policy goal of sustainability in its ecological, economic, social, cultural and governance dimensions. Examples of research tasks that are based on such an integrated perspective on socio-ecological systems are (adapted from Baumgaertner and Quaas (2010) and Kajikawa's (2008) surveys of the literature):

- Analysis of the interaction between physical (for example bio-physical, energy-matter) and socio-economic (for example based on monetary and non-monetary values) variables in socio-ecological systems, for example in ecological economic modelling and analysis;
- Analysis of dynamic socio-ecological systems, taking into account feedback and the emergence of system properties such as thresholds, critical loads, and limited resilience in social, environmental and coupled socio-ecological systems;
- Analysis of different types, degrees and patterns of uncertainty in our understanding of coupled socio-ecological systems;
- Analysis of conditions and mechanisms that affect the social, economic and political stability of socio-ecological systems, and analysis of stability patterns, vulnerability and systemic risks;
- Analysis of conditions and mechanisms that affect the transformability of socio-ecological systems, and the analysis of transition pathways towards sustainability.

2.3. A transdisciplinary research organisation for sustainability science

Dissatisfaction with the shortcomings of current methods of producing and validating scientific knowledge has given rise to various proposals for reconsidering and renewing the epistemological and social foundations of science. As part of this new "social contract for science" (Demeritt, 2000; Gibbons, 1999), not only would science "speak truth to power", but society would also "speak back to science" in identifying relevant topics and research priorities, questioning the relevance of specific methodologies and assumptions, validating the results in terms of their social robustness, and making normative commitments explicit.

2.3.1. Addressing situations of irreducible uncertainty, multiple values and high stakes

Silvio Funtowicz and Jerome Ravetz (1993) have attempted to better specify the terms of this social contract (and the contexts in which it is particularly needed). According to them, the traditional methodology of modern science, based on disciplinary and value neutral scientific expertise, is generally suitable for so-called "normal" contexts. In such contexts the elements of human and bio-physical systems can be validly separated for research purposes, uncertainty is relatively low and natural resource limitations are not relevant. In contrast, **when uncertainty is high and when the systemic interconnection of various systems and the resource constraints cannot be ignored, a different mode of organization of scientific research is needed based on transdisciplinary collaboration between scientific and sustainability stakeholders' expertise**. In these so-called post-normal contexts, the description of facts through a unique methodological lens and the unidirectional path from research to policy conclusions are likely to prove inappropriate.

In their seminal article on *Science for the Post-Normal Age*, Silvio Funtowicz and Jerome Ravetz (1993) identified two key challenges for science in post-normal contexts: the challenge of **dealing with uncertainty** and the generalisation of **extended peer review for improved quality management of the scientific process**. According to their analysis "now that the policy issues of risk and the environment present the most urgent problems for science, uncertainty and quality are moving in from the periphery, one might say the shadows, of scientific methodology, to become the central, integrating concepts. Hitherto they have been kept at the margin of the understanding of science, for laypersons and scientists alike. A new role for scientists will involve the management of these crucial uncertainties; therein lies the task of quality assurance of the scientific information provided for policy decisions" (Funtowicz and Ravetz, 1993, p. 742).

In response to these and other calls for a "new social contract" for science and the need for extended peer review, a large body of literature on transdisciplinary, community-based, interactive and participatory research approaches as well as empirical projects has been generated (Lang et al., 2012). Transdisciplinarity** in particular has been at the heart of these emergent practices of sustainability. Although an open and still evolving concept, there is a growing consensus that the **key features of transdisciplinary research are the integration of scientific and various extra-scientific expertise from the relevant stakeholder communities and the linking of scientific problems with societal problems** (Jahn, Bergmann and Keil, 2012). More specifically, sustainability scholars define transdisciplinary research as a "reflexive, integrative, method-driven scientific principle aiming at the solution or transition of societal problems, and concurrently of related scientific problems, by differentiating and integrating knowledge from various scientific and societal bodies of knowledge"

(Jahn et al., 2012, p. 26-27). For example, people directly affected by an environmental problem will have a keener awareness of its symptoms, and a more pressing concern with the quality of official reassurances, than those in other roles (Funtowicz and Ravetz 1993). Thus their societal body of knowledge can function in an analogous way to that of professional colleagues in the peer-review or refereeing process in traditional science. An historical example of the possible contribution of such extended expertise is the use of the inhabitants of the city of Lyme, whose lay expertise lead to the recognition of a new disease, later called "Lyme's disease", which had not previously been recognised as being a new disease by the conventional scientific experts.

2.3.2. An illustrative model of a transdisciplinary research process

The lack of experience with transdisciplinary research practice, when dealing with problems of strong sustainability, has led to a long history of failures of research projects that has been well documented in the literature (Lang et al., 2012, p. 33-34). Familiar problems are the lack of transferability of the scientific research results into practice, or even the misuse of results to legitimate unintended actions; the lack of integration across knowledge types, organisational structures, communicative styles, or technical aspects; and the underrepresentation of relevant issues in the definition of the problems to be addressed.

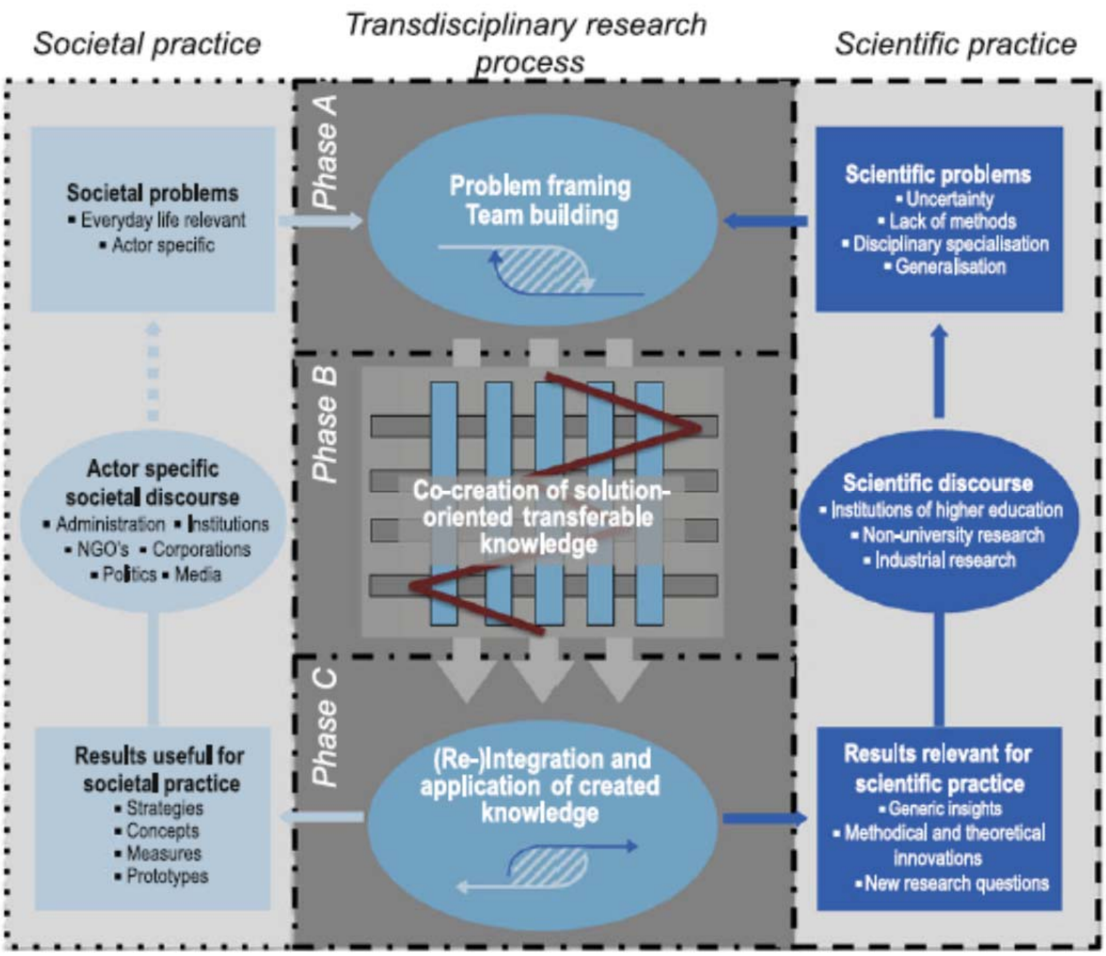

Figure 2: Conceptual model of an ideal-typical transdisciplinary research process

(Source: Lang et al., 2012, p. 28)

To cope with these and other issues, transdisciplinary researchers propose an “interface practice” between a societal practice of social problem solving and a scientific practice of interdisciplinary analysis. The interaction between these two practices is typically organised in three main components (Lang et al., 2012, p. 27; see also Figure 2), including: (a) the collaborative framing of the problem and the building of a collaborative research team composed of scientific and non-scientific experts on the relevant scientific and societal bodies of knowledge; (b) joint knowledge production through collaborative scientific research; and (c) the integration of scientific results into societal practice (for example as a diagnostic tool that can be used by the actors concerned) and in the scientific practice (for example, by learning from system failures that were discovered in the collaborative research project, but not initially predicted by the formal models). This schematic representation of the research cycle has been further elaborated to include the many iterations of this process in practical research programs. This and other well tested examples of research design, clearly show the possibility of integrating conventional scientific disciplinary expertise into a mutual learning process among researchers and other actors, in a broadened organisation of the quality management of the overall research cycle.

Section 3. Learning from transformative science approaches for sustainability

Over the last two decades sustainability science has gained acceptance as a new research field to address the fundamental challenges raised by the interactions between increasingly interconnected human and natural systems (Yarime et al., 2012; Van der Leeuw et al., 2012). Since its inception, sustainability science has evolved to become a solution-oriented interdisciplinary research field inspired by successful initiatives of participatory research practices between scientific and extra-scientific expertise. More recently, sustainability science emerged at the centre of a broad set of research and innovation activities relevant to society's effort to support an effective transition towards strong sustainability (Clark and Dickson, 2003).

However, sustainability science today faces important challenges in its attempt to overcome the inertia of existing disciplinary and value neutral research frameworks. First, in spite of growing evidence of the need to develop major transformative research efforts for sustainability, **many research efforts for sustainability are still based on mono-disciplinary thinking, equilibrium analysis and simplified mathematical models** applied to complex problems. Second, scholars are faced with a **lack of attention in sustainability research to pressing new issues** that were initially considered at the margin of their concerns, but which now appear to put a damper on many sustainability efforts, **such as the global financial crisis and socio-ecological catastrophes generated by the widespread use of high-risk technologies.** The financial crisis had a major impact on the decline in policy support for sustainable development, in particular through the slow-down of the funding of major environmental policy programs as a consequence of the budgetary discipline imposed on states. The impact of the use of high risk technologies can be witnessed by a series of well-documented ecological catastrophes, amongst which the nuclear accident at Fukushima is a tragic example. This not only had important ecological consequences, revealed *inter alia* by alarming studies on genetic mutations in butterflies as a consequence of exposure to radiation (Hiyama et al., 2012), but has also led to major socio-economic consequences for the population of Japan.

Much can be learned from existing efforts by scholars and practitioners to build a viable alternative way of organising research on sustainability, which goes beyond the shortcomings of conventional disciplinary scientific research practices. To this end, this section will examine a set of transdisciplinary and interdisciplinary research programs in the field of economics and environmental sciences, which have made major contributions to sustainability science, and highlight some of the challenges they face in overcoming disciplinary inertia. This section both examines two key areas of research that have been prominent amongst sustainability scholars since the Brundtland report, that is **natural resource management and the rethinking of economic growth**, and more recent attempts by scholars and practitioners for integrating the issues of **financial globalisation** and **governance of technological development** into the strong-sustainability research agenda. More specifically, the following sub-sections will examine major transformative science approaches in:

(a) ecological economics for natural resources and ecosystems management (**section 3.1**.);
(b) Earth System Science for ecosystems management on the global scale (**section 3.1.**);
(c) integrated and multi-criteria assessments as an alternative to GDP as measure of economic development (Gross Domestic Product) accounting (**section 3.2**.);

(d) post-keynesian macroeconomics as an alternative to the neoclassical modelling of financial markets (**section 3.2**.);
(e) transition approaches to the transformation of socio-technological systems (**section 3.3**);
(f) Veblean evolutionary economics approach to long-term innovation processes (**section 3.3**).

Section 3.4. concludes and draws conclusions for the organisation of the research process in sustainability science.

3.1. Rethinking natural resources and ecosystems management in integrated ecological and economic systems

There is an emerging consensus in the field of natural resources and ecosystems management regarding the need to adopt a complex systems perspective on natural resources and ecosystems management, as shown for example through a survey of senior scientists of the American Association for the Advancement of Science (Berkes, Colding and Folke, 2003a, pp. 1-2). First, according to the scientists who took part in the survey, the analysis of natural resource and environmental problems needs to take the complexity of the interactions between natural and social systems into account, in addition to the recognition that natural and social systems are complex systems in themselves (Norgaard, 1994; Berkes and Folke, 1998). Second, there is a consensus amongst these scientists on the need for broader public participation. Scientific research needs to be undertaken with greater attention to its social context, and the interaction between science and society is increasingly seen as important (Jasanoff et al., 1997). The kind of research that is needed may be "created through processes of co-production in which scholars and stakeholders interact to define important questions, relevant evidence, and convincing forms of argument" (Kates et al., 2001).

To summarise, **sustainability scientists recognise that the management of global and regional resources is not an ecological problem, nor an economic one, nor a social one alone**. Sustainable management of these resources is a combination of all three. **And yet, much scientific research practice is still far removed from adopting an integrated perspective across these three dimensions** (Holling, 2003, p. xviii). For example, sustainable designs by **ecologists driven by conservation interests** often ignore the need for an adaptive form of economic development that emphasises individual enterprise and flexibility. Economists who are driven by an **industrial and technological development** perspective often act as if the uncertainty of nature can be replaced by human engineering and incentive based controls, or ignored altogether. Finally, those driven by social interests often act as if **community development and empowerment** can surmount any constraints of nature or of external forces. As a result, as highlighted by Holling (2003, p. xix) : "**as investments fail, the policies of government, private foundations, international agencies and non-governmental organisations (NGOs) flop from emphasising one kind of partial solution to another**. Over the last decades, such policies have flopped from large investment schemes, to narrow conservation ones, to equally narrow community development ones, to libertarian market solutions. There has been lots of despair over failures but little benefit from the learning that has occurred".

3.1.1. The pathology of the conventional mono-disciplinary approaches to natural resources and ecosystems management

Paradoxically, the ability of scientists and policy makers to provide solutions to the extinction and depletion crisis has not followed a parallel path to the development of sophisticated analytical tools and technologies, available to increase our understanding and capacity for action. In the area of resource and environmental management more specifically, there was a great deal of faith in our growing scientific understanding of ecosystems in ecology and in the application of sophisticated market mechanisms to problems such as air pollution and fishery management through individually allocated and transferable quotas (as reflected, for example, in the perspectives that were at the heart of the Rio Convention in 1992). However, ever since, a gap has been developing between environmental problems and our lagging ability to solve them.

In spite of these flaws, **dominant perspectives in ecology, economy and social participation studies still adopt simple mathematical or theoretical models in disciplinary approaches, leading to widespread ineffective management strategies**. For example, **in the field of ecology, both scientists and policy makers still massively rely on the ecological concept of maximum sustainable yield***, in spite of the available evidence of the shortcomings of this concept (Berkes et al., 2003a, p. 7). Indeed, for much of ecology and resource management science, complexity is still a subversive idea that challenges the basis of population and yield models. However, as early as 1977, Larkin (1977) pointed out in a seminal paper that the maximum sustainable yield concept assumes away such complexity as food-web relations and focuses on single species yield, in isolation from other dynamics. Another study, by Lugo (1995), pointed out that trying to quantify supposedly sustainable levels of yield in tropical forests rarely leads to ecosystem sustainability. If the objective is conservation, a strategy focusing on the resilience – the ability of a complex system to regenerate or resist in the presence of external shocks – of ecological processes such as plant succession, may be the most effective way to promote tropical forest sustainability. Therefore a combination of qualitative analysis of key processes contributing to adaptability and resistance to external shocks and quantitative analysis of the interaction amongst a small set of structuring variables (Gunderson, 2003, p. 40) seems a more useful approach for informing management decisions than simplified models of single variables only.

Similar simplified modelling and disciplinary thinking prevails in many of the economic approaches towards sustainability. Indeed, the prevailing thinking, even in the models that integrate both economic and biophysical variables in the scientific exercise, is still one of equilibrium or partial equilibrium analysis – based on Walrasian general equilibrium systems – which can only predict smooth, reversible behaviours (Patterson and Glavovic, 2012). The systematic evacuation in these models of non-equilibrium phenomena, such as systems crises, thresholds leading to system collapse or unpredictable dynamics, is clearly ignoring the evidence of the many sudden system collapses or qualitative shifts in coupled socio-ecological systems that have been documented in the literature, such as the sudden collapse of the cod fisheries in Northern Canada in the 1980s (Stern, 2011). In a broader context, the marginalisation of system risks and uncertainties in academic economics and by policy makers has now been recognised as one of the important causes of the current financial crisis (as will be discussed below in Section 3.3.3 (Colander et al., 2009)). Rather than sticking to equilibrium models that seem ill-suited to deal with strong sustainability problems, a more promising road seems to be to recognise the complex system features and learn from other disciplines (such as policy and planning sciences) with a longer history of dealing with issues of risk and uncertainty. This would not lead to the abandonment of economically-oriented methods: rather, complex systems thinking leads to integration between these methods and methods from other disciplines and enriches them by embracing concepts such as adaptive management (Holling, 2001) or multi-criteria assessment.

Finally, even in approaches that favour co-production of knowledge between scientists and stakeholders, the interaction of scientists and stakeholders is often based on simplified modelling tools which are used and presented as a basis for the discussion. Such a reliance on simple equilibrium models prevents a broader debate occurring, for instance on the role of uncertainty and the ways to organise adaptive, iterative learning processes.

For example, in a well-studied case of the environmental assessment of the sudden die-off of sea grass in the Everglades in Florida Bay (South California, US), in the 1980s, a set of seven simple isolated variables were proposed to the stakeholders and contrasted as possible hypothesis for explaining the die-off (Gunderson, 2003, p. 40). As a result, policy makers presented the problem as a smooth trade-off between the hydrologic restoration of the ever dryer Everglades on the one hand and negative species response to the pumping of fresh water in the ecosystem on the other hand. According to the model, the fresh water resulted in the die-off of the sea grass and the decline in wading-bird species that depend on that sea grass ecosystem. However, the tinkering with water regulations in the Everglades that resulted from this simplified analysis has led to compromise options with lose-lose outcomes for all interests involved. Policy makers focused their action on one supposed cause (lack of freshwater) of the crisis which was, in reality, caused by a combination of several interacting human and environmental factors, such as water use by agricultural practices and tourism, to the point where extra water was delivered to the Bay, with the counterproductive result of hydrologic restoration being delayed rather than accelerated (Walters, 1997).

The failures to build integrated approaches in ecology, economics and social sciences for natural resources management have led to what Holling has called "the regional resource and development pathology" (Holling and Meffe, 1996), the main features of which are the rapid reduction of diversity and spatial variability of ecosystems. Typically, even if in an initial phase new policies succeeded in reversing some of the negative trends, subsequent implementation action based on narrow and rigid action fails to remain open to systemic interdependencies, uncertainties and the need for iterative, adaptive management. The result, in rich regions, is short periods of "spasmodic lurches" of learning (Holling, 2003, p. xviii), with expensive actions directed to reversing the worst of the consequences of past mistakes later. One example is the expensive effort undertaken now to restore the Everglades ecosystem – the largest restoration effort that has ever been attempted in the US. In poorer regions, the result is dislocation of people, with uncertain results for the long-term improvement of the ecosystems (Holling, 2003).

3.1.2. Ecological economics as a transdisciplinary research effort for integrating complex economic and bio-physical system dynamics

The empirical evidence of the natural resource management "pathology" gathered by scholars and practitioners of natural resources and ecosystems management clearly shows the need to move towards an integrated perspective on socio-economic and bio-physical systems. The latter recognises the role of the interaction amongst multiple and multi-scale processes, with a view to bridging the gap between scientific knowledge on the one hand and the ability to govern the transition towards sustainability on the other.

However, institutional resistance and disciplinary inertia lead to a slow recognition of these requirements of sustainability research in contemporary science practice. The slow recognition of the need to adopt an integrated perspective to the complex economic and bio-physical system dynamics in sustainability research is especially strong in the field of economics. This is partially related to the belief in a physics-like positivistic epistemology by large parts of the scholars of the discipline (Spash, 2012), but is also due to the political climate of neo-liberal deregulation and unilateral pro-market globalisation that prevailed in much environmental policy during the last two decades of the 20th century.

After a set of conceptual and methodological innovations that followed the publication of ground-breaking works in the 1970s, such as the *Limits to Growth* report by a team of scholars at the Massachusetts Institute of Technology (Meadows et al., 1972) and Herman Daly's work on the steady-state economy (Daly, 1977), **the entire thrust of the work on sustainability in economics seemed to have been narrowed down by the mainstream mono-disciplinary and neo-classical thinking during the 1980s** (Holt and Spash, 2009). Mainstream economists simply asserted that, with its optimisation models and welfare theory, neoclassical economics is able to produce theoretical explanations of how environmental problems can be evaluated and solved. They argued that most environmental problems are anomalies correctable by taxes or tradable permit markets (Holt and Spash, p. 6). **According to these economists, there is no need to go beyond a worldview of rational utility-maximising agents and profit-maximising firms. Resources are considered generally substitutable and, where they might run out, price changes are expected to stimulate new backstop technologies and resources**.

Frustration with this outlook and methodology was growing. As a response, in 1987, ecological economists established their own journal for transdisciplinary research (*Ecological Economics)* and created the International Society for Ecological Economics a year later. The main difference between ecological economics and the mainstream is the interdisciplinary focus of ecological economics and its pluralistic methodological approach, combining field research, qualitative, comparative case studies, statistical analysis and mathematical modelling amongst others. This is in clear contrast with mainstream economics which, as articulated by Norgaard is "dominated by one pattern of thinking and one standard of proof, respectively the market model and econometrics" and where "field knowledge and observation *per se* are little valued" (1989, p. 37). For example, in the early discussions on sustainability, leading mainstream environmental economists like Dasgupta and Heal (1974) and Solow (1974) claimed that there were no fundamental scarcity problems. Scarcity was only relative as there was always the opportunity of substitution. The key point is that this argument was not based on empirical observation, but followed directly from the usual modelling assumptions of the neo-classical economic framework (Vatn, 2009, p. 123; see also the discussion in Section 1.1.).

Taking issue with conventional economics that often downplays the role of the environment, and conventional ecology that downplays socio-economic factors, **ecological economics tries to bridge the two disciplines to promote an integrated view of economics within the ecosystem (Costanza, 1991). Among the defining characteristics of ecological economics are: the view of the economic system as a subset of the ecological system; a primary interest in natural capital; a greater concern with a wider range of values; and longer time horizons than those normally considered by economists** (Berkes et al., 2003a, p. 11). **Ecological economics emphasises irreversibility, hence real or historic time, and path-dependency** (Vatn, 2009, p. 123). This has brought ecological economics to adapt concepts from complex systems theory, emphasising the multi-scale attributes of socio-ecological systems and the features of ignorance and radical uncertainty that is fundamental to the knowledge of these systems.

Within these set of common assumptions, some researchers in ecological economics have adopted methodologies that are closer to conventional environmental economics, while others have developed more innovative interdisciplinary and transdisciplinary approaches (see, for example, the debate on methodology in Spash, 2012 ; Baumgaertner and Quaas, 2010 ; van den Bergh, 2010; Illge and Schwarze, 2009). As with the other approaches analysed in this report, their contribution to sustainability science will therefore depend on their ability to combine an interdisciplinary approach with the development of an ethical framework for strong sustainability and a transdisciplinary organisation of the research process (see also section 3.5).

The interdisciplinary approach to ecological economics requires the understanding of the key concepts and language of other disciplines, but also changes in knowledge in the disciplinary fields as a result of the interaction between the different subject areas. On the one hand, the role of the environmental sciences in ecological economics changes in the light of the social sciences, by recognising irreducible uncertainty and the systemic interconnection of various components of the systems. On the other hand, the key role of the distribution of rights to land and natural resources has been reconsidered in the economic analysis. Indeed ecological economics recognises the fact that past moral choices with respect to the distribution of rights to land and natural resources are not value neutral and also affect the calculation of values expressed in markets today, and the access to capital, land and education that affect income (Norgaard, 2009, p. 84). Moreover, value systems beyond the optimal satisfaction of individual needs and wants need to be tapped to consider whether we want to give future generations the same rights as we enjoy today. The focus on non-utilitarian values leads in turn to criticism of commensurability of values and an adoption of lexicographic* preferences that cannot be ranked on an ordered preference scale, as in conventional neo-classical economics (Spash, 1998, 2000). In short, the transdisciplinary research program of ecological economics integrates the idea that sustainability is also a matter of rights and ethics, and is not confined to economic and ecological considerations alone.

3.1.3. Global science partnerships to address global environmental change

a. The Millennium Ecosystem Assessment

Sustainability scientists have used ecological economics to develop major new concepts and approaches for dealing with natural resources and ecosystems' management. Some of these have found an ever broader acceptance by policy makers and practitioners, such as the concepts of ecological footprint, multi-criteria analysis based on incommensurable lexicographic preferences and adaptive co-management of ecosystems. **A prominent example which illustrates the growing influence of the concepts developed in ecological economics is the vast international assessment exercise that was undertaken under the program of the Millennium Ecosystems Assessment.**

The Millennium Ecosystems Assessment, released in 2005, is an international synthesis by over 1300 of the world's leading scientists, which analysed the state of the earth's ecosystems and provided summaries and guidelines for decision-makers in a set of 5 Volumes. The Assessment proved to be a much more open forum than the mainstream approach to natural resource and ecosystems management reviewed above. In particular, by adopting an integrated perspective (see figure 3.1 for the conceptual model developed for the assessment), and involving a broad range of stakeholders in the process, the participants in the assessment exercise readily saw how markets to save trees to sequester carbon, for example, are being established in poor nations where the poor are "willing" to stop using forests because the rich have the economic power to buy up the rights of the poor to stop them from using other ecosystem services of the forest (Norgaard, 2009, p. 92). As a consequence, carbon sequestration is cheaper than it would be in a world with less income disparity. The rich can continue to drive their sports utility vehicles (SUVs) because the poor are willing to forego using their forests. Once this was made clear within the assessment exercise, it was very difficult to use prices generated in markets as neutral values. In short, the open participatory process of the Millennium Assessment began to deconstruct the dominant "cure-all" market solution and propose a more integrated and open normative framework.

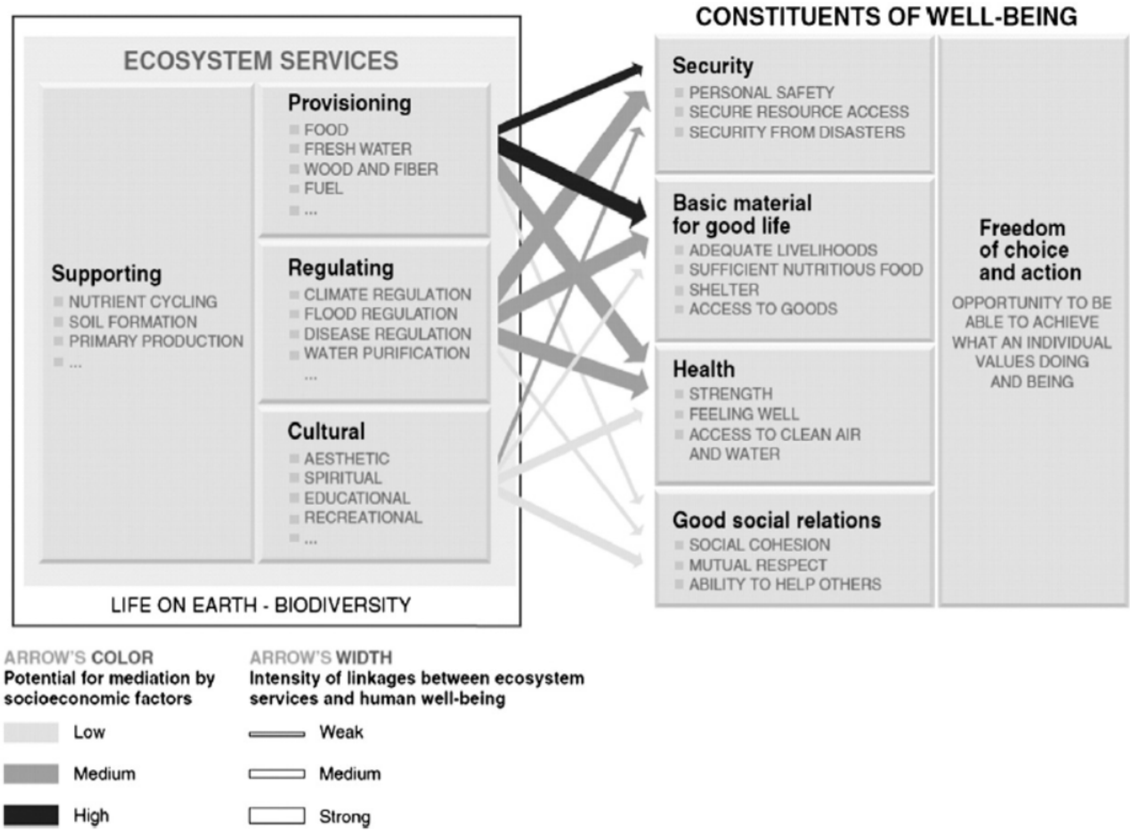

Figure 3.1: Linkages between ecosystem services and human well-being

(Source: MEA, 2005)

By adopting a transdisciplinary perspective on socio-ecological interactions, instead of the simplified *a priori* utilitarian framing of mainstream economics, the relationship between ecosystem services and human well-being is illuminated in a richer way (Polishchuk and Rauschmayer, 2012). This is particularly clear in the case of **local cultural practices that have long remained undervalued in mono-disciplinary economic analysis.** For example, a case study on coastal fisheries in Sweden shows how different local communities have independently developed dynamic, self-regulating patterns in order to adapt to the naturally fluctuating fish resources and to preserve the fishery ecosystem on which they rely for their livelihood. In depth analysis revealed patterns such as the conscious integration between land based and fishery activities, which allowed the fishers to switch between a diverse set of occupations, and the seasonal rotation of fishing areas between the fishers in the coastal community, where the allocation is decided by drawing lots (Hammer, Jansson and Jansson, 1993). In other cases, the analysis showed that market mechanisms, conventional command and control regulation, and community development appear to have opposite strengths and weaknesses, suggesting that institutions combining aspects of these various types of arrangements may work better than any approach alone.

For example, the fisheries tradable permit system in New Zealand has added co-management institutions to market institutions in a successful manner (Stern, 2011). Another example of hybrid arrangements for protecting ecosystems' services is the regulation of the Mississippi River and its tributaries. Instead of relying on a state based top-down approach for addressing the risks of flooding and the regulation of various uses, a participatory approach was adopted that included the Corps of Engineers, the Fish and Wildlife Service, local landowners, environmental groups and academics from multiple disciplines. Consensus was reached over alternative management options and a better balance found between the various values than would have been the case in the conventional regulatory approach alone.

In this context it is important to note that **a more recent review of global assessment studies, The Economics of Ecosystems and Biodiversity (TEEB, see www.teebweb.org), uses a less advanced set of methodologies, compared to the Millennium Ecosystem Assessment exercise**. The TEEB explicitly recognises the limits of monetary and quantitative valuation of ecosystem services. In addition, this report recognises the value of local case studies, such as those that have been conducted to support the Millennium Assessment. However the main studies reviewed in the TEEB report are quantitative cost-benefit studies that poorly integrate the innovative methodologies developed over the last decades to conduct integrated assessments. From the perspective of sustainability science, the kind of analysis produced in the TEEB report therefore needs to be more closely articulated to non-quantifiable environmental values and a transdisciplinary mode of research organisation. Otherwise, as also argued elsewhere (Spash, 2011), there is a risk that the effort will remain a purely rhetorical one with little impact on real world policy making.

A more promising initiative that directly builds upon the innovative interdisciplinary methodologies used in the Millennium Assessment is the Intergovernmental Science-Policy Platform for Biodiversity and Ecosystem Services (IPBES) (Vohland et al., 2011). The IPBES has been installed officially by a decision of the United Nations General Assembly in December 2010. The main improvement over the Millennium Ecosystem Assessment is a stronger focus on the transdisciplinary dimension of the research. Nevertheless, it is still a young organisation, and its effectiveness will crucially depend on the support it will receive from stakeholders and policy makers (Larigauderie and Mooney, 2010).

These models and proposals, developed in large part by ecological economics' scholars, are not to be considered as new panaceas. However they have proven to provide scientifically sound and policy relevant knowledge for sustainability. In particular, they have shown that bringing the full range of voices to the table leads to a fuller scientific understanding of the socio-ecological interactions. Further, to the extent that agreement is found, it is reached through shared human judgement and reasonable argument based on a plurality of methodologies, rather than the discovery of a mathematical model or a meta-ethics that unites all (Noorgaard, 2009, p. 94).

b. A decade of Earth System Science Partnerships

A second practical application of integrated scientific approaches to socio-ecological interactions is the vast program of the Earth System Science Partnerships (Lawton, 2001; Reid et al., 2010). These partnerships were established by **four global environmental change programs – DIVERSITAS, the International Geosphere-Biosphere Program, the World Climate Research Program, and the International Human Dimensions Program on Global Environmental Change**. In 2001 these programs joined forces to intensify cooperation through an overarching interdisciplinary research program. The research communities represented in this partnership contend that the earth system now operates "well outside the normal state exhibited over the past 500000 years" and that "human activity is generating change that extends well beyond natural variability – in some cases, alarmingly so – and at rates that continue to accelerate" (Steffen et al., 2004). To cope with this challenge, the four global change programs have called "urgently" for an "ethical framework for global stewardship and strategies for earth system management" (Steffen et al., 2004).

Crucial to this scientific enterprise are **interdisciplinary joint projects on carbon, food, water and health. In these joint projects, scientists and policy makers address problems which require collaboration between various stakeholders (for example researchers, decision makers, engineers, civil society and private sector representatives).** One of the strengths of these coordinated international research initiatives is that they bring together social and natural scientists to integrate different disciplinary concepts, tools, data and methods (Ignaciuk et al., 2012, p. 150). They are operated by officers with professional research and coordination experience and supported by one major host institution, along with several regional offices.

An important example of a joint project is the project on Global Environmental Change and Food Systems (GECAFS). This project was formulated to develop a broader food security research agenda, beyond the dominant disciplinary focus of most researchers and organisations in the "food security" domain, which is on agricultural issues (Ignaciuk et al., 2012, p. 152). In this program, food systems are conceptualised as coupled social-ecological systems, in which vulnerability arises from multiple stressors operating across different dimensions (for example temporal, spatial and institutional) and scale levels. The main lessons of the outputs of this program are the relevance of adopting a complex systems approach to food security issues and the importance of a highly consultative and inclusive approach (Ingram, Ericksen and Liverman, 2010). In particular, researchers recognised the need to engage with a wide range of stakeholders. Stakeholder collaborations included the strategic partnerships with key international bodies that were established in the early phase of the project, amongst which the partnerships with the Consultative Group on International Agricultural Research (CGIAR) (Ignaciuk et al., 2012, p. 152).

Our understanding of the earth system's natural dynamics has advanced greatly in recent years, and now provides a sound basis for evaluating the effects and consequences of human/driven change. The Earth System Science partnership clearly contributed to this endeavour. The new program Future Earth, sponsored by the International Council of Scientific Unions is currently replacing the partnerships. Future Earth is a new 10-year international research initiative that will develop the knowledge for responding effectively to the risks and opportunities of global environmental change and for supporting transformation towards global sustainability in the coming decades. Future Earth will mobilise thousands of scientists while further strengthening partnerships with policy-makers and stakeholders to provide sustainability options and solutions.

The major challenge of the successful development of earth system science concerns the level of integration of the social sciences and, even more, humanities. At present, conflicting scientific cultures can impede the integration of the human dimensions of global environmental change in earth system science. The norms and mode of functioning of natural sciences have tended to dominate. However, as emphasised by the promoters of the Earth System Science partnerships (Ignaciuk et al., 2012, p. 156), without understanding "social and political dynamics, aspirations, beliefs and values, and their impact on our own behaviour, we only describe the world's physical, biological and chemical phenomena, observe and document their changes at different scales, and apply technology to secure access to resources, but would ultimately fail to ensure sustainability". In this context, they call for "interdisciplinary research that bridged disciplines and involves stakeholders" in the organisation of research programs that can contribute to solutions for a sustainable world.

3.2. Rethinking growth for the transition to strong sustainability

Since the publication of the first major studies of the environmental crisis in the 1970s, there has been a growing realisation in national governments and multilateral institutions that it is impossible to separate economic development issues from environmental issues. Many forms of development erode the environmental resources upon which they must be based, and environmental degradation can undermine human aspirations for a higher quality of life and the basic right to a healthy environment for all. For instance, inequality of access to resources and poverty in developing countries leads to economic pressure to overexploit the natural resource base (WCED, 1987, p. 3). On the other hand, human prosperity depends on the functioning of vital life processes carried out by nature, including the stabilisation of the climate, protection of watersheds and ecosystems contributing to the purification of drinking water, and the protection of nurseries and breeding grounds.

To address the interdependence between environmental and economic issues in the transition towards sustainability, scholars have shown that there is an urgent need to rethink our conceptions of economic growth. As discussed in Section 1.1, because of the impossibility of decoupling between economic growth and material throughput of the economy, scientists need to consider the limits of the planet's capacity to regenerate vital resources and absorb waste in their models of economic development. Moreover, **a wealth of studies show that the current economic indicators, mainly based on a measure of the monetary value of a countries' market activities in terms of its Gross Domestic Product (GDP), are neither a good indicator of human welfare, distributive justice or higher quality of life**. However, in spite of these well-known failures of the growth indicators, they are still the dominant way policy makers and the media present progress or decline in a country's development and are the basis on which policy makers build their economic policies. This undisputed priority assigned to GDP – or the more fine-grained related indicators such as those based on national average real individual income – in politics is again well illustrated by the current media attention and public debate on the financial-economic crisis and necessary responses (van den Bergh, 2011). This attention reflects an **extreme preoccupation with getting back as soon as possible to a fast GDP growth path that takes priority over limiting well-being impacts due to massive unemployment or degradation of ecosystems services, for example**.

The scientific debate on rethinking economic growth for reaching environmental and social justice is complex and multi-faceted. So far it has been dominated by a focus on specific questions concerning alternative measurement indicators for national economies or the implementation of alternative models for post-growth economies (Jackson, 2009b). Although these approaches clearly take the challenge of strong sustainability more seriously than the dominant approach focused on growth in GDP, a key issue which is still overlooked is the need for a critical scrutiny by citizens and stakeholders in society of the reasons why some types of growth, and some types of indicators, are considered more valuable than others (Muraca, 2012). To bridge the gap between science and society, scholars face the challenge of articulating the new approaches to growth, and the new indicators, to various institutional contexts which embody different sets of legitimate values (Thiry, 2012). This is witnessed, for example, by the difficulty in promoting an alternative approach to growth in policy circles, where the main response has been to try to save the GDP indicator, or at best to suggest some adaptations. To illustrate the contribution of sustainability science, this section reviews some of the strategies for coping with the insufficiencies of the conventional GDP indicator.

3.2.1. GDP as the largest information failure in the world

In his overview of the debate on growth and the environment, Jeroen van den Bergh qualifies the use of the GDP indicator as the "largest information failure in the world". As he puts it:

"GDP information influences all agents in the economy: consumers, savers, investors, banks, stock and option markets, private companies, the government, central banks and international organisations. Because of the misleading nature of GDP information, economic agents take wrong decisions from the perspective of social welfare. Given the many shortcomings of GDP as a measure of social welfare and the economy-wide effects of GDP information, year after year, one has to reckon with a large loss of social welfare. This is especially true in the long run, due to cumulative effects of structurally misleading information, which imply socially undesirable directions of investment and innovation" (van den Bergh, 2009, p. 125).

Even though shortcomings in the use of the GPD indicator as an indicator of welfare or progress have been well documented in academic circles, it is important to repeat the critique (Stiglitz et al., 2009). **Indeed the massive uncritical use of the GDP indicator by economists working in business and government, and by policy makers, educators and journalists, has led to an uncritical acceptance of this dominant framing of policies in the broader society as well**. The criticism of the GDP indicator by sustainability scholars has generated a wealth of data from interdisciplinary analysis into the determinants of human welfare, prosperity and distributive justice, which are highly relevant for informing possible development paths that are built upon principles other than an increase in GDP or average real individual income.

From a technical perspective, GDP (Gross Domestic Product) is the monetary market value of all final goods and services produced in a country over the period of a year. The real GDP per capita (corrected for inflation) is generally used as the core indicator for judging the position of the economy of a country over time or relative to that of other countries. As the result of a set of historically important uses of the GDP (such as the determination of tax revenues for war expenditure and early econometric methods in need of aggregate data (van den Bergh, 2009, p. 122)), it has evolved implicitly, and often even explicitly, into the key measure of a country's social welfare, as witnessed in the official statistics of the OECD, the World Bank and the IMF to name but a few.

However, theory does not offer any support for the use of GDP as a measure of social welfare (van den Bergh, 2011; Stiglitz et al., 2009). **According to studies on subjective well-being, somewhere between 1950 and 1970, the increase in mean welfare stagnated or even reversed into a negative trend in most rich countries, despite a steady pace of GPD growth** (Layard, 2005). To take one example, a study by Sheffield University prepared for the BBC showed that, even though monetary incomes in the formal market economy doubled on average between 1970 and 2000, the "loneliness" index increased in every single region of the UK that was measured. Commentators across the political spectrum agree on a social recession in the same period, evidenced by rising rates of anxiety and clinical depression and a loss of trust across society (Jackson, 2009b, p. 144).

GDP, with its focus on market transactions, excludes informal transactions between people (van den Bergh, 2011, p. 885). As a consequence, GDP growth in both developed and developing countries often results from a transfer of informal activities to formal market activities, in which

case the benefits that are measured were already enjoyed before. However, this transfer is considered as GDP growth, even if abandoning the informal activities leads to new market transaction costs or negative consequences that now have to be paid for, such as the increasing need to commute to work if the formal labour market grows in scale. Obviously the transition to a formal market economy also has some advantages, such as the division of labour and specialisation. **However, the optimal balance between formal and informal activities cannot be judged with the GDP indicator, since GPD omits the informal dimension of the economy**.

Finally, natural capital depreciation is not reflected in GDP, which only measures the monetary value of the expansion of market activities. One consequence is that the substitution of basic conditions – like space, serenity, and direct access to nature and water – by market goods – like roads or installations for water purification – will be reflected as an increase in GDP and therefore considered as progress (van den Bergh, 2009, p. 133).

To ensure that policy more systematically incorporates insights about what matters for real welfare, scholars have developed as set of alternative indicators which represent a clear improvement over GDP. The most influential example is the Index of Sustainable Economic Welfare (ISEW: Daly and Cobb, 1989). Other indicators are the Genuine Progress Indicator (GPI), the Sustainable Net Benefit Index (SNBI) (Lawn and Sanders, 1999) and the Index of Economic Well-Being (IEWB) (Osberg and Sharpe 1998). These indicators represent a correction of the regular GDP by adding or subtracting certain partially-calculated indicators (money amongst them) to/from GDP. For instance, the Index of Sustainable Economic Welfare (ISEW) includes corrections for the costs of environmental protection and repair, depletion of non-renewable resources, labour inequalities and distribution of income inter alia (van den Bergh, 2007, p. 13). The main advantage of the indicators based on the ISEW is that they attempt to correct for a wide variety of GDP imperfections in a strong sustainability framework. This distinguishes these attempts from other, more restricted alternative indicators, such as the Genuine Saving Index, which has been adopted as a central indicator by the World Bank. However, a common defect of the indicators based on the ISEW is that they would require more robust monetary valuation in order to develop into acceptable indicators of social welfare. This is in many cases impossible to attain, because of the non-monetary and/or non-market nature of many aspects of welfare.

A more promising approach seems to lie in the use of composite indexes that combine the various indicators that are considered to capture relevant aspects of human well-being. Unlike the previous types of indicators, this does not generate an overall calculated monetary value (van den Bergh, 2009, p. 125). The best-known example of this type is the Human Development Index of the United Nations, which aggregates a number of indicators: GDP per capita, life expectancy at birth, adult literacy rate, and combined primary, secondary, and tertiary gross enrolment ratios in the educational system. Other composite indexes have been developed, in particular to illustrate the extension of the Human Development Index to issues of income inequality and political freedom (Dasgupta, 2001, Chapter 5). Further, to arrive at a more complete picture of sustainable development, indicators of environmental sustainability (such as those provided by the ecosystems' services approach discussed above) need to be included in the composite indexes (for a useful evaluation of ecosystem's services through the capabilities approach, see Polishchuk and Rauschmayer, 2012).

However, beyond the debate on new technical measures for quantifying welfare, scholars face the challenge of using the new indicators in various institutional contexts which embody different values (Thiry, 2012). Indeed, evidence on the role of information and knowledge for policy making shows that policy actors seldom use information as a direct input to their decisions (Bauler, 2012). This evidence highlights **the importance of a solid understanding of the general political and institutional context as a prerequisite for indicators to play a more productive role in policymaking** (Bauler, 2012; Sébastien et al., 2012). One proposition that attempts to address this challenge is developed in the next section on integrated multi-criteria assessment.

3.2.2. Integrated and multi-criteria assessment methods for sustainability accounting

Advocates of the growth mantra have been repeating for years that economic growth is the best ally for distributive justice and a necessary condition for a high quality of life. This simplified picture is clearly contradicted by the evidence on welfare and subjective well-being collected in the context of the debate on the GDP indicator reviewed above. A common defence by growth advocates is to claim that such criticism, however necessary, leads to the adoption of an "anti-accounting" or an "anti-innovation" position. Such criticism seems to confuse the proven information failure of the GDP indicator for informing policy on the one hand and a position that would abandon informed decision making on growth and sustainability on the other. In particular, it neglects the vast literature on, and the growing experience with, possible alternatives for assessing human welfare and prosperity that can be constructed for improving the decision making processes.

First, the criticism of GDP as a welfare indicator and its role in public debates and policy does not lead to a critique of the system of local, national or global accounts (based, for example, on the alternative indicators of sustainable economic welfare briefly discussed above (van den Bergh, 2009, p. 127)). Accounting systems provide detailed, disaggregated pictures of the flows of goods and services in the economy, which are increasingly complemented by data on informal markets, natural resources and environmental damage. Abandoning the myth of an aggregation of all these components into one single monetary indicator does not mean that this information cannot be used to improve decision-making processes on complex issues such as financial planning, economic policy and environmental management.

Abolishing GDP and the unilateral focus on the growth in monetary value of formal market transactions does not imply a plea against innovation, nor a rejection of the many benefits of formal markets, at least when these are balanced and evaluated against broader social goals and not considered as ends in themselves. Indeed growth and degrowth are not ends in themselves, but have to be assessed within broader frameworks of human welfare. For instance, according to a growing number of analysts (Weaver, 2011, p. 179), growth in individual incomes is still needed in poorer countries to overcome poverty. By contrast, a shift away from further material growth in the already-wealthy countries would help release environmental space for growth elsewhere and would allow to reduce the inequalities between countries and within countries. Innovation is needed to bolster eco-efficiency, but frameworks must exist to enable the gains so captured to secure absolute reductions in the throughput of the global economy.

The method of multi-criteria analysis in particular aptly illustrates the contribution of alternative methods of sustainability accounting (Funtowicz et al., 2002; Vatn, 2005, Chapter 12). Multi-criteria analysis has been **developed as an alternative to conventional cost-benefit analysis tools**, which are more generally at the root of the scientific assessment models used to build the GDP indicator and its proposed improvements (such as the Index of Sustainable Economic Welfare). Cost-benefit analysis assumes value commensurability between the different objectives – that is the possibility of measuring them according to a common, mostly monetary, metric – and compensability – that is the assumption that a loss observed in one attribute or good can be compensated for by a gain in another (for example compensation for loss of availability of natural resources by using technical means to produce equivalent welfare benefits).

Needless to say, in the context of the analysis of strong sustainability problems, such assumptions are highly flawed. Moreover, cost-benefit analysis is based on finding the optimal solution to a decision-making problem based on the Kaldor-Hicks variant of the Pareto rule, which terms a solution optimal if the sum of the gains outweighs the sum of the costs (Vatn, 2005, p. 212). This approach ignores the value judgements involved in the distribution of benefits and, more generally, in providing the weights to the various gains to be considered, unless one pre-supposes a society where all individuals have identical preferences (as is often done in economic modelling (Vatn, 2005, p. 214)).

The core structure in a multi-criteria analysis is the multi-criteria assessment matrix, as illustrated in Table 2.1. for a specific problem situation: a transport issue (Vatn, 2005, p. 339 and 344). The first step is to define a set of alternative solutions. A transport problem may be solved by building a railway, setting up a bus system or building a motorway. Next, a set of criteria is defined, where monetary costs, landscape changes, time saved, accidents, pollution and so on may be relevant. The impact of each alternative for each criterion are measured in the most relevant dimension, such as money, hours of time saved, ordinal ranking of landscape impacts, etc. If an alternative is better than all other alternatives on all criteria, we have a so-called ideal point. This is not usually the case, and the analysis leads to the definition of an efficiency set, based on all the alternatives that are not strictly dominated by another alternative on all criteria. Finally, to be able to rank these alternatives, an explicit, value-based, weighting amongst the criteria is needed and an algorithm to rank the alternatives based on this weighting has to be implemented (widely used algorithms include MAUT (Nijkamp, Rietveld & Voogd, 1990), ELECTRE (Munda, 1995) and REGIME (Hinloopen and Nijkamp, 1990)).

Table 2.1: A scores table for a transport problem

		Alternatives		
Criteria	Units/scales	Motorway (a)	Train (b)	Bus (c)
1. Costs	Million euros	20	40	15
2. Time reductions (per person)	Minutes/day	25	15	10
3. Emissions	Tons/year	1000	120	350
4. Landscape effects	+++/---	---	-	--

(Source: Vatn, 2005, p. 344)

This short presentation of multi-criteria analysis gives only a very simple illustration of some of the basic issues involved when systematising multiple objectives and integrating them into an overall assessment. In practice this method needs to be combined with other methods, depending on the information needs and data availability in each decision situation.

The three main approaches that have been developed so far are multi-criteria analysis (Funtowicz et al., 2002; Vatn, 2005, Chapter 12), deliberative evaluation processes such as citizens' juries and consensus conferences (Vatn, 2005, Chapter 12) and integrated modelling (Boulanger and Bréchet, 2005). In addition, a combination of these approaches has often proven effective as a tool such as "deliberative monetary valuation" or "participatory multi-criteria analysis" (for an overview, see Stagl, 2012). The main advantage of these methods is that they allow a large amount of data, relations and objectives that are generally present in real-world decision making to be considered, so that the decision-making problem at hand can be studied in a multi-dimensional manner (Funtowicz et al., 2002, p. 57).

As general tools for sustainability accounting, multi-criteria analysis, deliberative evaluation and integrated modelling have demonstrated their usefulness in many situations of decision making on complex sustainability problems. One of the most prominent examples is the vast sustainability impact assessment undertaken at the EU's DG Research to assess the environmental impacts of various scenarios of trade liberalisation (George and Kirkpatrick, 2007). Another prominent case, already discussed above, is the use of multi-criteria analysis in green national accounting (for an overview of the various approaches see Funtowicz et al., 2002, pp. 68-75). These methods cannot solve all sustainability problems by themselves, but they do provide insights into ways of arriving at political compromises in the case of divergent preferences, in particular by increasing the transparency of the choice process between various sustainability pathways. Indeed, since Integrated and multi-criteria assessment methods allow multi-dimensional and incommensurable effects of decisions to be taken into account, they appear to be a promising framework for the micro- and macro-governance of the transition to sustainability under conditions of complexity.

3.2.3. Post-Keynesian perspectives on the financial crisis: beyond value neutrality and the marginalisation of systemic risks

The environmental impact of the functioning of the global financial system has received far less attention than the explicit pro-growth economic policies of national governments and international agencies, which have led to ever-increasing pressure on natural resources and ecosystem services. However, sustainability scholars increasingly recognise that the **deregulation of the financial markets over the last two decades,** which was part of a global strategy for sustaining growth by facilitating access to capital markets, **is a major factor that reinforces the pressure on the environment and the social inequalities generated by the current development model** (Jackson, 2009b; Clapp and Dauvergne, 2011; Weaver, 2011). For instance, **easy access to credit for private consumers**, has encouraged and facilitated private debt as an alternative to public debt, irrespective of the social and ecological consequences (Jackson, 2009b). Another example is the **volatility of financial markets** that results from widespread speculation. This volatility has lead prices for commodities, natural resources and the financial derivatives based on these, to swing sharply from record highs and back down again in a way which is disconnected from any consideration of social or ecological impacts of this volatility (Clapp and Dauvergne, 2011, p. 217).

Sudden and unexpected crises such as the global financial crisis of 2008 only reinforce the **short-term mentality among investors in currency markets**. Similarly, the money invested in stocks and bonds through mutual funds and in other financial derivatives demands short-term gains as well. So most investment ends up with the firms that promise such gains (Clapp and Dauvergne, 2011, p. 218). Critics worry that it increasingly makes more financial sense, for example, to harvest an old-growth forest and invest the proceeds in financial markets today, than it does to harvest the forest sustainably over a number of years. Such realities prompt firms and the banks that back them to pursue investment projects that lead to environmental destruction in the short run, with little consideration for the long term. By operating this way, financial markets naturally tend to discriminate against firms that promote sustainable practices (Clapp and Dauvergne, 2011, p. 218).

Sustainability scholars therefore highlight the need to **broaden the scope of sustainability science to include issues such as the analysis of the flaws of unregulated financial markets, the ramping problem of widespread speculation, and the systemic risks of the financial system** that lead to costs for society that are not born by the financial institutions themselves. **One promising perspective for addressing these issues that has caught the attention of sustainability scholars is that of post-Keynesian macroeconomics** (Holt and Spash, 2009). The framework of post-Keynesian macroeconomics emerged in response to the marginalisation by neoclassical macroeconomics of the phenomenon of recurrent economic and financial crises and the neglect of the long academic legacy of earlier economists' study of crisis phenomena.

a. *Systemic failures of academic economics*

According to a set of prominent academic economists in Europe and the United States, the financial crisis of 2008 clearly highlights the systemic failure of dominant academic economics in the neoclassical vein (Colander et al., 2009). According to these scholars, the roots of the systemic failure are twofold. First, and most importantly, abstract equilibrium or near-equilibrium modelling leads to the systematic marginalisation of the issue of systemic risks and instabilities in the financial system, whether by reducing it to probability accounting through sophisticated risk management models (most of which are too abstract to be compared with data) or by defining these risks simply as lying outside the responsibility of the participants in the market. The most well-known example of the first strategy is illustrated by the belief, originally shared by former Fed Chairman Alan Greenspan, that it suffices to introduce a sufficient number of appropriate derivative instruments to eliminate all uncertainty from the market. The second strategy can be found in the belief that it is not the job of economists to warn the public about possible misuse of their models. This can be illustrated by scholars who recognise the possibility of systemic risks, but who nevertheless consider that the concern for systemic risk should not be the concern of the banks, because of the governments' responsibility to provide costless insurance against a system-wide crash (see Krahnen,2005) or Krahnen and Wilde,2006 for a defence of this position).

The second systemic failure is the disconnection of economic modelling from other empirical analysis such as social dynamics. Indeed, neoclassical macroeconomists adopt hypotheses of social and human behaviour in their models that have been widely contradicted by empirical evidence. In particular, the assumption of a uniform "individual representative agent", who calculates the probabilities of all future happenings in maximising his or her own utility, as the unit of analysis in financial markets, is in stark contrast to real-world social dynamics, based on interactions between heterogeneous economic agents which have different information sources, motives, knowledge and capabilities (Colander et al., 2009, p. 9). In a similar way, the scientific basis of current ideal growth rates adopted in the macroeconomic models can be queried. These are typically set at around a permanent GPD growth of 2% and beyond (Vatn, 2009, pp. 130-131), but seldom substantiated by an empirically informed analysis of the limits of available natural resources (or at least their availability at low cost in the short term) and their impact on growth and post-growth options for the economy.

b. The new neo-classical synthesis

Notwithstanding several public reactions of embarrassment and even *mea culpa* within the profession (Krugman, 2009), it has been rather striking to notice that part of the profession has seen in the crisis a confirmation of the robustness and accuracy of the mainstream paradigm. Robert Lucas, the doyen of modern macroeconomics and Nobel Prize laureate, expressed such a point of view in a letter published in 2009 in *The Economist* (Lucas, 2009). In that letter he expressed support for the mainstream paradigm by affirming that the neo-classical framework predicts that a situation such as the global financial crisis cannot be predicted. The argument is quite straightforward: “One thing we are not going to have, now or ever, is a set of models that forecasts sudden falls in the value of financial assets, like the declines that followed the failure of Lehman Brothers in September 2008. This is nothing new. It has been known for more than 40 years and is one of the main implications of Eugene Fama's ‘efficient-market hypothesis’, which states that the price of a financial asset reflects all relevant, generally available information”.

Lucas’s reasoning seem to implicitly suggest that situations such as the financial meltdown of September 2008 can only be explained on an *ex post* basis as the result of an exogenous shock and not as the potential outcome of an inter temporal coordination failure amongst economic agents (Leijonhufvud 1997; Sethi, 2012) nor as the result of an endogenous development embedded in a complex market economy leading to intrinsic instability (Sethi, 2012). The framework which has emerged from this argument is known in academic and public policy circles as the “new neo-classical synthesis”.

The core theoretical apparatus of this mainstream paradigm is constituted by the dynamic stochastic general equilibrium (DSGE)* model. This model assumes, amongst other things, a transaction-cost free complete market and forward-looking economic agents modelled through the device of the uniform representative economic agent. The major problem of this model is that, despite its many refinements, it is not based on, nor confirmed by, empirical research or behavioural hypotheses. Rather, the assumptions explicitly result from the adoption of microeconomic assumptions of markets that are always in equilibrium, irrespective of the economic cycle. These assumptions are a necessary theoretical construct for merging macroeconomics with the Walrasian dynamic equilibrium approach as updated and formalised by Arrow & Debreu (1954; De Vroey, 2009; Blanchard, 2000). This *coup de force* produced a destabilisation of the classical conception of the role and effectiveness of fiscal and monetary policy for promoting welfare and employment in macroeconomics, and provided microeconomic foundations to the monetarist offensive based on stabilisation of the so-called economic fundamentals.

This framework constitutes the backbone of the new generation of medium-scale models under development at the International Monetary Fund, the Federal Reserve Board, the European Central

Bank (ECB) and many other central banks. It has also provided the theoretical underpinnings to the stability-oriented strategies to counter inflation adopted by a majority of central banks in the industrialised world (Galí, 2008).

However, in spite of the widespread use of this theoretical model, an increasing number of scholars recognise the inherent limits of this approach (see the discussion in Padilla, 2012). First, the conception of uncertainty underpinning DSGE models is one where stochastic processes are characterised by the ergodicity assumption. The ergodic axiom imposes the condition that the future is predetermined by existing parameters. Consequently the future can be reliably forecast by analysing past and current market data to obtain the probability distribution governing future events. In brief we are never disappointed in any other way than when we lose at roulette, since "averages of expectations are accurate" (Muth, 1961).

Second, to make this model analytically tractable in mathematical calculus, researchers assume one uniform representative economic agent, who uses one specific probabilistic calculus to determine his or her future rational expectations. As explained by Rajiv Sethi (2012), this is a consequence of the overall equilibrium framework. According to Sethi, equilibrium in an inter temporal model requires not only that individuals make plans that are optimal, conditional on their beliefs about the future, but also that these plans are mutually consistent. Therefore, large scale asset revaluations and financial crises, from this perspective, arise only in response to exogenous shocks and not because many individuals come to realise that they have made plans that cannot possibly all be implemented (Sethi, 2012).

c. An example of an interdisciplinary framework for macroeconomics

In order to build a more empirically sound and politically relevant model, post-Keynesians over the years have developed a different approach which can account for the problems of widespread speculation and systemic risks in the financial system (Holt and Spash, 2009, pp. 3-4). In particular, they have developed a notion of social rationality, in which habits and herd behaviour can create bubbles and lead to recurrent crises in the absence of regulated financial markets. Using path-dependent models, they have explained the persistence of sub-optimal situations, including persistent high unemployment in developed countries. Post-Keynesians have also emphasised that the future is uncertain, rather than known with some probability distribution, which has lead them to stress the role of government policy and regulation in order to cope with the unforeseen consequences of economic choices.

The various insights of post-Keynesian economics are **directly relevant** to the debate on the post-growth economy and the regulation of financial markets with the view **to implementing the vision of strong sustainability**. For example, James Juniper (2009) and Jerry Courvisanos (2009) use the emerging macroeconomic **framework of post-Keynesian thinking to bring out the consequences of uncertainty in connection with business decisions on environmental innovation and investment for sustainable development.** They show how group behaviour can have a cumulative effect: it can lead to major breakthroughs in environmental investments, or it can result in long-term damage to the environment. Another important contribution of post-Keynesian economics has been to **incorporate the classical concepts of class conflict over the annual social surplus, and the importance of real physical costs into economic models of production.** As shown by Gowdy et al. (2009), theoretically consistent production models based on the work of Pasinetti, Rymes, Sraffa and others, using vertically integrated input-output relationships, have proved to be powerful tools in characterising the real structure of modern economics. A case in point is Pasinetti's formal theory of transformational growth, where only the increased fulfilment of vital human capabilities counts as growth, while environmentally destructive production practices and imperialist military spending is discounted as negative growth (Pasinetti, 1981). This model is an elegant illustration of how sustainability can be factored directly into alternative macroeconomic models.

The core ideas of post-Keynesian macroeconomics that emerge from this literature can be characterised as follows (Holt and Spash, 2009, p. 3):

- the recognition of the prevalence of uncertainty (recognising the prevalence of matters where there is no scientific basis on which to form any calculable probability whatever);
- the recognition of the historically path-dependent nature of economics (instead of supposing that the system is heading towards an equilibrium);
- the impact of social rationality on individual decision making; and
- a focus on growth in the income of individual agents striving to satisfy their needs instead of a focus on the price system (which is no longer considered as an appropriate information mechanism revealing information for individual decision makers, but as one affected by speculation and market power).

Many of these core ideas offer great opportunities for sustainability science, especially by adding new tools to study important issues, such as the instability and intra-generational distribution issues of modern capitalism. This is despite the fact that the focus on income growth is at odds with the need to integrate the limits of the planet's resources into the analysis of human agency and economic development. However, the drawbacks of the focus on expanding demand in Keynesianism are increasingly recognised by post-Keynesians themselves and, as seen above, even post-Keynesian scholars have started to integrate the problems of environmental sustainability into their framework (see Mearman (2005) for an overview).

One of the key consequences of the innovations introduced by the post-Keynesian framework is the requirement to develop an interdisciplinary research program related to the role of expectations and heterogeneous processes of belief formation and competing narratives on the future, under the constraint of non-ergodic uncertainty. Such a program must arise within the borders of macroeconomics and emerge from the need to overcome the epistemic closures highlighted above. Macroeconomics needs, in that respect, to build an open-ended interdisciplinary research program aiming *inter alia* at creating a broader spectrum of stylised facts and analytical tools, where not only interdisciplinary economic approaches such as Veblenian evolutionary economics (see Section 3.4.2 below), but also disciplines such as social psychology, agent-based models, anthropology and organisational sociology play a crucial role.

3.3. Addressing democratic choice in socio-technological transitions

Sustainability scholars and policy makers widely recognise that innovation in its various forms has a crucial role to play in realising the kind of transformative change needed to address the interdependence between environmental and economic issues (Stamm et al., 2009). In this context, the idea that we need to fundamentally change research, technology and innovation policy has continuously gained support in the debates about sustainable development and, more recently, in the European debate on Grand Challenges (European Union, 2008). Indeed, **for realising long-term transformative change, more will be needed than individual product or process innovation at the level of the firm**. **Rather, comprehensive system innovations, that is novel configurations of actors, institutions and practices that bring about new modes of operations of entire sectors or systems of production and consumption should be implemented** (Weber and Rohracher, 2012, p. 1037).

Despite a growing literature on the complex "hybrid" socio-technological nature of innovation, many citizens, policy makers and scholars still put the main emphasis in their support for innovation on "technical fixes", and hardly deal with this more fundamental type of transformative change of the modes of innovation that are needed for the transition to sustainability. **Even prominent post-growth scholars** such as Tim Jackson (2009b) (focusing on investment in clean technologies) and Jeremy Rifkin (2011) (proposing a massive conversion to decentralised solar energy) **put great emphasis on technical fixes or green investment for overcoming the sustainability crisis, without questioning the many complex and discrepant positions over knowledge, values, meanings and interests that define the real-world trajectories of scientific research and technological innovation**.

Against this background, leading scholars of "science, society and technology" suggest that dominant assumptions about science, sustainability and progress need to be rethought (Pauwels, 2011, p. 113). They argue that notions such as scientific "object", "safe limits" of technologies, or "risk" for example are in themselves ambiguous and in need of further debate over the processes of innovation (Wynne, 2007). Additionally, the concept of sustainability-oriented innovation systems (Stamm et al., 2009) will always include an array of complex normative meanings that lose form by being reduced to questions of a "technological fix".

The discussion in the scientific community around the new frontier science of synthetic biology aptly illustrates the hybrid socio-technological nature of scientific research and technological innovation (Pauwels, 2011, p. 114-115). Synthetic biology is presented in the US press coverage as a key solution to address the challenges of sustainable development, by developing customised organisms with powerful new capabilities. These customised organisms can be programed to fight diseases and create new materials for manufacturing or producing an abundant source of clean, renewable energy (Ballon, 2008). However, opposite perspectives emerging from the civil society are voiced in the press to contest this. Fearing that "frankencells" will threaten ecosystems, environmental groups have condemned synthetic biology as a grave biosafety threat to people and the planet (Ballon, 2008). Moreover, several voices from the academic sector have warned that the technology may develop in an unsustainable way with regard to environmental and social concerns (Rodemeyer, 2009). As a consequence, there are serious social, ethical and safety questions surrounding this new and promising technology (Pauwels, 2011, p. 133). The purpose of these questions is not to stifle innovation processes or cause undue alarm, but rather to expand awareness on what effects synthetic biology could have on both the political systems and our conception of humanity as a whole (Pauwels, 2011).

To implement long-term transformations of socio-technological systems, sustainability scholars and policy makers need to understand the systemic interconnections of the many social trajectories of technological innovation, ranging from risks for the environment and ecosystems, controversies between scientific communities, economic parameters, policy-making processes and cultural values and concerns. In response to these challenges, science and technology scholars have developed various theoretical frameworks for promoting innovation in the transition to sustainability (such as transition management, strategic niche management or the multi-level perspective on socio-technological transitions). In addition, evolutionary economics scholars have deepened our understanding of long-term historical processes and their role in problems of persistent technological lock-ins. The following section reviews the key features of these promising fields of transdisciplinary research and assesses its contribution to the research agenda of sustainability science.

3.3.1. From firm level innovations to sustainability transitions

a. The innovation systems' perspective as a thin baseline

The standard rationale for policy intervention in the conventional firm-level approach to innovations is based on **market failure arguments** as developed by Arrow (1962). The main argument is that a fully competitive, decentralised market system will provide a sub-optimal level of investment in knowledge development as a consequence of the public good character of certain types of knowledge, potential spill-over effects, and the short-time horizon applied by market actors in their investment calculations (Weber and Rohracher, 2012, p. 1041). This under-investment justifies both **public subsidies for basic knowledge** development and the shaping of specific protection and incentive structures such as the **system of intellectual property rights**. In addition, innovation scholars recognise that mechanisms are needed to improve the structure and the dynamics of the innovation systems, for instance by fostering interactive learning between firms and universities or building adaptive capacities within firms (Weber and Rohracher, 2012, p. 1042).

This innovation-system perspective has been widely accepted as the basis of technology and innovation policy. For instance, the Organisation for Economic Co-operation and Development (OECD) uses the national innovation concept as an integral part of its analytical perspective (Sharif, 2006). The OECD facilitates the diffusion of good practice of research, technology and innovation by providing statistics, analysis and recommendation for its members. Intellectual property rights, innovation-related tax incentives and the facilitation of closer university/industry relationships are part of the standard repertoire of proposed policies that are widely adopted by OECD member countries.

The market failure and systems failure arguments of the innovation-systems perspective are useful and valid, but they are confined to assessing the structural deficits of innovation systems, which **fall short of addressing the process of transformation of the socio-technological systems needed for the transition to strong sustainability**. Transition scholars, such as Weber and Rohracher (2012, pp. 1042-1044), have identified a set of challenges for governing such a transition that are not included in the innovation-systems perspective.

For understanding the long-term transformative processes of innovation in socio-technological systems, a first challenge for sustainability scholars is to address the question of the overall **normative orientation of the transformative change**. This goes beyond analysing how to generate new innovations as efficiently and effectively as possible. The direction is defined, for example by the identification of major societal problems or challenges and the development of so-called "visions" by coalitions of key players. Second, the long-term character of transformative change, associated with the uncertainty surrounding this process, has to be addressed. This requires the processes of monitoring to be analysed in particular with respect to normative goals, and adaptation strategies to be developed. A key research question for transition scholars in this context is therefore to examine how socio-technological systems can **develop the ability to monitor, to anticipate and to involve actors in open-ended processes of adaptive self-governance**. Third, **coordination problems at multiple policy levels, and amongst the broader network of users and stakeholders**, need to be addressed, above and beyond the focus on coordination problems of firms, universities and other research and development actors.

b. Reconnecting innovations and social practices

Scholars of socio-technological systems have developed various approaches to address these questions. In spite of the many specific models and theories developed by transition scholars, these approaches can be analysed as models of socio-technological policy arrangements with two core concerns (Boulanger, 2012): first, developing a conceptual framework for understanding societal changes at the level of socio-technological systems (called the multi-level perspective on transitions) and second, developing a model of governance of such systems (called transition management).

The **multi-level perspective** aims to analyse long-term transformative changes in complex socio-technological systems. In this approach social change is analysed as the outcome of the dynamics between three systems, which form a nested hierarchy (Boulanger, 2012; Weber and Rohracher, 2012; Geels and Schot, 2007): first, the system of technological **niche innovations**, which functions as a source of variety, test bed and an "engine for change"; second**, regimes** (such as the energy systems) providing structures, cultures and practices shared by all the actors in the socio-technological; and, third, socio-technological **landscapes**, which represent an exogenous environment of slowly changing cultural norms, values and structures beyond the direct influence of niche and regime actors (such as increased awareness of and concern for sustainability). In this approach, **transitions can be triggered by a combination of niche innovations, pressures from changes in the landscape and problem solving at the regime level** as depicted in Figure 3.2.

The **policy aspect of transition theory is usually called transition management**. It consists of a methodology for initiating and/or steering on-going transitions so that the new socio-technological regimes will be compatible with sustainable development (Boulanger, 2012). The main elements of the process are the identification of a group of frontrunners who can work out an integrated problem and system analysis, a process of envisioning mid- to long-term future scenarios, the conducting of transition experiments, and continuous monitoring and evaluation by all the actors involved.

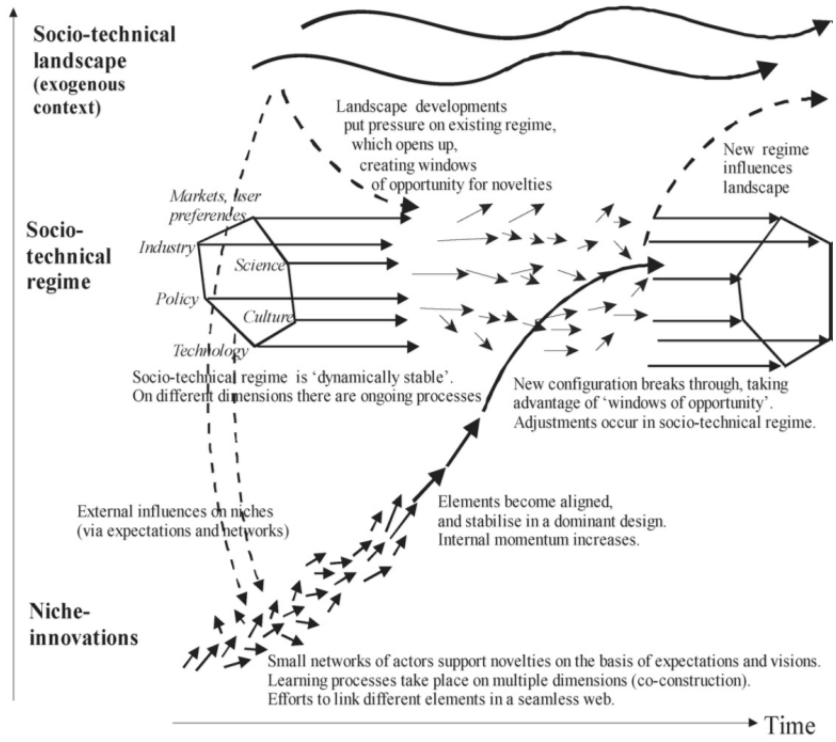

Figure 3.2: Typology of sociotechnical transition pathways

(Source: Geels and Schot, 2007, p. 401)

The transition approach (with its various sub-fields and methodology) is a promising way forward to overcome the shortcomings of the firm-level innovation perspective and the illusion of easy automatic adoption of "technological fixes" for addressing the challenge of strong sustainability. **One of the main contributions of this approach to sustainability research, is to have developed a practice of transdisciplinary research for sustainability** (Boulanger, 2012). As pointed out by Grin, Rotmans and Loorbach (2010, p. 107), "our transdisciplinary approach [to transitions] does not only rely on the input of scientific knowledge and expertise, but also on participatory research. Because transition research also seeks to contribute to a more sustainable society, action research plays a prominent role as well. The exchange of knowledge between scientists and societal actors to which our approach gives rise does not follow a linear path but rather entails a societal process of co-production between the parties involved". For example, in the Netherlands, a small network of university researchers and policy consultants produced the original transitions storyline (Rotmans, Kemp and van Asselt, 2001) and developed the research into socio-technological transitions in close co-operation with policy makers.

The transition approach was adopted in 2001 by the Dutch Government as the appropriate language for its Fourth Environmental Policy Plan and is currently used in several other countries (Germany, UK, Finland, Belgium and Switzerland to name just a few). However, transition approaches, even if they have mainly been used in a sustainable development context, essentially develop **a general theory of socio-technological transitions, and not a theory of strong sustainability or integrated socio-ecological relations**. Indeed, even though this approach has been predominantly used in a sustainable development context, the approach in itself does not have a conceptualization of sustainable development (Boulanger, 2012). This lacuna has led to increasing frustration and tensions for example in a major initiative on transition in Flanders, in the domain of waste and sustainable materials, where the initial dominant orientation in terms of reduction of waste materials has been overtaken by actors focusing primarily on the creation of a market for the supply of waste as secondary products (Paredis, 2011).

Along with science, technology and society approaches more generally, **transition approaches** are useful tools for sustainable development but **deserve to be further explored in more specific ways in order to contribute more fully to the key principles of sustainability science** highlighted in this report. **In particular, the socio-ecological interactions and dependencies between the socio-technological and the ecological system should be directly integrated into the analysis itself** (instead of appearing on the margin as an external motivational factor or a set of framework conditions).

One promising way forward in this direction is the attempt to connect transition research to other disciplines that have a more long-standing experience with interdisciplinary analysis of socio-ecological relations (such as geography). For example, to study energy transition policy in urban areas, which integrates the concern for re-connecting the economy of the city with its local natural resource base, the city and its region can be analysed as a place where interactions between different transition processes take place and thus synergies and hindrances between different technological transformations may become transparent. As suggested by Coenen et al. (2012, p. 976), in such a perspective cities and regions can be considered as major nodes in wider networks of actors that may simultaneously develop their local resources and access and influence resources at different spatial scales. In this respect, as Coenen also suggested, it is encouraging that transition research has started to engage increasingly with urban policy-makers and stakeholders to account for a more coherent and multi-scale perspective on sustainability transitions (Loorbach, 2007). In a similar way, Marina-Fischer Kowalski develops an innovative approach that creates a stronger connection between transition research and the ethics of strong sustainability. This so-called "metabolic" approach to transitions combines the analysis of transitions between socio-technological regimes with an analysis of the average individual energy need in each of the regimes (Fischer-Kowalski and Rotmans, 2009).

3.3.2. The contribution of Veblenian evolutionary economics to addressing long-term historical processes of innovation

The multi-level perspective on transitions discussed above can be usefully combined with the framework of Veblenian evolutionary economics, which can easily accommodate inter-disciplinary approaches to socio-technological transitions (in particular, given that Veblen himself was both an economist and a sociologist and was inspired by various disciplines including biology, instinct psychology and pragmatist philosophy). Given the need to integrate ecological analysis more directly into the study of socio-technological systems, a promising perspective in this context would be the coupling of insights from the framework of Veblenian evolutionary economics and the multi-level approach to transition management with the general perspective of ecological economics. Such a combined approach would provide a more promising way forward (both theoretically and on an applied basis) to governing socio-technological transitions than the current systems-innovation perspectives.

The field of technological innovations and the problems of technological lock-in aptly illustrate the contribution of evolutionary economics to sustainability science. This field has generated a great deal of research since the first publication of "An evolutionary theory of economic change" (Nelson and Winter, 1982). Although the contribution of Nelson and Winter to the field of evolutionary economics is immeasurable (it is often quoted as the book that marked the birth of modern evolutionary economics), this school of thought in evolutionary economics (i.e. neo-Schumpeterian and Simonian) does not appear as readily useful for a sustainability science perspective on technological innovation as, for instance, the literature on path-dependence, which is inherited from the works of Thorsten Veblen.

The key contribution of the historical Veblenian evolutionary economics to the study of long-term transition processes is to provide a radically distinct perspective with respect to the ahistorical and mechanistic reductionism characterising mainstream economics. Indeed, as clearly shown by Veblen and his followers, the Cartesian/Newtonian influence on economics was decisive (Veblen, 1898; Maréchal, 2007). It led to a model based on "mechanistic reductionism". Indeed, not only does this reductionist model explain whole economies on the basis of one sole agent/firm – through the assumption of the representative agent – but the characterisation of that agent/unit is reduced to its mechanical properties as illustrated by the *Homo Oeconomicus* construct. As claimed by Foster (1997, p. 432), the Cartesian/Newtonian legacy also means that we are left with a linear and ahistorical paradigm in economics insofar as it does not "depict a process unfolding in history".

In order to overcome the shortcomings of this model for the study of long-term transition processes, **evolutionary economics introduced two pregnant ideas: the multi-level nature of economic evolution; and path-dependent processes**. As Witt (2004, p. 124) puts it, the consequence of the approach adopted in evolutionary economics is that "the question is not how, under varying conditions, resources are optimally allocated in equilibrium (…)", but rather "why and how knowledge, preferences, technology and institutions change in historical processes, and what impact these changes have on the state of the economy at any point in time".

The inherent inertia that goes together with a path dependent process can be illustrated by the famous QWERTY case (David, 1985). Although this keyboard design was developed for deliberate and justified reasons (i.e. to avoid the letter bars clashing), the main criteria for this decision are no longer relevant in today's computer era. In spite of this, the design is still the most commonly used today, although there are other, more efficient, designs available. This is what Foray (1997, p. 745) called the "persistence of obsolete intentions".

The example of technological lock-in is but one instance of how evolutionary economics in a Veblenian perspective can usefully inform sustainability science. It is worth noting, however, that evolutionary economics was not intended to provide an answer to the challenge of the transition towards sustainable societies. In this sense, it is not prescriptive of any direction. What evolutionary economics can be useful for is providing a radically distinct perspective on the crucial issue of economic evolution and human behaviour. It can serve as a scientifically robust, philosophically sound and empirically appropriate framework to deal with complex socio-economic issue in an alternative manner to that which prevails in mainstream analysis.

Indeed, as the model of mainstream economics has been strongly criticised by many different scholars from distinct disciplines and for distinct reasons (among them the puzzling presence of some degree of altruism in human behaviour that cannot easily be accommodated by mainstream hypotheses), decision-makers are increasingly eager to access alternative perspectives. This is especially true in environment-related domains where the issues at stake often display inherent characteristics (complexity, irreversibility, deep uncertainty, etc.) that challenge core economic assumptions, and which render mainstream economic theory inappropriately equipped to deal with the problems posed. More precisely, **evolutionary economists show that what is needed, given the failures of economics to build a theory of long-term socio-economic transitions, is a framework resting on a different view of individual rationality and allowing for richer and more complex causal relationships to be accommodated.**

Veblen made an important contribution to the development of such a model, which is highly relevant to sustainability science. In particular, he developed a more realistic model of human behaviour centred on the notion of habits and social learning. Resorting to habits is undoubtedly a rational way to proceed given the constraints of daily life and the obvious limitedness of cognitive resources. This alternative approach for understanding rationality of behaviour is in sharp contrast to the utilitarian approach, which considers that every economic decision can be analysed as a discrete situation. **One application of the approach of Veblen is the importance of destabilising habits prior to providing individuals with an incentive to make punctual decisions, such as implementing a subsidised energy-efficient investment.** In particular, contemporary research has shown that an incentive, such as providing an energy subsidy, is processed differently in a case with a perturbation of habits and a case without a perturbation of habits (Maréchal 2010).

It follows from this brief discussion of Veblen's perspective that economic phenomena cannot be adequately studied without accounting for their historically contingent nature both through path dependency and through their interlocking with the wider context in which they occur. Applying this argument to the issue of how environment-friendly technologies evolve inevitably leads to the idea that our economies need to address the institutional and cultural aspects of economic choices in order to escape from the current lock-in of the carbon socio-technological system (Unruh, 2000; 2002; Maréchal, 2012).

3.4. Beyond interdisciplinarity: the need for strong sustainability ethics within a transdisciplinary organisation of the research process

The research programs discussed in this section all attempt to overcome the insufficiencies of "value neutral" and "ivory tower" modes of organization of scientific research. For example, the case of the flooding of the Mississippi river shows the need to integrate values of various communities of interests, when elaborating ecological management scenarios (see section 3.2.3). To address this challenge, the Fish and Wildlife Service adopted a participatory ecological economics approach. In this manner, the Service was able to address the problem in a more successful way, compared to previous attempts based on top down bureaucratic approaches using so-called neutral scientific expertise gained from bio-physical models.

Many researchers recognize the failures of mono-disciplinary, value neutral science to tackle the main challenges for governing coupled social-ecological systems, such as persistent uncertainty over future outcomes and the entanglement of facts and values. As seen through the research programs discussed above, **researchers have attempted to integrate the three core dimensions of sustainability science to overcome these failures**.

3.4.1. The role of ethics of strong sustainability and stakeholder involvement in sustainability science

The **first dimension, interdisciplinarity**, is present in all the sustainability research programs discussed within the scope of this report. Indeed, most of these programs were first developed to overcome persistent failures in existing mono-disciplinary approaches. The latter are now well-documented in the scholarly community. Examples discussed above include the dramatic failures generated by the use of mono-disciplinary environmental models in the management of the Everglades in Florida; the continuing use in economics, even in academic circles, of the GPD indicator as a measure of human welfare; and the failure to take into account social dynamics beyond firm-level processes in the analysis of technological innovations for sustainability. In response to these failures, sustainability scientists over the last two decades have developed interdisciplinary approaches such as multi-criteria assessment, ecological economics modelling and multi-level transition management, amongst others, that can better address the specific features of sustainability problems.

As shown though the analysis in this report, interdisciplinarity alone is not sufficient for realizing the purposes of sustainability science. For example, irreversible loss of non-renewable natural resources such as genetic resources and ecosystems clearly restricts the range of possible actions of present and future generations, which has **ethical implications** that reach beyond the hypothetical-deductive analysis of the complex socio-ecological dynamics. In this respect, just setting up interdisciplinary research programs, without an explicit framework for implementing a strong sustainability ethics, will not necessarily lead to the expected transition to strong sustainability. Nevertheless, the need to integrate a strong sustainability ethics does not imply the adoption of a uniform ethical position. Rather, a common framework for discussion is needed in order to assess and evaluate the available arguments leading, for example, to the choice of certain thresholds of use of natural resources. Examples discussed in this section of efforts in that direction are the integration in transition management studies of environmental impact studies of the technological choices, both regionally and globally (see section 3.3.1.), or the discussion on the level of solidarity between present generations in the calculation of allowable carbon footprint per capita (see section 2.1.).

Further, as stated in the introduction, the explicit goal of sustainability science is to produce basic and applied research that can make a contribution to solving practical problems and assist societies in their transition to strong sustainability. As such, it has been qualified as strategic or transformative science. Building ethically justified frameworks for interdisciplinary research will only be effective for supporting societies in their transition to sustainability if such a framework is translated into a practical process for reconciling multiple values and multiple perspectives on problem framing. Many cases show the failures to bridge the science-society gap in sustainability research without explicitly constructing a **transdisciplinary** research process. For example, the innovation systems approach does not develop a transdisciplinary approach to tackle the social acceptability of new technologies and the social learning on their effective use for more sustainable behaviour. As a result, the approach fails to support a broad social transition to sustainable production and consumption even if it increased our understanding of firm-level technical innovations for sustainability (see section 3.3.1). In contrast, transition theory scholars developed various analytical approaches by directly involving the stakeholders of the technological transition paths. A prominent illustration of such collaboration is the way the transition management scholarship has been organised in close collaboration with policy officials and technology stakeholders in the Netherlands.

The key message that comes out of the review of the literature of leading sustainability approaches therefore is **the need to combine the three dimensions of sustainability research**. On the one hand, for reaching the goal of sustainability science as a transformative science, interdisciplinary alone is not sufficient. To achieve these goals, interdisciplinarity needs to be combined with an ethical framework that explicitly address strong sustainability and with a transdisciplinary organisation of the research process. On the other hand, transdisciplinary collaboration without systematic interdisciplinary research is also insufficient. Indeed, a transdisciplinary process might lead to build a satisfactory ad hoc solution for a sustainability problem, but the latter can hardly be qualified as sustainability science. One example of a contribution to strong sustainability that was not organised as a systematic interdisciplinary sustainability research program is the sustainability plan of the city of Rome, which has been developed with the contribution of the school of architecture of the Sapienza University in Rome. This research support was organised through a multi-stakeholder approach, but was not designed as a systematic sustainability research endeavour. Although this plan certainly has provided an important set of possible solutions for the city of Rome, it rather has the feature of decision support or consulting, than sustainability research. In contrast, the University of Tokyo also built a partnership with the local authorities for multi-stakeholder research on low carbon economies. In this latter case, this research program had both a transdisciplinary and systematic interdisciplinary research dimension. The contrast between these two examples will be discussed in some more depth below in section 4.4.

3.4.2. Sustainability research in economics

The need to combine the three core dimensions of sustainability research has been analysed in more depth in this report in the particular case of **the interdisciplinary approaches developed within economics**. Most researchers in economics are involved in the conventional mono-disciplinary approach to science inherited from the mathematical hypothetic-deductive model of Newtonian physics (Mirowski, 1989). This approach is by far the dominant mode of organizing economic research and leads to a clear separation between facts and values, a focus on quantifiable use and non-use values and ultra-specialised expertise. As in other scientific fields, this proto-typical way of doing science has proven very productive in situations of high predictability of outcomes and well identified quantifiable problem situations. However, this conventional mono-disciplinary approach has clearly proven inadequate for addressing the connections between economic constraints, the environmental limits of the planet and sustainability ethics.

In contrast, **transdisciplinary sustainability research in economics is characterised by a focus on a broader set of ethical values, in addition to the quantifiable use values considered in conventional mono-disciplinary research**. In particular, to address the transition to strong sustainability, non-quantifiable values such as cultural values of ecosystems' services, intergenerational equity and intrinsic preferences of nature should play an equally important role in analysing environmentally sound economic behaviour (see table 2.2). From a methodological perspective, this requirement has lead researchers to combine various methodologies, ranging from monetary and non-monetary quantitative methods, to large-scale comparative qualitative research and case study methodologies. From an organisational perspective, the integration of the ethical perspective has led to involve sustainability stakeholders in the choices amongst the various scenarios for integrating the planets' finite resources into the scientific research.

Table 2.2: Transdisciplinary sustainability research in economics

	Conventional basic research or applied research in economics	Transdisciplinary sustainability research in economics
Commitments concerning the planet's finite resources/carrying capacity	Focus on direct use values, non-use values only considered in a common metric with the direct use values	Integration in the research of non-quantifiable non-use values (cultural values, intergenerational equity, intrinsic preferences)
Theoretical approach of socio-ecological systems	Mono-disciplinary, quantitative analysis of the economic sub-subsystem	Interdisciplinary research, multi-method research combining quantitative and qualitative methods among others
Practical approach of the science-society interface	"Value-neutral" advice to policy, mono-disciplinary peer community	Input of sustainability stakeholders in the research process ; extended peer review; organization of a process for reconciling/combining various values and perspectives on problem framing

Well-established practice of sustainability research, such as ecological economics and multi-criteria accounting, aptly illustrate this new mode of research organisation in economics. Increasingly however, other research programs in economics are also addressing sustainability issues in an interdisciplinary way, such as can be seen in behavioural economics' collaboration with environmental psychology and sociology (Reeson, 2008; Videras et al., 2012; Cardenas and Stranlund,

2000) or in the Veblenian evolutionary economics and post-keynesian macroeconomics discussed above.

Three final comments are appropriate in order to qualify this analysis of existing transformative science approaches for sustainability. **First**, although the analysis in this report mainly focuses on economics, environmental sciences and science, society and technology studies, the need to combine interdisciplinarity with an ethical framework of strong sustainability and a transdisciplinary organisation of the research process is a more general feature of sustainability science. **These conditions also apply to other disciplines within sustainability research, such as political science (Ostrom, 2007), psychology (Earl, 2005) and history (Costanza et al., 2012) amongst others**. Indeed, **these specific conditions are related to the nature of the sustainability problems at hand, characterised by features of strong uncertainty, coupled complex system dynamics and entanglement of facts and values** as highlighted throughout section 2 and 3.

Table 2.3: Progressive implementation of the three dimensions of sustainability research in the transformative science approaches analysed in this report

	Sustainability ethics	Inter-disciplinarity	Trans-disciplinarity
Sustainability science approaches analysed in this report			
Ecological economics	++	++	++
Multi-criteria accounting	++	++	++
Post-Keynesian macroeconomics	+	+++	++
Veblenian evolutionary economics	+	+++	+
earth system science	++	+++	+
Transition approach to socio-technological systems	+	++	++
Other illustrations from the literature			
Political economy of commons (Ostrom, 2005; Benkler, 2006; mainly drawing upon political science, ecology and anthropology)	++	+++	+
Environmental Behavioural Economics (Richter and van Soest, 2012; Frey and Jegen, 2001, Hudon, 2008; mainly drawing upon economics, environmental psychology and	+	+++	+

sociology)			
	+ → early stage ++ → well developed +++ → fully integrated		

Second, as shown by our analysis, the innovative approaches within sustainability science **integrate the three core dimensions of sustainability research with various degrees of strength**. For example, in post-keynesian macroeconomics, the focus is more on the interdisciplinary dimension and the social relevance of economic science than on the ethical framework. Nevertheless, as seen above, recent developments have started to integrate the issue of strong sustainability into the models. In contrast, earth system science develops an elaborate complex system approach to coupled socio-ecological systems within an ethics of strong sustainability. But earth system science only recently has further developed the requirement of transdisciplinarity, in particular in the latest science plan of the Earth System Science partnerships (Ignaciuk et al., 2012). The variation amongst the sustainability science programs discussed in this report has been schematically represented in table 2.3.

Third, sustainability research still faces many **institutional barriers**. These barriers will be discussed in more detail in the next section. For example, training opportunities for transdisciplinary research are still lacking and interdisciplinarity in funded research projects is hampered by lack of transdisciplinary expertise in research evaluation committees. Therefore, the establishment of sustainability as a full-fledged research endeavour, on the same footing as for example industry oriented research or non-oriented fundamental research, will require a gradual social learning and institutionalization process. To reach this goal, both exemplary sustainability science programs that already strongly implement each of the three dimensions of sustainability science and emerging strategic researches for sustainability that integrate the three dimensions to a lesser degree, deserve to be supported. This issue will be more fully explored in the remainder of the report.

Section 4: Building institutional capacity for sustainability science

Promoters of sustainability science within the research and policy-making community face the critical challenge of establishing this new field of research as a recognised scientific practice. In spite of the growth of the sustainability science community, the challenge remains a particularly difficult one as sustainability science leads to two main transformations of conventional science practice: first, the adoption of the methodological tools and epistemology of interdisciplinary analysis of socio-ecological systems and, second the adoption of a transdisciplinary research practice to overcome the dichotomy between science and society in governing the transition towards sustainability.

4.1. Overcoming disciplinary inertia in the development of sustainability science

As sustainability problems are complex, scholars are confronted with the crucial task of integrating knowledge and information from various academic disciplines, including natural sciences, engineering, social sciences, and humanities. However, the current trend is that the academic landscape consists of separate clusters of individual disciplines (Kajikawa et al., 2007). Few studies have analysed the **actual practice of interdisciplinarity in sustainability science**. One way to analyse such practice is to look at bibliometric data and to analyse the existing interdisciplinary practice based on a simple metric of the "tripartite" model of sustainability, which envisions sustainability as the combination of equitable economic growth, social well-being, and a thriving natural resource basis (Schoolman et al., 2012). As will be shown below, this tripartite model needs to be further refined, in particular in relation to the way the role of economic growth is envisioned in the model. Nevertheless, for the purpose of assessing the current situation of interdisciplinary research on sustainability, this model provides a good starting point.

On 30 April 2012, Ethan Schoolman and his team published a bibliometric analysis of the articles containing the word "sustainability" in either the title or keywords, in the approximately 16 500 peer reviewed journals of the Scopus database that were published between 1996 and 2009 (Schoolman et al., 2012). The goal of their analysis was to answer three questions: (i) is sustainability research truly more interdisciplinary than research generally? (ii) to what extent does research grounded in one pillar draw on research from the other two? and, (iii) if certain disciplines or pillars are more interdisciplinary than others, what explains this variation? The results are shown in Figure 3.3.

Figure 3.4 compares the references to other pillars in each of the disciplines. The result clearly shows that articles with the key word "sustainability" (the circles) are more interdisciplinary than scientific research generally (the filled symbols). The two figures combined show that **most "sustainability" publications are publications in the environmental pillar, but that sustainability papers in environmental journals tend be far more mono-disciplinary** (the crossed circles on top of Figure 3.4) **than sustainability papers in the social and economic journals** (the other circles in Figure 3.4).

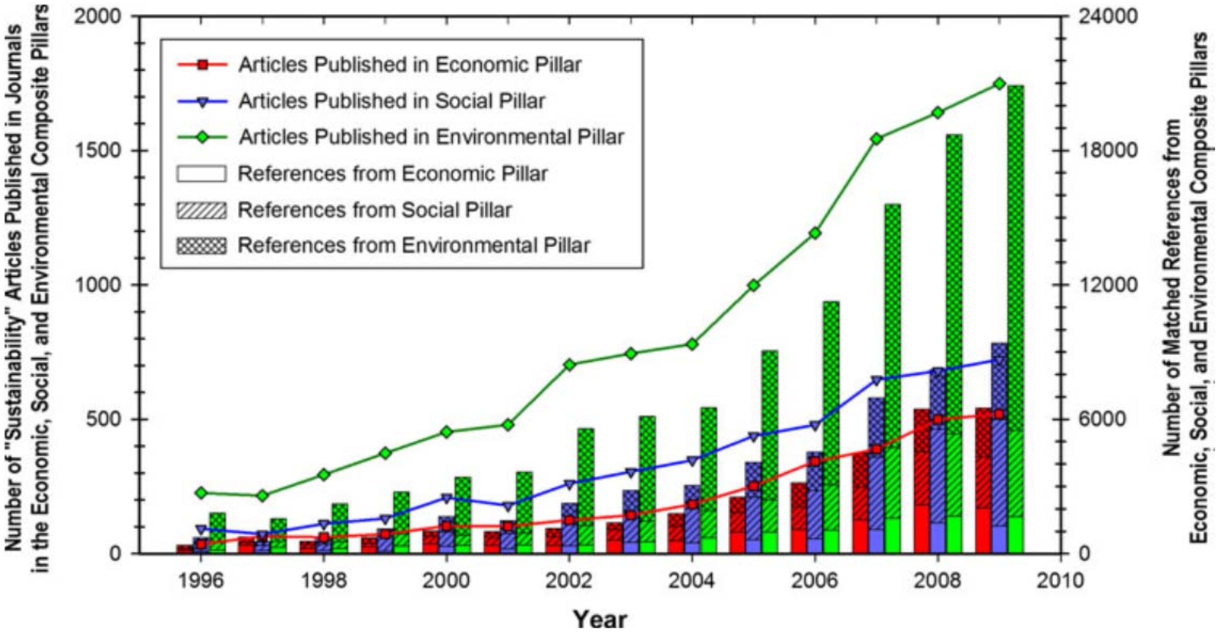

Figure 3.3: Bibliometric analysis of articles on sustainability (I)

Number of articles (lines with filled symbols, left axis) and number of corresponding references (stacked bars, right axis) from composite sustainability pillars: economic in red (left bar, squares); social in blue (centre bar, triangles); environmental in green (right bar, diamonds). The classification of references sources are indicated by the bar hatchings (Source: Schoolman et al., 2012).

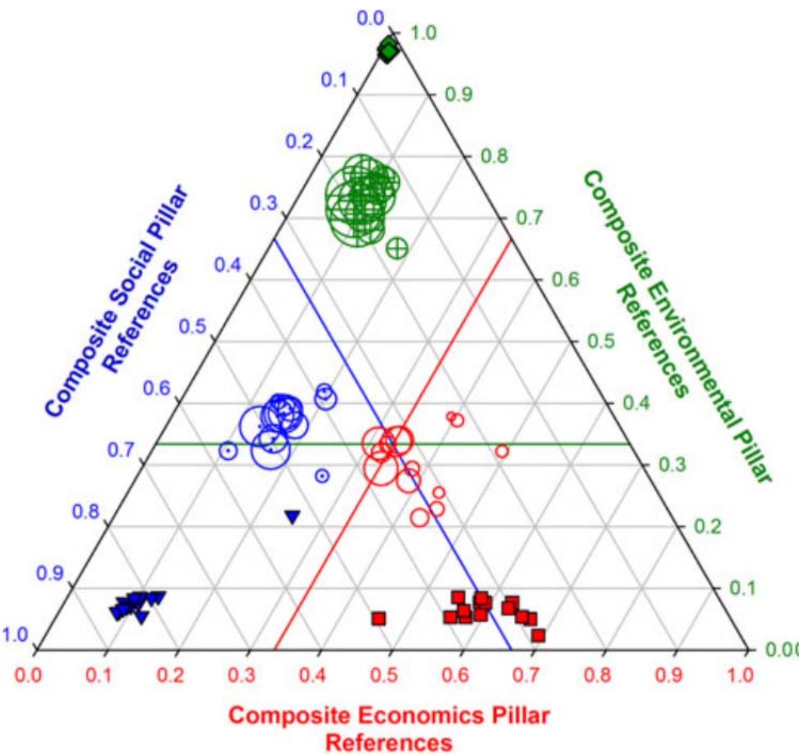

Figure 3.4: Bibliometric analysis of articles on sustainability (II)

References to research in other pillars in sustainability research. Annual averages of ''sustainability'' (hollow circles) and ''baseline'' (filled symbols) articles from each pillar: economics (empty circles and filled squares); social (dotted circles and filled triangles); environmental (crossed circles and filled diamonds) (Source: Schoolman et al., 2012).

These results indicate that sustainability science, while more interdisciplinary than other scientific fields, falls short of the expectations inherent in the tripartite model. The pillar with the fewest published articles on sustainability – economics – is also the most integrated, while the pillar with the most articles – environmental sciences – draws the least from other disciplines. Closer analysis of these results by Schoolman and his team shows that interdisciplinarity** comes at a cost: sustainability research in economics and the social sciences is centred around a relatively small number of interdisciplinary journals, which, although growing, have become comparatively less valued over time, when compared to the growth of mono-disciplinary journals (Schoolman et al., p. 77). Nearly 70% of sustainability articles in the economics pillar and 68% of those in the social science pillar are from journals cross-listed in the Scopus journal database with at least one other pillar. But **as sustainability publishing in economics and social sciences is centred on a small number of cross-listed journals (and the majority of journals in the Scopus database are not cross-listed, i.e. is mono-disciplinary**), then is seems possible that interest in **sustainability science may have difficulty growing beyond these journals and reaching a wider audience**.

As indicated by Schoolman et al. (2012, p. 78), the results of this study are consistent with the idea that disciplinary inertia and institutional obstacles have had an impact on the structure of sustainability science. Where sustainability research has the widest audience – in the environmental sciences – incentives to establish connections across "pillars" of knowledge – such as the social and economic analyses – are probably reduced, and we find that fewer such connections are made. Where the number of sustainability publications is still relatively small – in economics and the social sciences – researchers have strong reasons to establish connections with scholars across academia. In addition, the relatively insular nature of interdisciplinary work on sustainability in the economic and social pillars makes it difficult to reach a wider audience.

The findings of this review suggest that, if sustainability science is to live up to its interdisciplinary and transdisciplinary research requirements, researchers must be provided with greater incentives to draw from other fields than their own. To address the complex sustainability issues therefore requires practical strategies for integrating the key features of interdisciplinarity and transdisciplinarity in the existing research environment and to overcome the institutional and organisational barriers to reaching that goal.

4.2. Major institutional barriers for the development of sustainability science

Scholars have identified a set of major institutional hurdles to be overcome in establishing sustainability science as a major recognised scientific research practice on the same footing as other well-recognised research programs focused on socially relevant operational issues (such as engineering and medicine − so-called "relevant" research, see European Commission, 2009, p. 12). These include the further development of interdisciplinary methodologies encompassing the social and environmental sciences, the transformation of institutional structures (such as incentives for conducting research and career reward systems) (van der Leeuw et al., 2012), the initiation of collaboration with stakeholders outside of academia (Yarime, 2011), as well as the development of a coherent set of sustainability competences and effective pedagogical approaches (Wiek, Withycombe & Redman, 2011).

Underlying several of the institutional, organisational and pedagogical barriers is the belief by scientists, science policy makers and funders that taking a program oriented, relevant-science, approach is going beyond the remit of science (Jaeger 2009). Indeed, sustainability scientists clearly not only analyse problems and discuss possible solutions, but also support the implementation of measures to deal with the problems at hand in collaboration with key stakeholders and assume the role of an active participant from the point of view of a normative interest in strong sustainability issues (Jaeger, 2011, p. 196). However, **academic and other basic research institutions rarely give credit for the kind of transdisciplinary research effort envisioned by sustainability science**.

A second barrier is the existing research evaluation procedure, which generally does not support the type of open, iterative and adaptive learning processes with stakeholders that characterise sustainability science (Weaver and Jansen, 2004). As a practical and normative-oriented science, sustainability science cannot determine a specific objective *ex ante*, because the problem to be dealt with has to be agreed first with the other stakeholders, and the normative goals and values need to be clarified during the research process itself with these research partners (see the discussion of the ecological footprint indicator in Section 1). In other terms, sustainability science is "goal-searching" and not "goal-driven" (Weaver and Rotmans, 2006). Furthermore, external evaluation is often ill-equipped to deal with the adaptive management explicitly built into the project, to allow adaptive learning from both initial solutions and failures (Jaeger, 2011, p. 196; Ostrom et al., 2007).

In addition, as argued by Susanne Lohmann (2007), procedures for reviewing manuscripts, grant applications, and applications for academic positions and promotions strongly favour specialisation. All these forms of evaluation rely on mono-disciplinary peer review. As Lohmann notes, peer review generally means that the work of a specialist is reviewed by other specialists in the same method, with the same area of expertise and/or with the same or similar substantive concerns. Scholars who engage in multiple methods or disciplines, in a transdisciplinary research context, will probably be evaluated by disciplinary specialists rather than other practitioners of multi-method or transdisciplinary research. In this process, Lohmann argues, the reviewers are not likely to fully understand all the methods, the rationale for mixing methods, or the challenges involved in multi-method research. Indeed, specialists tend to discount the results of unfamiliar methods, references to works in other fields, publications in journals outside their own discipline, and interdisciplinary publications.

A **third major barrier** is related to the **lack of educational approaches that are problem driven and that promote experiential learning in multi-stakeholder contexts**. The acquisition of competences that are key to sustainability science (Wiek et al., 2011), such as "strategic competences" (the ability to collectively design and implement transformative governance strategies towards sustainability) and "normative competences" (the ability to collectively map and negotiate sustainability values, principles and goals), are clearly not part of the requirements to be fulfilled in the usual science curriculum, while other core competences, such as complex-systems thinking and long-term future-oriented scenario building have only been integrated to a limited extent in academic training. Considering the core characteristics of sustainability science, it seems reasonable that students should acquire in-depth expertise in one or two of the key competences of sustainability science and a solid grounding in the others.

As shown by Amy Poteete and her co-workers (Poteete, Janssen and Ostrom, 2010, p. 19), the requirements for training for sustainability science contrast with the existing supply of intensive methodological training curricula and programs at graduate and post-graduate level. Training in quantitative methods has been a standard component of graduate programs in economics, political science, and sociology throughout the post war period. Likewise, opportunities to supplement in-house courses with intensive training in more specialised quantitative methods have been available for decades. By comparison, options for training in interdisciplinary quantitative and qualitative methods were rare until recently. Even if the opportunities for such training are growing, students and researchers interested in multi-method interdisciplinary research find it still difficult to gain adequate training in non-quantitative methods (Siegel et al., 2007).

A **final hurdle** for the field of sustainability science is the **lack of appropriate mechanisms for organising the participation by legitimate communities and stakeholder groups** (van der Leeuw et al., 2012, p. 118). Often, reaching and involving relevant communities is complicated by language and cultural differences, insufficient expertise, lack of empathy as well as lack of time. Even when the correct people are gathered together in the same room, negotiating personalities, languages, and cultures can be overwhelming. Power disparities among stakeholders and trust in the process can limit participation even when attendance is achieved (van der Leeuw, et al., 2012). These tensions between scientific and extra-scientific expertise may stem from the reality that academics have little experience of conducting participatory research. Moreover, these shortfalls are more likely to occur in a higher educational system that fails to train students in experiential learning in multi-stakeholder contexts. In today's system institutional rewards for researchers are predicated on high impact journals where action-oriented research is not well represented, and where academic research projects rarely fit the long-term relationship and capacity building required for meaningful participatory engagement and transformative change.

Most of the barriers to a major, consolidated effort in sustainability science will not be removed without far-reaching institutional change (Jaeger, 2011, p. 197): first, changes in the educational system to strengthen the core competences of sustainability science are necessary; second, collaboration and networking with stakeholders in society around common sustainability objectives needs to be expanded and deepened; third, the existing institutions that support science and technology in the current governance structure for knowledge require major adjustments in order to improve the link between science, policy and society. The following sections briefly review each of these three tasks of institutional capacity building for sustainability science.

4.2.1. Incorporating sustainability into higher education institutions

In attempting to further establish sustainability science in academia and basic research institutions, scholars and policy makers have to manage the complex process of the institutionalisation of a scientific field. This process encompasses the founding of educational and research programs, the establishment of academic societies and associations, as well as scientific journals and textbooks (Ben-David, 1971). Of these many challenges, probably the greatest of all concerns the **transformation of the core missions of the modern research university**. The integration of research into the core activities of the modern university during the 19th century signified the first major transformation of higher education institutions. During the 20th century, the capitalisation of scientific knowledge in the service of the economy in the so-called "entrepreneurial university" has led to a second major transformation. At present, the new modes of organisation of research called for by the sustainability transition could lead to a third major transformation, called by some the "**third academic revolution**". The focus of this third transformation will be on the sustainable development of the local and regional communities associated with the major research universities and on the promotion of larger socio-technological transitions towards strong sustainability (Yarime et al., 2012, p. 109).

Both the current incentive and reward system of the research university and the existing mode of university/industry collaboration in the service of the needs of industry remain important and well established social benefits of modern higher education institutions. However they are clearly insufficient for implementing the type of multi-stakeholder collaborations required for solving complicated and interconnected sustainability issues.

The concept of sustainability was first introduced in higher education systems at an international level by the UNESCO-UNEP International Environmental Education Program in 1975, jointly administered by the United Nations Educational and Cultural Organisation (UNESCO) and the United Nations Environmental Program (UNEP) (UNESCO, 1984). Since then, a number of national and international declarations relating to the integration of sustainability issues in higher education institutions have been developed (Wright, 2004; Yarime et al., 2012). **The Talloires Declaration of 1990 (Association of University Leaders for a Sustainable Future, 2011) was the first official declaration made by university presidents, chancellors and rectors of a commitment to sustainability in higher education. This declaration proposed an action plan for incorporating sustainability in teaching, research, operations, and outreach at colleges and universities (ULSF, 1990.**) It was soon followed by the Swansea Declaration adopted at the conclusion of the Association of Commonwealth Universities' Fifteenth Quinquennial Conference in 1993.

At the European level, an early initiative was the Co-operation Program in Europe for Research on Nature and Industry through Coordinated University Studies (COPERNICUS), which was established by the Conference of Rectors of Europe (CRE) to promote a better understanding of the interaction between humans and the environment and to collaborate on common environmental issues. In this context, the **Conference of Rectors created the CRE COPERNICUS Charter for Sustainable Development in 1994** and co-organised the COPERNICUS conference held for the World Summit on Sustainable Development Rio + 10, which lead to the Lüneburg Declaration on Higher Education for Sustainable Development in 2001.

Finally, on the global scale, another important declaration in the early period of the establishment of sustainability science was the **Ubuntu Declaration on Education, Science and Technology for Sustainable Development in 2002**, with the signatories of major academic institutions such as the United Nations University (UNU), the International Association of Universities, the Third World Academy of Science, the African Academy of Sciences and the Science Council of Asia, as well as the International Council for Science amongst others.

A variety of **frontier education programs** have been implemented for integrating sustainability at higher education institutions since these major declarations were developed in the 1990s. A well-established program, focusing on transdisciplinary education in complex sustainability issues, is **the graduate program in sustainability science (GPSS) of the Graduate School of Frontier Sciences at the University of Tokyo**, introduced in 2007 (Onuki and Mino, 2009). The core of this program consists of the provision of integrated and holistic approaches, along with case study analysis of particular situations to learn the necessary skills for applying such approaches to major sustainability issues. Through a variety of case studies students learn skills such as systems thinking, facilitation and negotiation necessary for consensus building, and sound understanding and appreciation of cultural diversity. Throughout these case studies, students are urged to revise and reformulate the problems at hand and acquire a comprehensive understanding distinct from the implicit assumptions made in formulating the original problem.

One of the major features of the program is its **collaboration with policy makers and stakeholders outside academia established at the University of Tokyo**. For example, through the involvement of the graduate school in the project on a bright low-carbon society (for the low-carbon development of Kashiwa city) students from various graduate programs actively participate in the diverse social experiments of each research group (Onuki and Mino, 2009). By doing so, they learn transdisciplinary approaches to interwoven problems which require technical solutions, collective action and open-ended ethical goal setting. As various types of stakeholders in society are involved in these social experiments, students can also learn how to communicate effectively with people and organisations that do not necessarily share or understand academic terminologies and curiosities. This educational role is then extended to the community and to the stakeholders involved, all of whom may monitor and appropriate the results via annual public conferences, grey literature (i.e. reports, online working papers, etc.) and academic journals.

Extra-academic collaborative and participative sustainability research has been established at various higher education institutions throughout the world. Although this model of the reform of higher education institutions is still in its initial stages, these programs nevertheless show promising strategies for integrating sustainability issues into higher education through experiential learning, based on in-depth case study methodologies and collaboration and networking with external stakeholders. In addition, opportunities for intensive training in qualitative methods and in multi-method research have expanded over the past decade (see Poteete et al., 2010, p. 19). For example, the consortium on qualitative research methods holds an annual intensive seminar on qualitative and multi-method research. The US National Science Foundation has supported methodological training programs for the social sciences, including month-long courses such as the empirical implications of theoretical models (EITM) program, which offer training in how to combine multiple quantitative methods within a single research program (Granato, Lo & Wong, 2010a, 2010b). Opportunities to develop more specialised qualitative research skills include the summer school in methods and techniques offered by the European Consortium for Political Research, and, in the United States, the Inter-University Consortium for Political and Social Research.

Overall, progress on campuses, has, however, been rather slow (Velazquez, Munguia and Sanchez, 2005). This slow pace of higher educations' movement towards sustainability has been particularly influenced by the **conventional university appraisal systems that do not seriously consider sustainability perspectives in their evaluation methodologies** (Yarime et al., 2012, p. 104). Currently, higher education systems are under considerable pressure to **perform on citation indexes and technology transfer statistics, which only give only a partial picture of the universities' social role, especially if they invest in extra-academic collaborative and participative sustainability research**. **If modified appropriately, assessment and appraisal systems could be a significant force** for promoting the integration of sustainability research in higher education institutions (Fadeeva and Mochizuki, 2010).

To achieve a far-reaching impact, research administrators and science policy officials should design and implement sustainability assessments of higher education institutions in an integrated manner (Yarime et al., 2012, p. 104). Sustainability assessment systems of educational institutions usually evaluate issues such as: the usage of energy, water, and other materials; sustainability education as a core function along with the incorporation of sustainability issues in teaching, research and service; and cross-institutional actions (Shriberg, 2002). Most existing assessment systems, however, evaluate the aspects of education, research, and outreach rather separately. To encourage higher education institutions to move more effectively and consistently towards sustainability, **university appraisal systems should provide a holistic assessment that encompasses the establishment of academic programs based on experiential learning, institutionalisation of sustainability research communities and networks, and collaboration with external stakeholders involved in sustainability projects** (Yarime et al. 2012, p. 104).

4.2.2. Strengthening the sustainability science community

As witnessed by the endorsement and signature of the major international declarations, the research and science policy community shows a growing interest in embracing sustainability issues in research and education. **The community actively pursuing sustainability science is however highly fragmented** (Jaeger, 2011, p. 192). Except for some major initiatives discussed below, the communities and networks of sustainability scientists that currently exist are often oriented towards specific topics, such as climate change, development, water management or biodiversity. Prominent examples of these "topical" communities on the global scale are the Earth System Science Partnerships for the integrated study of the earth System discussed in Section 3.2.3 above; the Resilience Alliance, which comprises scientists and practitioners who collaborate to explore the dynamics of socio-ecological systems (www.resalliance.org) and the Integrated Assessment Society (http://www.tias.uni-osnabrueck.de/tias.php) for the development and use of integrated assessment. However, in spite of the importance of these initiatives and their often path-breaking contributions to sustainability science, they are few in number, without any connection between the participating scientific communities (apart from some individuals).

Several initiatives have been launched to overcome this state of relative fragmentation. Amongst the most important are global networks that gather major university research institutions and a set of non-university research partners (Yarime et al., 2012, p. 108). Historically important networks are the **Alliance for Global Sustainability**, created in 1997 by four technical universities (the University of Tokyo, MIT, the Swiss Federal Institute of Technology and Chalmers University of Technology) to launch jointly-sponsored sustainability research projects (see box 4.3. below), the network of Japanese universities initiated by the University of Tokyo in 2005 (the **Integrated Research System for Sustainability Science**) which launched the journal *Sustainability Science* with the United Nations University, and the **International Network for Sustainability Science** in 2009, which organises the International Conference on Sustainability Science, already in its third edition in February 2012.

In Europe, the **European Sustainability Science Group (ESSG)** is a first step in broader community building. As Jill Jaeger has pointed out, the individuals and institutions that form the ESSG are a "good starting point", but the group is at present too small to fully represent sustainability science (Jaeger, 2011, p. 192). In parallel, major national-level research programs and research networks have been set up that have attracted EU-wide attention such as the **Sustainability Transitions Network (KSI) in the Netherlands** or the **Network for transdisciplinary research at the Swiss Academy of Arts and Sciences**. More recently, the transitions research community in Europe has set up a new network, the **Sustainability Transitions Research Network** (STRN), aimed at supporting the emerging community of researchers by the organisation of major conferences, post-graduate courses and programs and publications. The *rationale* of this new network, as stated by the initiators, is clearly to overcome the current fragmentation: "In Europe, many fields of research, such as innovation and governance research already have well-established networks. What is currently missing however is a network program that brings together researchers with a common interest in sustainability transitions, but from a variety of different research fields: industrial transformation, innovation and socio-technological transitions; integrated assessment; sustainability assessment; governance of sustainable development; policy appraisal; researchers working on reflexive governance; the resilience community; the ecological economics community; groups of energy, environment and sustainability modellers; and a core sustainability transitions community" (www.transitions network.org/about).

Incentive structures and institutional frameworks, such as the **post-graduate programs** and the **international conferences** set up by integrative research networks, and the development of long-term career paths based on the competences acquired in these cross-cutting networks, are particularly important for the further institutionalisation of the field of sustainability science. By developing extensive mobility and promoting transformational research in collaboration with stakeholders, sustainability science will be able to create promising opportunities for young people not only in academia but also in industry, business, and the public sector. Therefore, these emerging institutional arrangements will potentially have significant implications for cementing sustainability science more deeply in society over the long term (Yarime et al., 2012, p. 108).

A crucial step in the development of long-term career paths in sustainability science is the promotion of research opportunities at post-graduate level. Indeed, as stressed by Poteete et al. (2010, p. 260), ideally interdisciplinary scholars should have a solid command of their own method and discipline, but also have sufficient familiarity with other methods and disciplines to engage with them. One strategy for dealing with this trade-off, which has long been used in the biological and physical sciences, is the use of **postdoctoral appointments** that enable scholars with a PhD to practice the research skills they have acquired and learn new skills while participating in an interdisciplinary project. If funding for interdisciplinary research centres and networks were to grow, we could see an expansion of such postdoctoral opportunities across the ecological and social sciences and the humanities.

4.2.3. Developing long-term transdisciplinary research in sustainability science

The involvement of major universities and research institutions in ground-breaking educational programs and institutional networks clearly contributed to the growing recognition of sustainability science. Several funding agencies (such as the US National Science Foundation and the DG Research of the European Commission, responsible for the Framework Programs on the Environment) also invested heavily in interdisciplinary and collaborative training and research related to the study of social-ecological systems. These activities have led to a large body of literature on transdisciplinary, community-based, interactive, and participatory research approaches. Yet, to further implement the transformational agenda of sustainability science, **cross-sector and multi-stakeholder collaborations in sustainability research needs to be promoted on a much broader scale**. In particular, researchers and policy makers need to ask what type of **joint initiatives and networking with stakeholders will contribute to accelerating local, regional, or global transition processes towards sustainability**, and what kind of incentives and policies are required to further promote this type of multi-stakeholder driven collaboration for sustainability in higher education institutions.

In *The Third Industrial Revolution*, Jeremy Rifkin gives an example of such a major transdisciplinary program which has led the city of Rome to adopt an innovative sustainability plan for the city's energy policy (Rifkin 2011, p. 82-85). The program, coordinated by the **school of architecture of Sapienza University**, engaged in multi-stakeholder research to explore an ambitious action plan for revitalising housing in the city centre, along with job creation by attracting high-tech companies in the field of renewable energies and sustainable housing, the building of partnerships with these companies for local energy production based on renewable energies, smart electrical grids for connecting the privately produced energy, and finally a plan for reconnecting the city to local food production systems in the abandoned fields around the suburban areas to decrease the ecological footprint of the city's food consumption needs. This plan received wide support and has been adopted as the official strategic plan by the city of Rome.

A similar initiative was taken in Tokyo, through a collaboration between the local authorities in the district of **Kashiwa city and the University of Tokyo** (Yarime et al., 2012). This initiative, called the "Urban Reformation Program for the Revitalisation of a Bright Low Carbon Society" (see above, Section 4.3), received five years funding from the national government. The overall aim of the project is to design the blueprint for a low-carbon, elderly-citizen friendly community in the local vicinity of Kashiwa and to demonstrate its feasibility via a comprehensive series of social experiments. Both basic and applied research is being conducted by six groups: energy (development of solar heating and air-conditioning), senior mobility (trial of super-compact electric vehicles), clinical plant science (senior-citizen education project to alleviate crop diseases), agriculture and landscape planning (promotion of local agriculture and bio-mass production), city planning (unification of project and housing and services for the elderly), and lastly information systems (unification and information management). The partners for this project include the University of Tokyo, local government authorities, a think tank, local enterprises, NGOs and citizen groups. Although still in its initial stages, the project shows how transdisciplinary research programs can be set up to support multi-stakeholder intervention in society and to demonstrate the impact of particular policies or technologies for sustainability.

Urban planning initiatives seem especially suited for sustainability research. However, the emerging sustainability science programs have not been limited to complex urban transition processes, nor to developing research collaboration with stakeholders looking for basic scientific input for sustainability projects at the planning stage. **Transdisciplinary research has been set up for issues as diverse as the development of solar energy systems in rural areas of Argentina (Wiek et al., 2012), community driven implementation of payment for ecosystem services schemes (Weaver, 2011), and interdisciplinary assessment of synthetic biology contributions to sustainability (Pauwels, 2011),** to name just a few. Support for these initiatives by regional and national governments and stakeholders shows that higher education institutions are increasingly expected to play a key role in the collaboration and networking among academia, industry and the public sector to tackle the complex factors fuelling the sustainability crisis.

As highlighted throughout this report, there is an increasing call by scientists and policy makers for interdisciplinary and transdisciplinary research into sustainability issues. In Germany, for instance, transdisciplinary research is considered to be the key to the energy transition process enacted by the Federal Parliament of Germany in summer 2011. This new level of awareness and commitment is a tremendous opportunity, but it also bears the risk of using the reference to transdisciplinary research as a remedy for any kind of complex sustainability-related problem-solving activity (Lang et al., 2012, p. 40), without considering the necessary institutional hurdles to be overcome for the development of the goal-seeking, iterative and integrative approaches needed to address the complex issues of sustainability. As shown both in this report and by leading sustainability scholars, living up to the high expectations of transdisciplinary sustainability research will require structural changes in research organisation and funding, in order to build capacity for transdisciplinarity among students and researchers, as well as among stakeholders and decision-makers outside academia.

4.3. An institutional reform program for sustainability science

Achieving the goal of a full-fledged institutionalization of sustainability science will require efforts and actions to be taken on many levels of policy intervention. This situation can be compared to the emergence of applied research departments at the end of the 19th century, in universities in the United States and in Europe, on the model of the Massachusetts Institute of Technology (MIT) (see section 4.2 above). By organizing applied research at the university, researchers added a new component to the existing missions of the university, then centred around basic research (on the model of the Humboldt University) and teaching (on the model of the first European Universities). The development of transdisciplinary transformative research for sustainability will equally require to add new components to the research university, based on a gradual process of experimentation and transformation.

The **perspective of a process of gradual change** is consistent with the conclusion of the overview of promising and/or well established sustainability science programs in section 3.4. As highlighted in that section, the various sustainability research programs integrate the three dimensions of sustainability ethics, interdisciplinarity and transdisciplinarity with varying degrees of strength. For example, some of the research programs, such as the transition approach to socio-technological change, are more oriented towards problem solving and organised through a transdisciplinary process, while others, such as earth system science, have a stronger interdisciplinary focus. The three dimensions are clearly present in both these programs, but some of the dimensions are less/more developed in each of them.

Sustainability scholars introduced the distinction between strategic research for sustainable development and sustainability research (Jaeger, 2011, p. 187), which is a convenient way to capture this variability between the transdisciplinary and the interdisciplinary focus. **Strategic research for sustainability** refers to research support for sustainable development. The main focus of strategic research is on the transdisciplinary collaboration with stakeholders in the elaboration of solutions, such as by mobilising engineering knowledge that contributes to solve practical problems of sustainability. If such research in addition makes a certain effort to integrate strong sustainability and a systematic interdisciplinary modelling of the coupled socio-ecological system dynamics, then strategic research can be considered as a first level contribution to sustainability science. **The second type, sustainability research**, usually refers to the kind of **fully developed interdisciplinary research programs** discussed at length in this report. The focus of this second type is mainly on enhancing our understanding of the interactions between economic, socio-technological and ecological systems within a strong sustainability ethics perspective. However, as argued throughout the report, such sustainability research programs, insofar as their aim is to fully contribute to transformative sustainability science, have to develop, as far as possible, transdisciplinary approaches to organise a practical process for reconciling the plurality of ethical values and problem framings that play a role in the social context of the research, even if the latter are not yet fully institutionalised

The institutional challenges and barriers considered above add an extra layer of variation to these two main types. Indeed, both strategic research for sustainability and sustainability research are often still constructed on an ad hoc and temporary basis. As such, these two modalities for organising sustainability research do not consider the long-term institutionalization of sustainability research. The latter implies to address the issues of career rewards, post-graduate training, networking and capacity building for multi-stakeholder partnerships amongst others. It seems therefore relevant to distinguish between **full-fledged institutionalised research programs for sustainability** and the other two types. The distinction between the three modalities for organising sustainability research has been represented schematically in table 4.1.

Table 3.1: Gradual change towards fully institutionalised sustainability research

	Sustainability ethics	Inter-disciplinarity	Trans-disciplinarity	Example of prototypes
Strategic research for sustainability ⇩	+	+	++	Transdisciplinary approaches to policies for payments for ecosystem services (Weaver, 2011).
Sustainability research programs ⇩	+/++	++/+++	+	Joint Program on Global Environmental Change and Food Systems (Ignaciuk et al., 2012), see section 3.2
Fully institutionalised sustainability research	+++	+++	+++	Tokyo University (Yarime et al., 2012; Onuki and Mino, 2009), see section 4
	+ → early stage ++ → well developed +++ → fully integrated			

The most advanced case of institutionalised sustainability research discussed in the report is the graduate program in sustainability science of the Graduate School of Frontier Sciences at the

University of Tokyo (see sections 4.2.1, 4.2.2 and 4.2.3). The school offers trandisciplinary education on complex sustainability issues, combining technical courses and case study analysis. In parallel the school has established a research partnership with the local authorities of the district of Kashiwa city for research on urban reforms for low-carbon community development. This research program includes research clusters on energy, mobility, agriculture and information systems amongst others. The program is conducted in combination with a series of social experiments in the local communities. Students of the graduate program also participate in one of the research clusters and learn transdisciplinary research skills in connection with one of the social experiments. In addition, in 2005, the University of Tokyo launched the journal "*Sustainability Science*" in collaboration with the United Nations University, and set up the International Network for Sustainability Science in 2009, which organises every year the International Conference on Sustainability Science in one of the partner universities.

In Europe, science policy officials have set up major national-level research programs such as the Sustainability Transitions Network (KSI) in the Netherlands and the Network for transdisciplinary research at the Swiss Academy of Arts and Science (see a detailed description in box 4.4. below). Another interesting example of an institutionalised sustainability research programs is the Policy Research Centre on Transition for Sustainable Development (Transities voor Duurzame Ontwikkeling (TRADO)), funded by the Flemish government. This Centre is composed of research units of the KU Leuven, Ghent University, Erasmus University Rotterdam and the Strategic research centre Vision on Technology (VITO). The Centres assemble researchers from various disciplines, including political science, economics, bio engineering and architecture. The research program of TRADO focuses on different aspects of sustainability transitions that have been underdeveloped in the literature and that can support the Flemish Government's transition approach.

As argued throughout section 4.2 of the report, sustainability science will not be able to support, in an effective way, the transition to strong sustainability in the absence of such a long-term institutionalisation. In particular, **academic training is needed** to build specific research competences for sustainability research such as ethical argumentation, analysis of socio-ecological systems and multi method research. In addition, there is a need for a **greater recognition of interdisciplinary and transdisciplinary research within academia**, along with confidence building with sustainability stakeholders for transdisciplinary **research partnerships**. To move in that direction, senior science officials and directors of major higher education institutions and research institutions (Scholz et al., 2006; Schneidewind, 2010), have underlined the urgent need of taking a minimal set of **capacity building measures**, to be implemented in the three modalities for organising sustainability research discussed above:

4.3.1. Capacity building measures at universities and other higher education institutions

First, at the level of strategic science for sustainability, there is an urgent need of transforming existing research practices at higher education institutions. This is the most directly available form of bottom-up action that can be envisioned to move towards building a transdisciplinary research infrastructure for sustainability. The minimum conditions highlighted in the literature for such a transformation is the **organisation of sustainability research in a cross-cutting manner, beyond the borders of disciplines, faculties and colleges, and to give sustainability research a prominent role in the overall strategy of the institutions**. Worldwide, many higher education institutions have already taken that road, such as medium size universities in some German Länder (Lüneburg university and University of Greifswald (see for a detailed description box 4.1.below)) or larger universities in some regions in Japan (Tokyo university in the metropolitan area of Tokyo, see the discussion in the text). Leading figures of these transformations underline the importance of taking the following set of structural reform actions:

- The creation of explicitly designed **transdisciplinary professorships** (including nomination committees for such positions that are not organized along disciplinary logic). The Lüneburg University in Germany has created such a position in 2009.
- The building of **transdisciplinary research centres beyond faculty borders**, which can disseminate multi-method research and quality management systems for transdisciplinary research. The transdisciplinary research laboratory at the ETH Zürich is an example of a university that has taken the steps to create such a centre.
- Creation of **"bridge" fellowships/professorships for transdisciplinary sustainability research**, jointly engaged by higher education institutions and research institutions outside higher education institutions, on the model of research professors at research societies in Germany (Fraunhoffer or the Helmholtz societies for instance).

Box 4.1: An example of capacity building for sustainability research at higher education institutions.

Ernst Moritz Arndt Universität Greifswald
Institut für Botanik und Landschaftsökologie

The Institute of Botany and Landscape Ecology at the University of Greifswald, Germany, has a unique interdisciplinary profile, comprising biologists, ecologists, economists, social and political scientists, and philosophers. The Institute has a long-standing worldwide expertise in the field of landscape and paleo-ecology, and ecosystem dynamics.

Some highlights

- The Working Group Environmental Ethics hosts an interdisciplinary research group on social entrepreneurship (GETIDOS) with a specific expertise in ***empirical social research and collaboration with sustainability stakeholders*.**
- The Institute host ***an operational foundation*** (the Succow Foundation) dedicated to the protection of national parks and biosphere reserves in the countries of the Eastern European countries.
- The institute organizes *an* ***international master program*** in Landscape Ecology and Nature Conservation, with courses in environmental sciences, economics and ethics.

Capacity building

< GETIDOS received support from the ***Social-Ecological Research program of the Federal*** Ministry of Education and Research. As stated on the program's website, social-ecological research aims to develop strategies in order to solve social sustainability issues connecting ecological transformation of the society with social justice and economic demands. This kind of research requires the ***cooperation between natural and social scientists and involves social players*** (for example consumers, local authorities, businesses and NGOs).

< The Succow foundation at the Institute was established with the ***prize money*** from the Right Livelihood Award, established in 1985 with the support of a group of Swedish parliamentarians and with a network of recipients, donors, and other supporters covering five continents.

< The International Master Program (see above) receives ***support for tuition fees from*** the German Academic Exchange Service and from the Deutsche Bundesstiftung Umwelt

4.3.2. New tools for programmatic research funding

The second starting point for an effective institutionalisation of sustainability science is the set of existing programmatic research initiatives on sustainability development and/or environmental issues. Funding for such programmatic research at the regional, national and European level has already equipped some higher education institutions with competences for sustainability research. However, **rarely these have been fully exploited for their transdisciplinary research potential**. One major research project in Germany, the *Klimzug Program*, can illustrate this situation (cited as a failed opportunity by Schneidewind (2010, p. 125), current president of the Wuppertal institute for Climate and Energy Research). This program for the development of climate adaptation strategies for seven regions in Germany, which received 10 Million Euro's for 5 years, was a perfect candidate for transdisciplinary research, but in the project design and implementation this aspect remains nearly totally absent. **To overcome these failures, it is necessary to go beyond the conventional, purely descriptive-analytical organisation of programmatic research and move to the kind of transformative and ethically informed sustainability research that is needed for strong sustainability**. Interesting examples of such funded transdisciplinary research programs are the "Local Science Network for the Environment and Sustainability" funded by the Japanese Science and Technology Agency (see for a detailed description box 4.2. below), the TRANSMED project of the French National Research Agency for the transdisciplinary study of the future of the Mediterranean area (http://www.agence-nationale-recherche.fr) and the Policy Research Centre on Transition for Sustainable Development funded by the Flemish Government in Belgium. The following capacity building measures can be taken for integrating ethically informed transdisciplinary research in programmatic research funding:

- Integration of **requirements for transdisciplinary organisation of research and explicit justification of the choices** regarding options for a strong sustainability ethics as a condition for access to programmatic research funding for sustainability research
- Support for systematic exchange on methodologies and best practices for sustainability research between existing institutions involved in sustainability research:
    - Synergy **grants for** a consortium of institutions, with the view to **building cross-institutional methodological competences** on sustainability research

      Cross-institutional competence centres for sustainability research, which can integrate knowledge on sustainability research methodologies from higher-education and other research institutions

Box 4.2: An example of capacity building for sustainability research through tools within programmatic research funding.

The **Local Science Network for Environment and Sustainability** is part of the project on "Constructing a Pragmatic Science Community" funded by the Japan Science and Technology Agency (http://localsci.org/jst2en/outline.html). This projects aims to build a system to facilitate interactions between stakeholders, residential research institutions and visiting researchers in local efforts to address environmental issues. The project also addresses evaluation and feedback from local community stakeholders in such a system.

Some Highlights

- The Local Science Network fosters and supports scientists who can be useful partners to the local stakeholders that are responsible for solving problems
- The Local Science Network organizes a "Participatory Research Evaluation" system for use in evaluating the activities and research of scientists from the perspectives of both local communities and science itself.

Capacity building

< LSNES organizes ***residential research internships***, which involves training on how residential researchers work on problems and how they approach and apply research in the field.

< LSNES formulates "***Guidelines on Collaborations***", which the local stakeholders and scientists/specialists then use to motivate and evaluate each other and work together in scientific collaborations.

4.3.3. New research networks and institutions

Third, the full institutionalisation of sustainability research will require the creation of new research networks and/or institutions specifically dedicated to sustainability research. On the one hand, **new research networks** should be created to address one of the following tasks:

- Strengthening the **capacity to participate in international networks**, by gathering and disseminating best practices and know-how.
- Supporting the creation of **common transdisciplinary research infrastructures** such as peer reviewed open access journals, prices for sustainability research and annual conferences on transdisciplinary sustainability research.
- Promoting the **joint submission of funded research projects** at the regional, national and European level, amongst higher education institutions and research institutions outside higher education institutions.

Prominent examples of such networks are the Alliance for Global Sustainability on the international level (see detailed description in box 4.3. below) and the Sustainability Transitions Research Network (STRN) in Europe.

On the other hand, **full-fledged new institutions for transdisciplinary research**, on the regional, national or transnational scale, should be created in order to accomplish a long-term institutionalisation of sustainability research. The following institutions can contribute to that goal:

- **Regional or national panels**, on the model of the International Panel on Climate Change (IPCC), that make peer reviewed inventories of the best available scientific knowledge on strategies and solutions for transition to strong sustainability at the regional or national level
- A **fund for transformative sustainability research** that would specifically finance research topics emanating from sustainability stakeholders (in a competitive submission process of topics identified by these stakeholders). The aim of such fund (or part of an existing fund) would be to involve sustainability stakeholders in the definition of the salient and socially relevant research questions to be addressed in sustainability research.
- An **institute for advanced studies in sustainability research** (that can be organised in one location or in a network of partner institutions), which provides an infrastructure for hosting high level visiting scholars and coordinates work with graduate students and post-docs on innovative and path-breaking ideas for taking the sustainability research agenda forward
- An **advisory body for the development of sustainability research** at higher education institutions. Such a body can provide reports on international best practices and develop criteria for quality management of transdiscplinary sustainability research.

Examples of such new institutions that have an important capacity building role are the Institute for Advanced Studies in Potsdam (IASS), the Td-net at the Swiss Academy of Arts and Science (see a detailed description in box 4.4. below) and the International Climate and Environmental Research Centre in Oslo.

Table 3.2: Capacity building measures for transdisciplinary sustainability science.

Capacity building measures for transdisciplinary sustainability science	Illustrative examples cited in the report (*)
Capacity building measures at higher education institutions	Institute of Botany and Landscape Ecology (see box 4.1.) ; Lüneburg University, ETH Zürich and Graduate School of frontier sciences at Tokyo University (see text)
Establishment of transdisciplinary professorships	
Building of transdisciplinary research centres	
Creation of “bridging” fellowships	
Tools within programmatic research funding	Local Science Network for Environment and Sustainability (see box 4.2.); TRANSMED project and Policy Research Centre on Transition for Sustainable Development (see text)
Requirements of transdisciplinary organisation of research	
Requirements of strong sustainability ethics perspective	
Synergy grants for cross-institutional multi-method sustainability research	
Cross-institutional competence centres	
Research networks	**Alliance for Global Sustainability (see box 4.3.)**; Sustainability Transitions Research Network STRN (see text)
Sharing best-practices and know-how for international networking	
Common transdisciplinary research infrastructure (journals, conferences, prices)	
Joint submission of larger research projects	
Research institutions/platforms/panels	Td-net at the Swiss Academy of Arts and Sciences (see box 4.4.) ; IASS Potsdam and Centrr for International Climate and Environmental Research (Oslo) (see text)
Regional or national sustainability panels	
Organisation of stakeholder identification/submission of salient research questions	
Institute for advanced studies in sustainability research	
Advisory body on quality management procedures for transdisciplinary sustainability research	

These measures can be the object of new science policy initiatives or can be integrated in existing science policy initiatives. (*) The list of examples in the second column is only given for illustrative purposes. A full presentation of existing initiatives is beyond the scope of this report. Therefore, this list is not representative of initiatives existing in these or other countries.

The Regions and Communities in Belgium at present still do not have major institutionalised sustainability research infrastructures, with the notable exception of the Policy Research Centre on Transition for Sustainable Development funded by the Flemish Government discussed above. In spite of this, the sustainability challenges in the field of energy, mobility or agriculture – to name just a few – are as important as elsewhere. Therefore, the development of specific strategies, networks and institutions for sustainability research is likewise needed for addressing these challenges. The opportunities to move in that direction are certainly available. Indeed, universities and research centres in the Communities and Regions already develop various initiatives and research programs that directly can contribute to the building of such an infrastructure. However, without new ambitious initiatives at various levels of policy intervention, these current initiatives will fall short of upgrading their infrastructures to the level of international excellence already reached in similar Regions and Communities around the world.

Box 4.3: An example of capacity building for sustainability research through support for research networks.

The Alliance for Global Sustainability (AGS) (http://www.globalsustainability.org/) is a unique, international partnership between four science and technology universities:

- Swiss Federal Institute of Technology, Zurich (ETHsustainability)
- Massachusetts Institute of Technology (MIT/AGS)
- University of Tokyo (UT)
- Chalmers University of Technology (Chalmers)

Since its inception, the AGS has pioneered a new research paradigm that brings together multi-disciplinary research teams from the partner institutions. Strong, local programs engage faculty, students and senior research staff from across their respective institutes.

Capacity Building

< Flagship programs: building upon 10 years of collaborative research, the AGS has launched two ***flagship programs of integrated research, education, and outreach***:

- the "Energy Flagship" that focuses on select energy sectors under the theme "Near-Term Pathways to a Sustainable Energy Future."
- the flagship on food and water : "Secure Ecosystem Services for a Nourished World".

< Joint educational activities undertaken by AGS member institutions include the "***Youth Encounter on Sustainability***" and the "Delivering Research Results" project. The latter aims at creating a ***web-based educational resource*** to engage the interest of undergraduates in sustainability research, develop course materials and support their coursework and research.

< The AGS ***book series***, 'Science and Technology: Tools for Sustainable Development' (Springer) has published nine volumes with more in the pipeline.

< The ***Partnership Simulation*** tool, developed by MIT Professor Lawrence Susskind and his team especially for the AGS. The exercise is aimed at building capacity for starting and implementing an effective research partnership for sustainable development across academia/industry/civil society.

Box 4.4: An example of capacity building for sustainability research through building of new institutions.

td-net
Network for Transdisciplinary Research

Since 2008 **the Network for Transdisciplinary Research** (td-net) has been an initiative of the Swiss Academies of Arts and Sciences. The network was initiated to advance transdisciplinary research in all thematic fields. Its origins are, however, within the experiences made in the fields of environmental and sustainability research.

Some highlights

- td-net is the primary Swiss contact point for researchers and funders in the field of inter- and transdisciplinary research and teaching.
- As a platform, td-net advances the mutual learning between inter- and transdisciplinary researchers and lecturers across thematic fields, languages and countries and thereby supports community building.
- As centre of competences td-net disposes of expertise, methods and tools for coproducing knowledge. By use of these competences td-net supports inter- and transdisciplinary projects in research and teaching in order to bring them to fruition.
- td-net assists the Swiss Academies of Arts and Sciences in facilitating exchange and collaboration between disciplines and between science and society.

Capacity building

< The national ***inter- and transdisciplinarity conference*** is jointly organised by the td-net and the "Institut Universitaire Kurt Bösch" (IUKB). The conference aims to foster the exchange about the challenges of inter- and transdisciplinary teaching and research.

< The ***Swiss-academies award for transdisciplinary research*** *(td-award)* is given every other year in recognition of outstanding transdisciplinary work.

< Td-net will in the period 2012-2015 elaborate an ***overview of methods*** for coproducing knowledge, which assigns the methods to the specific problem they are suited to address; develop selected methods by practically testing and exploring them; and publish the application-driven overview of methods on their homepage.

Conclusion

A wide range of scientific communities, international organisations and policy makers have documented the unprecedented sustainability crisis that humanity faces today. This crisis is most clearly visible through the excessive depletion and degradation of natural resources that accompany the pro-growth economic policies throughout the world, but this degradation also has a strong impact on the social, environmental and economic well-being of present and future generations. The role of science in this new landscape is far from trivial. On the one hand, the rapid spread of the institutions of scientific research in Europe in the 17th and 18th centuries is widely considered as the root that lead to the industrial revolution and the subsequent growth in population, changes in global lifestyles and consumption patterns, which resulted in substantial (and globally disproportionate) improvements in human well-being (Mokyr, 2002). On the other hand, after centuries of triumph and optimism, science is now called on to remedy the pathologies of the global industrial system. Whereas it was previously understood as steadily advancing the certainty of our knowledge and control of the natural world, studies of science in society (Funtowicz and Ravetz, 1993; European Commission, 2009) show that nowadays science is increasingly seen as having to cope with many uncertainties in dealing with complex socio-ecological systems, value-based choices and the existence of a plurality of legitimate perspectives. In response, new styles of scientific activity are being developed.

As shown throughout this report, the challenge of strong sustainability cannot be addressed through the classical reductionist, analytical worldview which divides systems into ever smaller elements, studied by ever more esoteric specialisms. Indeed, sustainable development does not only call for changes in the configuration of socio-ecological systems, but most noticeably for transformations in the core values and worldviews that drive individual actions and organisations (Jaeger and Tàbara, 2011, p. 206). Science can contribute to such changes, but only if the sustainability challenges are addressed in an open, exploratory and learning mode. **New modes of organisation of research and new research partnerships between scientific and extra-scientific expertise are required**, together with a new generation of scientists aware of the challenges of strong sustainability. After over a decade of experimentation with new modes of organisation of scientific research for sustainability, **sustainability science emerged as a new mode of organisation of research characterized by a transdisciplinary and interdisciplinary research effort within an explicit ethical perspective on strong sustainability.**

In spite of the growing recognition of the urgent need for the further development of sustainability science, this report has highlighted **major epistemological and institutional barriers for changing the way in which science is organised and funded**. As shown through the detailed analysis of promising sustainability science approaches in ecological economics, earth system science and transition approaches in science, technology and society studies, the tendency to shift back to more classical reductionist and specialised approaches for providing policy advice is still widespread. Moreover, scholars typically do not immediately acknowledge the evidence that contradicts the well-established mono-disciplinary theories. Even after contradictory evidence has been acknowledged, improved theories do not emerge immediately or easily. Likewise, methodological practices do not always or immediately change in response to either theoretical developments or methodological innovations. Further serious obstacles arise from career incentives in higher education institutions, the dominance of mono-disciplinary peer review of research projects and promotions, and the lack of training opportunities for transdisciplinary research.

While there are no simple solutions to these challenges, **universities and funding agencies worldwide have repeatedly demonstrated their capacity to overcome institutional and epistemological barriers** by promoting exposure of scientists to multiple methods and disciplines in training, workshops and roundtables, and by supporting interdisciplinary and transdisciplinary research programs and networks that increase familiarity with sustainability research. Therefore, it seems worthwhile for the scholarly and policy communities to recognise the institutional and methodological barriers and strive to lower them by providing greater institutional and financial support. The institutional and structural arrangements that undermine trust amongst researchers by pitting different disciplines and methods against each other in competition for resources and status are more difficult to address. Career incentives that reward individual research more than collaborative research clearly discourage collaboration. However, reversal of these incentives is not impossible, as can be seen by the current situation where the amount of collaborative sustainability research varies across countries. Explicit recognition of and support for interdisciplinary and transdisciplinary research for governing the transition to strong sustainability might encourage coordinated efforts to alter institutional and structural arrangements more systematically and rapidly.

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Glossary

a. Glossary of key concepts

The key concepts of the glossary are marked in the text with a double asterisk (**), upon their first appearance in the executive summary or upon their first appearance in the main text.

Descriptive-analytical *versus* transformational mode of research

Sustainability science is being developed in a constructive tension between a descriptive-analytical and a transformational mode of research (Wiek et al., 2012). These two modes are necessary research components of sustainability research (Clark and Dickson, 2003). The descriptive-analytical mode of sustainability research is basically an advanced from of complex system analysis, applied to complex and dynamic socio-ecological systems (see for example Ostrom et al., 2007; Matson, 2009). The transformational mode is oriented towards practical solutions for sustainability problems. Therefore sustainability research in the transformational mode is confronted with the challenges of generating actionable knowledge, incorporating knowledge from outside academia, and dealing with different values and political interests. Typical research questions in the transformational mode are: (1) how socio-ecological systems would function and look like in compliance with various values (for example different ways to balance socio-economic needs and environmental capacities); (2) which transition pathways are viable and what strategies could be explored to move towards solutions.

References and further reading: Ostrom et al., 2007; Matson, 2009; Wiek et al., 2012; Clark and Dickson, 2003.

Interdisciplinarity

The US National Academies' report on interdisciplinarity defines interdisciplinary research as a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice (National Academies, 2004). In the particular context of sustainability science, the practice of interdisciplinary research results more specifically from the need to combine descriptive-analytical modes of research and transformational modes of research (see the glossary entry for descriptive-analytical versus transformational mode of research). In practice, this means to integrate research results from descriptive-analytical disciplines such as economics and environmental sciences, with research results from value based ethical inquiry and exploration of socially legitimate transition pathways.

References and further reading: National Academies, 2004; Jerneck et al., 2010.

Socio-ecological systems

The term socio-ecological system is used to model situations where social and ecological systems are linked through a set of dynamic interactions, which makes the delineation between the social and the natural system artificial and arbitrary (Berkes et al. 2003b). Human actions have had major impacts on biophysical systems for thousands of years. Yet, the scope and magnitude of the human forces operating in socio-ecological systems have risen dramatically, leading prominent scientists to conclude that we have entered a world of human-dominated ecosystems (Vitousek et al. 1997), even on a planetary scale (Crutzen and Stoermer 2000; Crutzen 2002). The specific objective of the research on socio-ecological systems is to investigate how human societies deal with change in these coupled systems, and how capacity can be built to adapt to future change. Dealing with separated ecological, social or economic systems alone is challenging enough. But the resultant socio-ecological systems are far more complex and dynamic than any ecosystem human societies have encountered previously. It follows that nonlinearities and the inevitable uncertainties associated with complex and highly dynamic systems need to be taken into account in the analysis of institutions to govern these systems.

References and further reading: Berkes et al. (2003b), Crutzen (2002), Crutzen and Stoermer (2000), Vitousek et al. (1997).

Transdisciplinarity

Transdisciplinary research complements conventional basic and applied research in problem fields characterized by complexity and uncertainty: "There is a need for transdisciplinary research when knowledge about a societally relevant problem field is uncertain, when the concrete nature of problems is disputed, and when there is a great deal at stake for those concerned by the problems and involved in dealing with them" (Pohl and Hirsch Hadorn, 2006, p. 20). Examples of such problem fields are migration, violence, health, poverty, global environmental change and cultural tranformation processes, among others. Transdisciplinarity implies that the precise nature of a problem to be addressed and solved is not predetermined and needs to be defined cooperatively by actors from science and the life-world. To enable the refining of problem definition as well as the joint commitment in solving or mitigating problems, transdisciplinary research connects problem identification and structuring, searching for solutions, and bringing results to fruition in a recursive research and negotiation process" (Wiesmann *et al*. 2008, p. 436). More specifically, sustainability scholars define transdisciplinary research as a "reflexive, integrative, method-driven scientific principle aiming at the solution or transition of societal problems, and concurrently of related scientific problems, by differentiating and integrating knowledge from various scientific and societal bodies of knowledge" (Jahn et al., 2012, pp. 26-27).

References and further reading: Wiesmann *et al*. 2008; Jahn et al. 2012; Pohl and Hirsch Hadorn, 2006.

Transition

The term transition has emerged as a key theoretical concept in the analysis of the sustainability crisis over the last decade. It refers to profound processes of change that involve both innovative practices and structural and cultural adaptations (Grin et al., 2010). This notion of structure has to be understood broadly, including physical infrastructure (physical stocks and flows), economic infrastructure (market, consumption, production), and institutions (rules, regulations, collective actors such as organizations, and individual actors). The notion of culture refers to the collective set of values, norms, perspectives (in terms of coherent, shared orientation) and paradigm (in terms of way of defining problems and solutions) (Loorbach and Rotmans, 2006).

References and further reading: Grin et al., 2010; Loorbach and Rotmans, 2006.

Uncertainty

Despite the enormous effort and resources that have gone into developing and applying methods for addressing uncertainty, there has been little concerted effort to see whether they contribute significantly either to knowledge or to policy. Even when there is little empirical data for solving policy problems, it is mostly treated by traditional statistical techniques. However, as John Christian Bailar, an expert in statistical methodologies, put it, all the statistical algebra and all the statistical computations may work against the need for disciplined thought and scientific rigour, because "the kind of random variability that we see in the big problems of the day tend to be small relative to other uncertainties". In particular, "random variability – the stuff of p-values and confidence limits, is simply swamped by other kinds of uncertainties in assessing the health risks of chemical exposure, or tracking the movement of an environmental contaminant, or predicting the effects of human activities on global temperature or the ozone layer" (Bailar, 1988, p. 19). Thus, from a scientific perspective, the validity of the conventional statistical approach to uncertainty for addressing sustainability problems is, at best, dubious. New methods must be developed for making our "ignorance usable" (Ravetz, 1990). In particular, different kinds of uncertainty need to be clearly expressed and analysed. As discussed in more detail by Funtowicz and Ravetz (1993, p. 743-744), there is a need to distinguish among inexactness, unreliability and irremediable uncertainty.

References and further reading: Bailar, 1988; Ravetz, 1990; Funtowicz and Ravetz, 1993.

Weak, intermediate and strong sustainability

Sustainability can be described as the "maintenance of capital" (Goodland and Daly, 1996). In case of economic sustainability it refers mainly to financial capital. For example, historically, at least as early as the Middle Ages, merchants wanted to know how much of their sales receipts could be consumed by their families without depleting the capital of their business (for example by using only the net profits, minus investment costs, for private consumption). More recently, the concept of sustainability is increasingly used in the context of the ecological crisis, where the term environmental sustainability refers to the maintenance, or at least non-declining, of natural capital. The latter is defined as the stock of environmentally-provided assets (such as soil and its microbes and fauna, atmosphere, forests, water, wetlands) that provides a useful flow of goods or services (see the concept of ecosystem services discussed in section 3.2.). Due to the degradation of natural capital, such natural capital, and not lack of technology or human-made capital, has in many situations become the limiting factor of socio-economic activities. For example, timber is limited by the remaining forests, not by saw mills, marine fishing by the remaining fish, not by fishing boats etc. In this context, one can distinguish between three degrees of sustainability: weak, intermediate and strong. These refer respectively to situations where only total level of capital has to be remain intact (so one type of capital can be totally depleted, without loss of well-being), only critical thresholds of each kind of capital has to be maintained and the different kinds of capital has to be kept intact separately. Strong sustainability is important when the different forms of capital are complements and not substitutes, for example a sawmill (human-made capital) is worthless without the complementary capital of a forest.

References and further reading: Goodland and Daly, 1996; Common and Stagl, 2005.

b. Glossary of key technical terms

The key technical terms of the glossary are marked in the text with a simple asterisk *, upon their first appearance in the executive summary, or upon their first appearance in the main text.

Dynamic stochastic general equilibrium models

These models aim to describe the behaviour of the economy as a whole by analysing the interaction of many microeconomic decisions, taking into account the fact that the economy is affected by random ("stochastic") shocks such as technological change, fluctuations in the price of oil, or changes in macroeconomic policy-making. The core set of microeconomic variables typically used as the starting point of these models are economic preferences (maximizing personal utility or maximizing firms' profits), productive capacity of the agents (for firms, typically specifying its capacity to produce a certain amount of goods, in function of given amounts of labour, capital and other inputs that are employed), and economic institutions (such as budget constraints, rules of monetary and fiscal policy) (Kydland and Prescott, 1982).

General/partial equilibrium analysis

General equilibrium analysis tries to give an understanding of the whole economy at equilibrium, starting with individual markets and agents. The first attempt in neoclassical economics to model prices for a whole economy was made by Léon Walras (1874). In partial equilibrium analysis, the determination of the price of a good is simplified by just looking at the price of one good and assuming that the prices of all other goods remain constant.

Lexicographic preferences and ordinal utility

An agent using "lexicographic preferences" ranks entities or aspects in order of choice but rejects the possibility of trading or substitution amongst these entities (Spash, 1998). Such preferences may be absolute, as animal rights, or bounded, as when some minimum living standard is required before such rights become operative (O'Neill and Spash, 2000). These types of preferences conform to the basic axioms of rationality in neo-classical economics but deny the principle of (gross) substitution, which implies that everything has a trade/exchange price. Many economists assume these preferences represent irrational viewpoints but evidence exists that they may be relatively common especially for environmental issues. In presence of lexicographic preferences, on cannot apply ordinal utility theory, which supposes that all pairs of alternative bundles (combinations) of goods can be ordered such that one is considered by an individual to be worse than, equal to, or better than the other.

Maximum sustainable yield

The maximum sustainable yield is the largest catch that can be taken, or the largest yield that can be harvested, that still allows the population to continue to reproduce indefinitely. However, conservation biologists widely regard the concept as misused because it focuses solely on the species in question, ignoring the damage to the ecosystem caused by the designated level of exploitation and the issue of bycatch (Walters and Maguire, 1996).

Multi-criteria evaluation

A typical multi-criteria problem is described by a finite set of feasible actions and a finite set of evaluation criteria (Funtowicz et al., 2002). In general, in a multi-criteria problem, there is no solution optimizing all the criteria at the same time. The multi-criteria evaluation methods allow decision makers to find compromise solutions taking into account different conflicting values. Increasingly multi-criteria analysis uses software and methods from qualitative comparative research (for an overview of these methods see Rihoux and Ragin, 2009).

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