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Article

Transdisciplinary Sustainability Science at Higher Education Institutions: Science Policy Tools for Incremental Institutional Change

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Abstract: At the very moment that humanity is facing a broadening ecological crisis, and that both policy makers and civil society are calling for a transition towards more sustainable societies, modern science seems incapable of providing operational solutions for managing this transition. In this context, both Noble prize laureates and high-level science officials have stressed the need of an in depth transformation of the modes of organization of scientific research for governing the transition to sustainable societies. However, existing analyses of on-going initiatives show that most of the barriers to a major, consolidated effort in sustainability science will not be removed without far-reaching institutional change. To address this challenge, this paper proposes an incremental institutional change approach, based on a gradual institutionalization process of existing initiatives. The analysis in this paper shows that strategic research for sustainability and reform of research funding mechanisms will only be effective if they are supported at the same time by reforms of career and training paths at higher education institutions. To promote this vision, the paper proposes a set of capacity building measures that can be undertaken at the level of research funding, higher education institutions and networking.

Keywords: sustainability science; transdisciplinarity; higher education institutions; research policy

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1. Introduction

Research over the last two decades has shown that human influences on global life-support systems have reached a magnitude unprecedented in human history [1]. On the one hand, pro-growth economic policies have encouraged rapid accumulation of consumption goods and technological innovations [2,3], and resulted in increased human prosperity in many parts of the world, although in a globally disproportionate manner. 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 have increasingly detrimental impacts on the wellbeing of present generations, in particular leading to a broadening ecological crisis and ever widening social disparities [4]. Concomitantly, these models present tremendous risks and challenges for future generations [5]. In response to these evolutions, the current debate on environmental sustainability has led to a growing consensus amongst policy makers and scientists of the need to adopt a strong sustainability ethics, which is characterized by the duty to preserve certain critical forms of natural capital, in order to preserve the capability of choice of present and future generations [5,6].

However, at the very moment that humanity is facing these major global sustainability crises, with wide-ranging impacts 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 guidance for governing the large-scale transformations needed to address the global sustainability challenges [7]. In this context, both Noble prize laureates, such as Elinor Ostrom [8] and Sir John Sulston [9], and high-level science officials [10] have stressed the need of an in depth transformation of the modes of organizing scientific research for governing the transition to sustainable societies.

To substantiate these claims, scientists 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 [11,12]. First, in dealing with sustainable development, there is a need for transformations in the core values and worldviews that drive individual actions and organizations. Science can contribute to such changes, but only if the challenges are addressed by the scientists in a collaborative, iterative and exploratory mode of organization of scientific research. Therefore, it is the responsibility of scientists to engage in new forms of collaboration with stakeholders and citizens, in the urgent search for understanding and supporting the implementation of feasible options for effective transitions to sustainable societies. Second, there is a need to remove practical and institutional barriers for the development of such goal-seeking, iterative and integrative approaches needed to address the issues of sustainability ([12], p. 201). This will require organizational changes in higher education institutions, but also institutional changes in funding and evaluation of science.

In response to the first need, sustainability scholars have developed a new field of research over the last two decades that combines a descriptive-analytical and a transformational mode of research for supporting the transition to sustainable societies [13]. These two modes are necessary research components of sustainability research [14]. The descriptive-analytical mode of sustainability research is based on an advanced form of complex system analysis, applied to dynamic coupled social-ecological systems (see for example [8,15]). The transformational mode, on the other hand, is oriented towards developing practical solutions for sustainability problems. As a result, sustainability science evolved both as an interdisciplinary and a transdisciplinary field of research: It is not only confronted with the challenge

of combining different disciplinary perspectives (interdisciplinarity), but also of incorporating analytic-descriptive knowledge from scientific expertise and actionable knowledge from extra-scientific stakeholder expertise (transdisciplinarity).

In response to the second—institutional—need, 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 at the level of networks for broader capacity building. Nevertheless, in spite of the wide recognition of the contribution of these 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 organization of the scientific research system. Indeed, serious obstacles arise from the lack of career incentives in interdisciplinary and transdisciplinary research in higher education institutions, the shortage of training opportunities in multi-method quantitative and qualitative case study research, and the dominance of mono-disciplinary peer review of research projects, of individual researchers and of higher education institutions themselves [16].

The limited growth of sustainability science 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 [17]. 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) [18]. The bibliometric 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 percent of these sustainability articles citing other articles from the social science journals and 10 percent 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.

To address the urgent need of capacity building for sustainability science, this paper proposes an incremental institutional change approach. Indeed, seen the existing epistemological and institutional barriers, the establishment of sustainability as a full-fledged research endeavor, on the same footing as for example non-oriented fundamental research or industry-oriented research, will require a gradual social learning and institutionalization process. To analyze the key components of this process, this paper reviews the broad literature on the organization of sustainability science that has emerged over the last decade, with the view to evaluate the contribution of on-going reforms to overcoming the main barriers for the further development of interdisciplinary and transdisciplinary sustainability science. The main lesson of this review is that strategic research for sustainability and reform of research funding mechanisms will only be effective if they are supported at the same time by capacity building for training and research at higher education institutions.

The paper is organized as follows. The first section reviews the major institutional barriers for the development of sustainability science. The second section proposes a framework to address these challenges through a process of gradual institutional change. The third section uses this framework to analyze the on-going reforms of the organization of research for sustainability research. The last section concludes.

2. Major Institutional Barriers for the Development of Sustainability Science

Scholars have identified a set of institutional hurdles to be overcome in establishing sustainability science as a major recognized scientific research practice on the same footing as other well-recognized modes of scientific research, such as non-oriented fundamental research or industry oriented research ([19], p. 12). The three barriers that received most attention are respectively: First, the lack of appropriate evaluation procedures for research funding [16]; second, the lack of training in key sustainability competences and effective pedagogical approaches for transdisciplinary research at higher education institutions [20,21] and, third, the deeper laying problem of lack of recognition and trust in these new modes of organization of research. This section briefly reviews each of these three barriers.

The first barrier highlighted in the literature is the existing evaluation procedure for research funding, which generally does not support the type of open, iterative and adaptive learning processes with stakeholders that characterize sustainability science [22]. 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. In other terms, sustainability science is "goal-searching" and not "goal-driven" [23].

In addition, as argued by Susanne Lohmann [24], procedures for reviewing manuscripts, grant applications, and applications for academic positions and promotions strongly favor specialization. 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. As a result, without major reform of review mechanisms, transdisciplinary and interdisciplinary research applications have a comparative disadvantage to regular mono-disciplinary submissions.

The second barrier is related to the lack of sustainability research and training capacities at higher education institutions. Considering the core characteristics of sustainability science, approaches are needed that are based on complex-system thinking and that promote experiential learning in multi-stakeholder interactions. In this context, scholars have identified two specific competences that are key to sustainability science, which are "strategic competences", mainly related to the ability to design and implement transformative process for moving towards sustainability in collaboration with stakeholders, and "normative competences", mainly related to the ability to collectively map and negotiate sustainability values, principles and goals [20]. These competences are not part of the requirements to be fulfilled in the usual science curriculum, while other important competences for sustainability science, such as complex-systems thinking and long-term future oriented scenario building, have only been integrated to a limited extent in academic training.

As shown by Amy Poteete and her co-workers ([25], p. 19), the requirements for training in sustainability science contrast with the existing supply of intensive mono-disciplinary 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 specialized 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 still find it difficult to gain adequate training in non-quantitative methods [26].

The most difficult barrier to be overcome at the level of higher education institutions however is the lack of appropriate mechanisms for building research partnerships with legitimate communities and stakeholder groups ([16], 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 lack of trust in the process can limit participation even when attendance is achieved [16]. These tensions between scientific and extra-scientific expertise may stem from the reality that academics have little experience of conducting participatory research. In addition, 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.

The third barrier, underlying several of the hurdles reviewed above, is the belief by many scientists, science policy makers and funders, that taking a program oriented, science relevant approach is going beyond the remit of science [27]. Indeed, sustainability scientists clearly not only analyze 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 active participants with a normative interest in sustainability issues ([12], p. 196). However, academic and other basic research institutions rarely give credit for this kind of transdisciplinary research effort envisioned by sustainability science.

3. Implementing Gradual Change through an Incremental Institutional Approach

Overcoming the institutional barriers for the development of sustainability science will require an in depth reform of the existing organization of scientific research. This situation of the emergence of an entire new modality of organization of research 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, based on the model of the Massachusetts Institute of Technology (MIT). At that time, by organizing applied and industry oriented research at the university, researchers added a new component to the existing missions of the university, until then centered around basic research (based on the model of the Humboldt University) and teaching (based on the model of the first European universities) [28]. The development of transdisciplinary research for sustainability, in direct partnership with stakeholders involved in social transformation processes, will equally require adding new departments and curricula

to the current organization of higher education institutions, along with a transformation of existing evaluation and incentive structures of research.

The envisioned reform process is needed to fill the gap between the current research practices and the requirements of fully developed trandisciplinary sustainability research. 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 [16,29]. The explicit goal of this interdisciplinary research field is to produce basic and applied research that can make a contribution to solving practical problems and assist societies in their transition to sustainability. Indeed, since its inception, sustainability science has evolved to become a solution oriented interdisciplinary research field inspired by successful initiatives of participatory research involving both scientific and extra-scientific expertise. More recently, sustainability science emerged at the center of a broad set of research and innovation activities relevant to society's effort to support an effective transition towards strong sustainability [14].

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 [14]. Such an interpretation, however, misses the close interrelationship between the transformational agenda and the need for innovative interdisciplinary approaches to analyze increasingly coupled human and natural systems, as can be seen for example in the need to rethink approaches both in political sciences, economics and psychology to address global sustainability issues [30,31]. Moreover, as highlighted in the report of the Monitoring Activities of Science in Society in Europe (MASIS) expert group on "Challenging Futures of Science in Society", prepared for the Directorate General Research of the European Commission [19], the combination of innovative theoretical research and a transformational perspective involving extra-scientific stakeholder expertise is not unusual in scientific research. Indeed, as stated in the report, the contrast between formal hypothetic-deductive scientific research on the one hand and socially relevant research on the other hand is not a contrast of principles ([19], p. 12). The contrast has more to do with the institutional division of labor 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 [32,33]. 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.

In this context, sustainability scientists have increasingly recognized the need to combine the interdisciplinary approach to coupled human/nature systems, integrating a plurality of legitimate perspectives coming from experts from distinct disciplinary backgrounds, with transdisciplinary approaches, which are based on the collaboration of scientific expertise and extra-scientific stakeholder expertise [7,34,35]. Some approaches within sustainability research, such as ecological economics [6,36–38] have already built an important body of transdisciplinary research and are increasingly influential in the academia and at policy level. More recent ones, such as models of transition management [39–43] or resilience thinking [44–46] are developing and gradually gaining in influence.

However, as also highlighted in current reviews of sustainability research, sustainability research programs integrate, with varying degrees of strength, the three dimensions of sustainability research, which are (1) the focus on transition towards sustainability, (2) an interdisciplinary approach of coupled human and natural systems and (3) transdisciplinarity research collaborations. For example,

some of the research programs, such as the transition approach to socio-technological change, are more oriented towards problem solving and organized 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 programs ([12], p. 187), which is a convenient way to capture this variability between the research programs. 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 mobilizing engineering knowledge that contributes to solving practical problems of sustainability. The second type, sustainability research, usually refers to the kind of fully developed interdisciplinary research programs envisioned in this paper. The focus of this second type is on enhancing our understanding of the interactions between economic, socio-technological and ecological systems within a strong sustainability ethics perspective. However, as argued above, such sustainability research programs, insofar as their aim is to fully contribute to transformative sustainability science, have to develop transdisciplinary collaboration with sustainability stakeholders for considering the plurality of ethical values and problem framings that play a role in the social context of their research.

The institutional challenges and barriers considered in this paper 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 organizing sustainability research do not consider the long-term institutionalization of sustainability research. The latter implies to address the issues of career rewards, graduate and post-graduate training, networking and long-term capacity building for multi-stakeholder partnerships amongst others. It seems therefore relevant to distinguish between full-fledged institutionalized research programs for sustainability and the other two types. The distinction between the three modalities for organizing sustainability research has been represented schematically in Figure 1.

Figure 1. Gradual change towards fully institutionalized sustainability research.

	Sustainability ethics	Inter-disciplinarity	Trans-disciplinarity	Key features	Key blockage points discussed in the text
Strategic research for sustainability	+	+	++	(A) Transdisciplinary problem solving with key sustainability stakeholders	Separation between the « descriptive-analytic » and « transformative » dimension of sustainability research.
Sustainability research programs	+/++	++/+++	++	(B) In combination with (A), systematically enhancing of our theoretical and practical knowledge of the interactions between economic, socio-technological and ecological systems within a strong sustainability ethics perspective	Lack of integration of strong sustainability prespective (both from ethics and in the combination between natural/social science research) in long-term research funding; lack of contribution of stakeholders expertise at the stage of project framing (ex-ante) and evaluation/translation of the results (ex-post).
Fully institutionalized sustainability research	+++	+++	+++	In combination with (A) and (B), institutionalized career rewards, graduate and post-graduate training, networking and long-term capacity building for multi-stakeholder partnerships.	Lack of recognition of transdisciplinary research in academic careers ; lack of training in combined ethical, social/natural science and transdisciplinary competences ; lack of organisational linkage/bridging between scientific and stakeholder expertise.
	+ (early stage) ; ++ (well developed); +++ (fully integrated)				

4. An Institutional Reform Program for Sustainability Science

Sustainability science will not be able to support the transition to strong sustainability in an effective way in the absence of long-term institutionalization of new modes of interdisciplinary and transdisciplinary research and education. To move in that direction, scholars recognize that it is crucial to reform the current evaluation procedure for research funding and to reform higher educational institutions. This section evaluates, in light of the main barriers reviewed above, to what extent such current efforts of reform can contribute to the long-term institutionalization process envisioned in this paper.

4.1. The Contributions of Reform in Funding and Evaluation of Research

The promotion of strategic research for sustainability clearly has contributed to the growing recognition of sustainability science. Yet, to further implement the transformational agenda of sustainability science, scholars and science policy officials highlight the need for new modes and mechanisms of research funding. In particular, these analysts consider that support, on a much broader scale, of long-term research projects based on cross-sector and multi-stakeholder collaborations is crucial to address sustainability issues in complex coupled human/nature systems.

In The Third Industrial Revolution, Jeremy Rifkin gives an example of such a major transdisciplinary research program which has led the city of Rome to adopt an innovative sustainability plan for the city's energy policy ([47], pp. 82–85). The program, coordinated by the school of architecture of the Sapienza University, engaged in multi-stakeholder research to explore an ambitious action plan for revitalizing housing in the city center, along with job creation, by analyzing an integrated set of tools. The core of the proposed toolkit included mechanisms for 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 collaboration between the local authorities in the district of Kashiwa city and the University of Tokyo [29]. This initiative, called the "Urban Reformation Program for the Revitalisation of a Bright Low Carbon Society", received five years funding from the national government. The overall aim of the program 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, 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 research 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 [13], community driven implementation of payment for ecosystem services schemes [48], and interdisciplinary assessment of synthetic biology contributions to sustainability [49], 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 paper, there is already an increasing call by scientists and policy makers for developing such long-term interdisciplinary and transdisciplinary research programs. 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. At the national level, some official recognition for sustainability research is also growing. In Germany, for instance, transdisciplinary research is officially considered to be the key to the energy transition process enacted by the Federal Parliament of Germany in the summer of 2011.

However, these research programs have rarely 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 ([50], 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 for five years, was a perfect candidate for transdisciplinary research, but in the project design and implementation, this aspect remained nearly totally absent.

The new level of awareness is therefore 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 ([51], p. 40). To avoid this pitfall, it is necessary to go beyond the conventional, purely descriptive-analytical organization of programmatic research and develop a set of mechanisms specifically designed for the kind of transformative and ethically informed sustainability research that is needed for strong sustainability. Based on the overview in his section, the following capacity building measures can be taken to integrate transdisciplinary sustainability research in programmatic research funding:

- Integration of requirements for transdisciplinary organization of research as a condition for access to programmatic research funding for sustainability research; in particular, project proposals should at least have a high score on each of the following three criteria: (1) broad interdisciplinary perspective combining natural and social science expertise; (2) explicit justification of the ethical choices regarding options for taking into account the limits of the Earths' resources and carrying

capacity; (3) collaboration with sustainability stakeholders in the framing and evaluation of the research program;

- Support for systematic exchange on methodologies and best practices for sustainability research between existing institutions involved in sustainability research; in particular, the supported institutions should at least show proven experience with transdisciplinary research collaborations;
- Synergy grants for consortia of institutions, with the view to building cross-institutional methodological competences on sustainability research; in particular such consortia should be based on the combination of ethical expertise, social and natural sciences and non-scientific stakeholder expertise;
- A fund for transformative sustainability research specifically financing research topics emanating from sustainability stakeholders (in a competitive selection of topics identified by these stakeholders); in particular, the aim of such a fund would be to involve sustainability stakeholders in the definition of the salient and socially relevant research questions to be addressed in sustainability research;
- Support for hybrid academic/non-academic competence centers for sustainability research; in particular competence centers should be a recognized reference for best available sustainability research methodologies from higher education and other research institutions, and methodologies developed by stakeholder organizations to produce actionable knowledge.

4.2. The Contribution of Reform at 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 institutionalization of a new scientific field. Beyond the reform of evaluation and research funding, this process encompasses the founding of new individual educational and career paths, the establishment of academic societies and associations, as well as scientific journals and textbooks [52]. 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 early 19th century signified the first major transformation of higher education institutions. During the 20th century, the capitalization 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 organization 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 [29].

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 these current missions of higher education institutions are clearly insufficient for implementing the type of multi-stakeholder collaborations required for solving complicated and interconnected sustainability issues in local and regional communities.

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) [53]. Since then, a number of national and international declarations relating to the integration of sustainability issues in higher education institutions have been developed [16,54]. 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 that explicitly put forward 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 [10]. 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 COPERNICUS Charter for Sustainable Development in 1994 and co-organized the COPERNICUS conference in preparation of 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, signed by major academic institutions throughout the world 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 developed for implementing sustainability research and training missions 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 [55]. 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 educational program is the interaction with stakeholders outside academia. For example, through the involvement of the Graduate School in the project on a "Bright Low-carbon Society" mentioned above, students from various graduate programs actively participate in the diverse social experiments of each research group of that project [55]. 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 organizations that do not necessarily share or understand academic terminologies and methodologies. 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 (such as reports and online working papers) and academic journals.

Hybrid academic/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 results in integrating sustainability issues into higher education through experiential learning, in depth case study methodologies and collaboration with external stakeholders. In addition, opportunities for intensive training in qualitative methods and in multi-method research have expanded over the past decade ([25], 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 [56,57]. Opportunities to develop more specialized 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 [58]. Leading figures of these transformations underline the importance of taking the following set of structural reform actions to further support these initial promising efforts [50,59]:

- 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 centers 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 center;
- The creation of "bridge" fellowships/professorships for transdisciplinary sustainability research, jointly engaged by higher education institutions and research institutions outside higher education institutions);
- The establishment of institutes for advanced studies in sustainability research.

4.3. The Contribution of Up-Scaling through Networking

As witnessed by the endorsement and signature of 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 ([12], p. 192). Except for some major initiatives discussed above, the currently existing communities and networks of sustainability scientists 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, the Resilience Alliance, which comprises scientists and practitioners who collaborate to explore the dynamics of socio-ecological systems and the Integrated Assessment Society 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, and rarely have a systematic connection to the reform processes in the higher education institutions.

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 ([29], 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, 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 organizes 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 ([12], 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 through the organization 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 state of 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 modelers; and a core sustainability transitions community" [60].

By developing extensive mobility and promoting transdisciplinary research in collaboration with stakeholders, research networks can 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 ([29], p. 108). However, the networks, as we argued above, will only live up to the high expectations of long-term transdisciplinary sustainability research if they can rely

on structural changes in funding of long-term research programs and a reform in the training and career paths at higher education institutions.

In this context, the pace of higher educations' movement towards sustainability is particularly influenced by the conventional university appraisal systems that do not seriously consider sustainability perspectives in their evaluation methodologies ([29], p. 104). Currently, higher education systems are under considerable pressure to perform on citation indexes and technology transfer statistics, which only give 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 [61].

To achieve a far-reaching impact, administrators and officials of the emerging research networks could design and implement sustainability assessments of higher education institutions in an integrated manner ([29], p. 104). Sustainability assessment systems of educational institutions usually evaluate issues such as the following: 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 [62]. 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 could provide a holistic assessment that encompasses the establishment of academic programs based on experiential learning, institutionalization of sustainability research communities and networks, and collaboration with external stakeholders involved in sustainability projects ([29], p. 104).

Based on the analysis of the role of the emerging research networks, the following capacity building measures can be taken for further up-scaling and integrating transdisciplinary sustainability research reforms at the level of higher education institutions:

- Supporting the creation of common transdisciplinary research infrastructures such as peer reviewed open access journals, prizes for sustainability research and annual conferences on transdisciplinary sustainability research;
- Promoting the joint submission of funded research projects at the regional, national and international level, amongst higher education institutions and research institutions outside higher education institutions;
- Strengthening the capacity to participate in international networks, by gathering and disseminating best practices and know-how;
- Creating regional or national panels, which 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;
- Establishing advisory bodies for the development of sustainability research at higher education institutions. Such a body can provide reports on international best practices, develop criteria for quality management of transdiscplinary sustainability research and organize sustainability assessment systems of educational institutions.

5. Conclusions

A wide range of scientific communities, international organizations and policy makers have documented the unprecedented sustainability crisis that humanity faces today. This crisis is most clearly visible through the global depletion and degradation of natural resources, but this degradation also has a strong impact on the social, environmental and economic wellbeing 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, although globally disproportionate, improvements in human wellbeing [63]. On the other hand, science is now called on to remedy the sustainability crises that are generated by this growth. In response, science policy officials and researchers at higher education institutions have started to promote new styles of scientific activity under the name of sustainability science.

To contribute to the further development of this new field of research, this paper assessed the three core requirements of transformative sustainability science in an integrated way, which are (1) an interdisciplinary approach to coupled human/nature systems, (2) an explicit integration of a strong sustainability ethics and (3) the development of extra-scientific transdisciplinary research collaborations. On this basis, the paper evaluated the contribution of current proposals for reform to the long-term establishment of sustainability science as a new mode of organization of research. Reform at the level of design and evaluation of research funding is a necessary condition to overcome the current bias—even in existing sustainability research programs—towards mono-disciplinary expertise and expert based "goal-driven" rather than collaborative "goal seeking" research. However, as shown by the analysis in this paper, this first level of reform is likely to have limited impact due to the lack in capacity at higher education institutions for accomplishing complex and time-consuming tasks related to the new modes of transdisciplinary and ethically informed research. While there are no simple solutions to this second challenge, it is both possible and necessary to, in a systematic manner, strengthen the exposure of scientists at higher education institutions to multiple methods and disciplines in training, workshops and roundtables, and to support interdisciplinary and transdisciplinary career paths. Finally, the institutional and structural arrangements that undermine trust amongst researchers by putting different disciplines and methods into competition for resources and status are more difficult to address. However, reversal of this lack of trust is not impossible, as can be seen by the current situation where the amount of transdisciplinary sustainability research varies across countries. The up-scaling of existing initiatives to reform through national and international networking can contribute to the building of trust amongst researchers and recognition for transdisciplinary research and thereby encourage coordinated efforts to alter institutional and structural arrangements more systematically and rapidly.

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Conflicts of Interest

The authors declare no conflicts of interest.

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