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SPECIAL FEATURE: ORIGINAL ARTICLE

Sustainability science: bridging the gap between science and society

From complex systems analysis to transformational change: a comparative appraisal of sustainability science projects

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Abstract Sustainability science is being developed in constructive tension between a descriptive–analytical and a transformational mode. The first is concerned with analyzing problems in coupled human–environment systems, whereas the second conducts research on practical solutions to those problems. Transformational sustainability research is confronted with the challenges of generating actionable knowledge, incorporating knowledge from outside academia, and dealing with different values and political interests. This study approaches the theory and promise of sustainability science through a comparative appraisal of five empirical sustainability science projects. We exemplarily appraise in how far sustainability science succeeds and fails in yielding solution options for sustainability problems based on an evaluative framework (that accounts for the particularities of sustainability science). The selected sustainability projects cover a range of topics (water, bioenergy, land use, solar energy, urban development), regions (from coastal to mountainous, from rural to urban areas, in several countries in Africa, Europe, and South and North America), spatial levels (from village to country levels), and research approaches. The comparative results indicate accomplishments regarding problem focus and basic transformational research methodology, but also highlight deficits regarding stakeholder participation, actionable results, and larger impacts. We conclude with suggestions on how to fully realize the potential of sustainability science as a solution-oriented endeavor, including advanced collaborative research settings, advances in transformational research methodologies, cross-case generalization, as well as reducing institutional barriers.

Keywords Transformational sustainability research · Evaluation · Actionable knowledge · Sustainability problems · Solution options · Impact

Introduction

About a decade ago, the field of sustainability science was launched (Kates et al. 2001), with significant ambivalence regarding its epistemology and methodology (Sarewitz et al. 2010; Wiek 2011). In one stream of its early reception, sustainability science has been conceptualized as an advanced form of complex systems analysis. Turner et al. (2003a) state in an article on sustainability science and vulnerability analysis: "The emergence of 'sustainability science' builds toward an understanding of the human–environment

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condition with the dual objectives of meeting the needs of society while sustaining the life support systems of the planet" (p. 8,074). The ultimate goal is a sustainable system dynamic (i.e., "meeting the needs of society while sustaining the life support system of the planet") or a "navigable" level of vulnerability to environmental hazards, respectively. The means to achieve this goal, an improved understanding of coupled human–environment systems, is through the application of advanced analytical–descriptive tools. What this systemic understanding entails is illustrated in the empirical applications of the proposed vulnerability framework (Turner et al. 2003b, p. 8,085): "These distinct coupled human–environment systems prove to be quite complex with regard to their vulnerability […] to environmental hazards, affected by social and biophysical processes and flows within and across the boundaries of the systems. In each case, external political and economic forces are reshaping regional and local environmental uses and coping capacities. Local stakeholders voice different concerns about these changes and are active agents responding differently based on their individual understanding and capacities." The authors conclude with respect to the link between systems knowledge (means) and sustainability (goal) (ibid., p. 8080): "The [vulnerability analysis] framework proves useful in directing attention to the interacting parts of the coupled system and helps identify gaps in information and understanding relevant to reducing vulnerability in the systems as a whole." It is important to recognize the critical assumption that improved understanding of the coupled human–environment system under consideration (including past and present social and biophysical processes, local environmental uses, external political and economic forces, stakeholder concerns and responses, etc.) will enable the reduction of vulnerability. This assumption, which can be reformulated as the supposition that a better understanding of the problem offers the solution to the problem, has been reiterated in conceptual contributions (e.g., Ostrom et al. 2007; Matson 2009), and is widely held in sustainability science projects (Blackstock and Carter 2007).

This descriptive–analytical or problem-focused mode has been broadened and countered with a solution-oriented approach to sustainability science. Clark and Dickson (2003) outlined a transformational agenda for sustainability science according to which "the research community needs to complement its historic role in identifying problems of sustainability with a greater willingness to join with the development and other communities to work on practical solutions to those problems" (p. 8,059).[1] This agenda suggests that "information […] relevant to reducing vulnerability in the systems as a whole" or to achieving sustainability needs to be broader than information on coupled human–environment systems or the structure of sustainability problems (Swart et al. 2004; Komiyama and Takeuchi 2006; Blackstock and Carter 2007; Sarewitz et al. 2010; Jerneck et al. 2011; Wiek et al. 2011). That means, the transformational mode suggests that sustainability science has to go beyond the questions of how coupled human–environment systems have evolved (past), are currently functioning (present), and might further develop (future). As a solution-oriented endeavor, sustainability science must address two additional streams of research questions: first, the normative question of how coupled human–environment systems would function and look like in compliance with a variety of value-laden goals and objectives, for instance, the balance between socio-economic needs and environmental capacities (Swart et al. 2004; Schultz et al. 2008); and, second, the strategic and operational questions that explore which transition pathways are viable for coupled human–environment systems and strategies that find what solutions to sustainability problems could be (Olsson et al. 2008; Loorbach 2010; Jerneck et al. 2011).[2] Clearly, sustainability scientists cannot solve complex sustainability problems on their own. The scientific and educational system constitutes one domain of society besides the economic, the policy and legal, the technological, and the socially and culturally ordered system, and all of them must contribute to transformations towards sustainability (Scholz 2011). In the transformational mode, scientists engage with a broad range of stakeholders from other domains of society, not only to improve the collective understanding of coupled systems (in particular, the human component), but also to develop joint and coordinated strategies for how to solve sustainability problems (van Kerkhoff and Lebel 2006). As Blackstock et al. (2007, p. 727) summarize: "The rationale for sustainability science reinforces the arguments for citizen and stakeholder social learning processes that should deliver increased understanding of complex systems, more durable and equitable solutions and increased capacity for active citizenship."

It is important to note that these additional streams of questions that demarcate the transformational from the descriptive–analytical mode of sustainability science are equally considered as *research* questions and not implementation tasks for persons outside of sustainability

[1] The concept of "solving sustainability problems" and "solutions for sustainability problems" does not follow a simple "command and control" approach, but is based on participation, coordination, iteration, and reflexivity (cf. van Kerkhoff and Lebel 2006).

[2] In the terminology of the vulnerability framework, the two proposed streams would entail: (1) research on what resilient human–environment systems (systems with manageable levels of vulnerability) would function and look like (visions or desirable future states); (2) research on what viable response options would transition the system from its current state to a resilient state.

science. Pertinent research questions include: What problem perceptions exist, do they conflict, and how can they be reconciled? What values and preferences are underlying (diverging) future visions? How can value-laden stances of future generations be included in visioning processes? What are effective and efficient transition pathways? What are generic institutional barriers and coping strategies in implementing transition strategies? Transformational sustainability research foresees a new role for scientists that has to be carefully reflected on; scientists no longer "only" analyze sustainability issues, but, rather, need to immerse themselves into decision processes that are embedded in societal transition processes and build socially robust knowledge—with necessary changes in research modes, incentive structures, and reward systems (Wiek 2007; Scholz 2011; Talwar et al. 2011; Lang et al. 2012).

Epistemological studies differentiate a spectrum of knowledge types required for sustainability transitions and solution strategies, including normative, anticipatory, and action-oriented knowledge (Grunwald 2004; Wiek 2007; Christen and Schmidt 2011). These somewhat "uncommon" knowledge types complement descriptive–analytical knowledge (description and analysis of past, current, and future states). They support sustainability decisions, actions, and transformations with direction (coherent visions and goals) and with operational structure (strategies and tactics for transformation). However, sustainability science seems to be still largely "trapped" in the safe space of descriptive–analytical knowledge production.[3] The reasons are obvious: first, there is the dominance of the descriptive–analytical paradigm in the evolution of scientific inquiry and institutionalization (Talwar et al. 2011); second, there is the lack of familiarity, training, and educational opportunities in transformational sustainability science, including issues of uncertainty, acknowledging the unknown, pluralism, dissent, conflict, and asymmetrical power relations in decision-making processes (van den Hove 2006; van Kerkhoff and Lebel 2006). Third, academic reward systems and career trajectories do not incentivize involvement in transformational research (Wiek 2007; Talwar et al. 2011). Thus, sustainability science is still characterized by the quest of how to move from complex systems thinking to transformational change.

This article outlines an analytical and evaluative framework specific to transformational sustainability science and presents several case studies on sustainability projects that aspire to comply with the criteria of transformational sustainability research. Considering the aforementioned inertia, our study pays special attention to the epistemological and methodological challenges which these transformational endeavors entail. However, there are other important aspects such as institutional and organizational structures that are critical for the success of transformational sustainability science, but that goes beyond the scope of this article. Complementary to the more top-down conceptual and theoretical contributions to sustainability science that have dominated the discourse in the last decade, our study addresses the theory of sustainability science from an empirically informed bottom-up perspective. It confronts theory with empirical projects by posing the question in how far we truly contribute to the solutions to sustainability problems, as opposed to "only" enhancing our understanding of these problems. Have we started to fulfill the claims and promises of transformational sustainability science? Did sustainability problems get solved through significant contributions from sustainability science efforts? Such a study provides a snapshot of the state-of-the-art in sustainability science and outlines future endeavors required to seize the full potential of sustainability science.

[3] There are several preceding scientific initiatives to leave the safe space of descriptive–analytical knowledge production and bridge science and practice, e.g., in transdisciplinary work, community-based participatory studies, action research projects, or scientific consultancy work (for a critical review and discussion of these, see Scholz 2011).

Project sample and analytical–evaluative research approach

The present study reviews a set of sustainability science projects and discusses in how far these projects transition from complex systems thinking to transformational change and, therefore, substantially contribute to sustainability problem solving. In short, we investigate in how far they fulfill (or do not fulfill) the promise of sustainability science (contribute to solving complex sustainability problems as theory and society demand) and what the challenges are in doing so.

We have chosen projects that have been identified as sustainability research projects, address a wide range of topics, capture different geographical locations, and employ diverse collaborative settings. According to the objective of this study, we have primarily selected projects that are developing (and testing) solution options as opposed to projects that develop decision support or social learning tools (Talwar et al. 2011). We deliberately selected projects which the authors are intimately familiar with, either through direct participation as investigators or through observation and evaluative studies. Obviously, this decision bears both advantages and disadvantages. Considering the nascent state of evaluative practice on sustainability science, we concluded that the advantage of detailed knowledge on processes and outcomes would outweigh the disadvantage of being biased towards our own studies (shedding a more favorable light on them). We also mitigated this type of bias through a collective critical reflection across all the case studies (see the "Discussion" section later).

Our study relies on previous evaluative studies on sustainability science projects (Kasemir et al. 2003; Blackstock and Carter 2007; Brundiers and Wiek 2011; Clark et al. 2011; Robinson et al. 2011; Talwar et al. 2011). However, we pursue our overall objective through the specific lenses of epistemology (what knowledge is being generated) and methodology (how is this knowledge being generated). As with most other academic pursuits, the credibility of sustainability science depends upon conducting empirical research using sound epistemological and methodological foundations. However, sustainability science underwrites a richer agenda of research and, therefore, needs to comply with a wider array of quality criteria (e.g., salience and legitimacy; Cash et al. 2003). Thus, we refer to sustainability-related studies from various strands of research in order to derive analytical categories and evaluative guidelines.

The following framework was employed to analyze the epistemological and methodological components of the sustainability science projects, as well as to evaluate and compare their strengths and weaknesses. For each sustainability science project, we analyze, evaluate, and provide recommendations for the problem/subject addressed, the method/process employed, and the results/impacts generated. Guiding questions are:

1. Basic project information:

   The topic, collaborating partners, duration, and any other key features.

2. Project analysis:

   a. Problem/subject: What sustainability problem was addressed in the project? And what was the explicit project goal (aspired outcomes)?
   b. Method/process: What sustainability research methodology was employed and what methods were applied? Who was involved in the research process, by whom, when, and how (participatory process) (Stauffacher et al. 2008; Krütli et al. 2010)?
   c. Results/impacts: What were the stated results? What type of knowledge was generated (analytical/descriptive, anticipatory, normative, strategic/action-oriented knowledge)? What positive impacts in the "real world" resulted from this project?

3. Project appraisal:

   a. Problem/subject: Sustainability science is widely recognized as a problem-driven endeavor concerned with the most pressing challenges which our societies face (Kates et al. 2001; Clark and Dickson 2003). The literature suggests that these so-called "wicked" problems have specific features, namely, they are life-threatening and urgent, have long-term impacts, are highly complex (systemic), and cannot be solved by simple remedies (Funtowicz and Ravetz 1993; Dovers 1996; Wiek 2011). As sustainability problems are "real-world" problems, stakeholders must express an interest in understanding the problem and exploring solution options (Cash et al. 2003; Clark and Dickson 2003; Jerneck et al. 2011). Moreover, stakeholders' willingness to adopt and implement solutions increases when they have a strong ownership of the problem (van den Hove 2006; van Kerkhoff and Lebel 2006; Clark et al. 2011). Thus, the evaluative questions are: Was the problem/subject addressed in this project a sustainability problem, i.e., did it feature the characteristics of a sustainability problem? Was the goal of the project to develop a solution for the problem? Did stakeholders express a legitimate interest in solving this problem?
   b. Method/process: There are several requirements suggested in the sustainability science literature with respect to methodology and process. First, the applied methods must be appropriate for addressing the key features of sustainability problems (e.g., a systemic analysis method is needed for addressing the systemic nature of the problem), and they must generate knowledge that is sufficient for solving the problem (e.g., a sustainability assessment method is needed to provide direction for the solution strategy) (Schultz et al. 2008; Jerneck et al. 2011; Wiek 2011). Second, sustainability science projects must engage in processes of co-production, in which scientists and stakeholders interact from problem framing to strategy implementation and problem transformation (Kates et al. 2001; Kasemir et al. 2003; Scholz et al. 2006, Scholz 2011). Thereby, consultative or extractive forms of stakeholder engagement tend to fail and are not sufficient in coping with sustainability challenges (van Kerkhoff and Lebel 2006; Clark et al. 2011). Thus, the evaluative questions are: Did the research framework and methods allow comprehensively addressing the sustainability problem and producing different types of knowledge sufficient to create "real-world" solutions? Was the research process participatory throughout the project, and were stakeholders engaged in interactive (non-extractive) collaboration with transparently balancing inputs and facilitating knowledge claims?
   c. Results/impacts: Sustainability science projects are not only problem-driven but solution-oriented

(Clark and Dickson 2003). In many cases, "real-world" changes and transformation cannot be accomplished through a research project alone, as inertia and resistance can be overwhelmingly strong and undermine real progress beyond the capacity of the project (Blackstock and Carter 2007; Talwar et al. 2011; Lang et al. 2012). However, as a minimum requirement, sustainability science projects ought to yield results that would be sufficient for solving sustainability problems (provide all the knowledge necessary), even if the actual implementation of the solution is being delayed or dismissed. Thus, the evaluative questions are: Were the generated results (types of knowledge) sufficient for significantly contributing to solving the sustainability problem? Was the addressed problem solved and what was the contribution of this project?

4. Recommendations:

   What would be improvements of the project regarding the problem/subject addressed, method/process applied, or results/impacts generated in order to better comply with the evaluative guidelines described above?

The evaluative and comparative study presented below does not apply a formal and comprehensive evaluation method. Considering the nascent state of such studies, case study appraisals and expert discussions yielded the results presented here.

Review of sustainability science projects

The following review first presents the descriptive and evaluative profiles of five projects, followed by a comparison of similarities and differences.

Methods and Tools for Integrated Sustainability Assessment (MATISSE): water sustainability in the Ebro River Basin, Spain (WP6)

Basic information

MATISSE (http://www.matisse-project.net/) was a project in the EU's 6th Framework Programme; it ran for 3 years (2005–2008). The project's overall aims were to achieve step-wise advances in the science and application of Integrated Sustainability Assessment (ISA) of EU policies, focusing specifically on how to create better assessment processes. The project's 6th work package (WP6) focused on the water domain and comprised six university centers or institutes around Europe, including Autonomous University of Barcelona, Lund University, Maastricht University, University of East Anglia, and Norwich University.

Project analysis

WP6's region of focus was on the water domain (quantity and quality) in the Ebro River Basin in northern Spain. Research efforts concentrated on the socio-economic challenges from increased water demand in conjunction with enhanced levels of water pollution over the past century, pressures created largely from increased agricultural production, and industrial and domestic activities in the basin region. In addition, reduced river sediment loads, land use change, and climate change were all environmental challenges considered (Valkering et al. 2008). The WP's objective was to develop and apply new policy-relevant tools and methods for ISA—particularly, strategic policy processes and longer-term transition management related to common pool resources (CPRs). The project focused on creating a process to transition from the current water management practices towards more sustainable-oriented practices by identifying who possesses agency and responsibility for resolutions in the basin, and how other stakeholders can be empowered.

Participants in the tool design included both engineers, who were responsible for tool development, key stakeholders (e.g., CPR users) located within the river basin, and participatory facilitators. Two stakeholder meetings were conducted during the tool development process in 2007 and 2008 in order to: (1) develop and (2) test the functionality and applicability of the tool. No specific design methodology was followed in the development of the gaming tool.

The result of the project was a participatory agent-based social simulation (participatory ABSS) model. The tool was based on linking several approaches—both analytical–descriptive and solution-oriented. The tool fused system dynamics modeling and GIS (e.g., hydrological, land-use modeling) to capture nature system causalities to both understand and support collective decision-making processes and social learning. In addition, agent-based modeling augmented by cultural theory typologies was used to develop a variety of consistent explorations of the model (Pahl-Wostl and Hare 2004). A completed tool, in the form of a fully functioning participatory ABSS model, however, came after the completion of the project and was never tested with stakeholders. The aforementioned tests indicated that stakeholders were positive to initial model prototypes, and that the initial phases of the game worked well amongst stakeholders where they were actively involved in coalition forming and policy design. Other impressions of the stakeholder processes indicated that game players were cooperative but resistant to altering their fundamental views (Valkering et al. 2008). In addition, experts with different academic backgrounds realized that the transdisciplinary work to integrate social and natural systems requires a common language for communication and cooperation in the development of the participatory tools, such as ABSS.

Project evaluation

The Ebro River Basin work did focus on sustainability problems in as far as the problems are life-threatening and urgent (e.g., global climate change), have long-term impacts (e.g., regional land use change), are highly complex (e.g., river water quantity and quality, sediment flows), and cannot be solved by simple remedies (e.g., trade-offs involved in integrated water management decision making). It is difficult to determine, however, if stakeholders were serious about solving the problems addressed. This was likely due to the limited number of stakeholder meetings and the inability to adequately develop problem ownership with the different sustainability challenges in the basin.

The first evaluative question about the appropriateness of the methodological approach is negligible. The project's goal was not to directly develop solution options for the identified sustainability problems. The explicit goal was to create a tool that can assist in developing solution options (see evaluation of the results below). The secondary goal was to gain additional insights into participatory processes themselves, which could be used in the development of other participatory gaming tools. However, the second evaluative question is relevant in this case, as it links the ownership with the results and the willingness to implement the results, to both develop and use the gaming tool. Stakeholders were involved in an interactive process for the development of the tool, but not from the very start of the work package. The stakeholder's diverse viewpoints were incorporated into the tool development process. Again, because of the limited number of meetings that took place, the stakeholder collaboration was not sufficient in balancing inputs and actually facilitating knowledge claims. Additional collaborative occasions for stakeholders would have been needed. Finally, the lack of an explicit design methodology left valuable existing methodological knowledge from decision support system design and operations research untapped.

The work package did not yield results sufficient for solving water-related sustainability problems in the Ebro River Basin. Knowledge deficiencies still existed with practical tool development aspects, such as to how integrate natural and social system parameters, as well as group facilitation. Dialog challenges, for example, stakeholders did not come to a common agreement about the actual (water) problem challenges in the basin, was another knowledge deficiency. Even more importantly, the ABSS simulation model does not provide a structured approach on to how to develop goal-oriented and actionable knowledge. As a simulation model, it is confined to (advanced) descriptive–analytical knowledge generation, but neglects the critical knowledge domains on what a sustainable Ebro River Basin would look like (in general), and how to realize the transition from the current state to this desirable state. The water sustainability problems in the Ebro River Basin have not yet been solved. Valuable insights were gained at a more general level with issues of trust-building amongst stakeholders and the time needed for both tool development and participatory processes, lessons which could be applied to solving the water sustainability problems in the region. The limited number of meetings (two) did reveal for stakeholders that the Ebro River Basin challenges were not necessarily centered on water itself, but, rather, on the institutional (power) structures on how water is governed in the region.

Recommendations

The stakeholders that participated in the initial meetings (problem framing and goal formation) represented only a small fraction of actual resource users. It is recommended that ways be explored to effectively involve the main players in the region regarding water use and to "scale up" such landscape-level solution-oriented processes into decision-making processes at higher levels (e.g., national, EU).

Another obvious recommendation is the more timely delivery of a functioning gaming tool. This would have enabled the insights into both methodological components and actual transformational change regarding the water sustainability challenges to be addressed. One can also speculate that, with additional stakeholder meetings, in conjunction with a fully functioning participatory ABSS tool, the trust and willingness to come to common solutions among participants would have increased.

Competence Platform on Energy Crop and Agroforestry Systems for Arid and Semi-arid Ecosystems—Africa (COMPETE)

Basic information

The objective of COMPETE (http://www.compete-bioafrica.net) was to identify pathways for the sustainable provision of bioenergy in Africa, specifically, in Botswana, Burkina Faso, Kenya, Mali, Senegal, South Africa, Tanzania, and Zambia. The project established a platform for policy dialogue and capacity building. The project was funded through the EU's 6th Framework Programme and ran for 3 years (2007–2009). It involved 44 partners, including scientists, practitioners, companies, and policy makers from Europe, Africa, Brazil, India, and Mexico.

Project analysis

The project addressed the interrelated problems of limited access to energy sources, low level of quality of life, and lack of livelihood opportunities in rural areas in Africa. These issues lead to a degradation of arid and semi-arid ecosystems caused by unsustainable land-use practices. Although significant areas of potentially productive land can be identified, hunger, limited food access, and a general lack of development hinder the productive use of this land. Subsistence farming dominates the agricultural sector, which is characterized by very low investments, degradation of land, and armed conflicts. The project goal was to address this problem through research into potential development pathways for bioenergy. Bioenergy systems offer opportunities for investment and infrastructure improvements in agriculture with the promise to diversify agricultural production, stimulate socio-economic development, and provide sustainable energy for local needs (fuel, electricity, heating). However, even though studies show a significant potential for bioenergy development (e.g., Smeets et al. 2007), concerns exist that bioenergy (biofuels) expansion may have negative impacts on biodiversity and natural resources through increasing competition over land and water resources. The project's goal was, therefore, to develop bioenergy as a solution option, in a way that is not detrimental for the environment. The results were intended to directly inform and support decision and policy making in African countries.

The project applied a set of methods, combining participatory GIS-based land mapping, socio-economic impact analysis, qualitative sustainability impact appraisal, and policy design. GIS-based land mapping identified suitable land where well-managed intensification of, or conversion to, bioenergy feedstock would have a low risk of causing detrimental effects (Watson and Diaz-Chavez 2011). Excluded from this potentially suitable land stock were all areas important for biodiversity, carbon stocks, environmental services, food security, rural livelihoods, and all protected areas. Land mapping techniques involved GIS (GLC database, FAOSTAT), aerial photography, field verification, literature review, and stakeholder participation. Following this mapping, the technical and economic potential of the identified land was spatially explicitly assessed based on land availability, yield maps, and production cost calculations (Wicke et al. 2011). GIS mapping and potential analysis was done in all eight countries, including Botswana, Burkina Faso, Kenya, Mali, Senegal, South Africa, Tanzania, and Zambia. An in-depth socio-economic impact analysis (economic feasibility and quality of life) was performed for an exemplary biofuel project in Tanzania to explore criteria relevant to "socially responsible" investors who plan to launch a bioenergy project in Sub-Saharan Africa (not pre- and post-impact assessment) (Portale 2010). Broader guidelines were then developed for the sustainability impact appraisal and tested through application to five bioenergy projects in Tanzania and Zambia (Diaz-Chavez 2011). The appraisal was based on a set of environmental, economic, social, and institutional criteria (e.g., Millennium Development Goals, fulfillment of energy needs, detrimental impacts on ecosystems, additional income for rural populations). The potential impacts were considered in specific contexts and how they relate to national or international issues (Buchholz and da Silva 2010). Policy design methodology was applied in the majority of the countries in order to develop policies that would support favorably appraised bioenergy initiatives and projects, mechanisms for monitoring and assessing sustainability, and/or establish reward structures for good practices. Participatory research settings were applied at different stages of the project in order to ensure the incorporation of traditional knowledge on land use practices and deliberation among stakeholder perspectives (e.g., state departments involved in bioenergy, grassroots stakeholders, farmers' associations, investors, companies, experts).

The project produced knowledge in different formats on current land use and land use changes, potentials for bioenergy technologies, improved agricultural practices, sustainability assessment framework, and good practice guidelines specific to the respective national and regional context. The mapping and impact assessment identified areas and technologies for bioenergy production that would generate energy for local needs and create livelihood opportunities, while avoiding land degradation and food–fuel conflicts (ensure food security). Good practice guidelines were produced to assist a balanced assessment of bioenergy projects regarding sustainability. A "Declaration on Sustainable Bioenergy for Africa" was developed in cooperation with high-level decision makers from Kenya, Mozambique, Tanzania, Uganda, and Zambia, identifying visions for bioenergy development in Africa, favorable market creation, land use strategies, and initiatives for capacity building (COMPETE Declaration on Sustainable Bioenergy for Africa 2008). The Declaration continues to inform the policy formulation process at national levels (Mozambique, Tanzania, and Mali) and regional levels (SADC Bioenergy Policy Tool), as well as providing inputs to the broader international discussion

(Roundtable on Sustainable Biofuels [RSB]). The Government of Mozambique has implemented land-use strategies such as agro-ecological zoning, recommended in the Declaration. The impact assessment tool, investor guidelines for land tenure, and customary land tenure systems have been recognized in the issued "Guidelines for Sustainable Liquid Biofuels Development in Tanzania" (United Republic of Tanzania, Ministry of Energy and Minerals 2010).

Project evaluation

The problem addressed in this project is a sustainability problem, featuring life-threatening and urgent issues (violent conflicts, lack of fulfillment of basic needs, tipping points of arid and semi-arid ecosystems in Africa), have long-term impacts (e.g., land degradation), are highly complex (interrelated social, economic, environmental drivers and effects), and cannot be solved by simple remedies (bioenergy is considered to be a complex socio-technical solution option). The goal of the project was to address the problem from a particular solution perspective, namely, the potential of bioenergy; alternative solution options were not considered or investigated. The project did involve different stakeholders but not in the early stage of problem framing. While we assume a legitimate interest in addressing this problem, stakeholder confirmation was lacking regarding the problem and the solution option (bioenergy).

The project applied methods that allowed addressing the problem in its complexity, yet, from a particular solution perspective (bioenergy). The project did employ a methodology that allowed creating different types of knowledge about the current state (mapping), potential future pathways (land-use options and technical–economic potentials), normative orientation (impact appraisal based on sustainability principles and criteria), and action-oriented guidelines (policy design) sufficient to create real-world solutions. There were some moderate flaws in the methodology taking into account the current state-of-the-art in future pathway analysis (advanced scenario and visioning methodology), impact assessment (pre- and post-impact assessment design; advanced systemic sustainability assessment methodology), and policy design (advanced intervention and transition research methodology). One major flaw was that the outlined methodology was not applied in all participating countries, which led, in some cases, to policy recommendations that were insufficiently supported by empirical evidence. A major flaw of the methodology was the lack of planning for comparisons, synthesis, and integration, which negatively impacted the generalizability of the project results. The project involved different stakeholders but not throughout the project (e.g., not in the framing stage). There was a lack of interactive participatory research, as the mode and level of participation was limited to rather consultative forms (interviews, round-tables, field visits). However, the participatory setting seems to have built capacity for policy formulation and introduced "the African perspective" into the international biofuels debate.

Solution options for the problem addressed were developed along the bioenergy trajectory. The knowledge generated—from the mapped current state to the assessed bioenergy options and guidelines—provides the knowledge sufficient for a strong contribution to solving the problem. Yet, the lack of follow-through in the application of the methodological framework in all countries and the lack of comparison and synthesis across the countries undermines the solution potential. Finally, the broad focus on Africa and the imposed technological focus on a bioenergy solution option limited the potential for comprehensively mitigating the problem. Several other strategies are necessary for this, such as improved agricultural practices that reduce area requirements for food production, rural development, and adaptation strategies. The problem still persists, and despite the implementation of the project, the results are still underway. In those countries where policies have been formulated, the implementation of a legislative and regulatory framework is lagging behind.

Recommendations

Potential improvement of the project's problem and goal definition pertains to explicitly limiting the scope of the project to particular regions and to coordinate the project with other solution-oriented research in order to develop complementary solution strategies (beyond bioenergy). Methodological improvements would be: first, the impact appraisal would benefit from a direct link to the mapping activities (systematic and criteria-based selection of areas for pilot projects and impact appraisal); second, the methodology would benefit from the adoption of rigorous approaches, for example, advanced sustainability assessment methodology and comparative exploration of alternative solution options; third, the methodology should have been standardized across the participating teams and countries as to following the same basic protocol (coaches for methodology could have supported this process). This would allow not only to develop evidence-based policy recommendation for all countries, but also to synthesize insights across the countries. Improvement of the participatory process would require engaging stakeholders and decision makers throughout all stages of the research project and in the implementation phase.

Sustainable Land-Use Practices and Adaptation to Global Change in Alpine Regions in Switzerland (MOUNTLAND)

Basic information

The project (http://www.cces.ethz.ch/projects/sulu/MOUNTLAND) deals with challenges of global change and its impacts on three mountain areas of Switzerland, specifically, in the Jura Mountains (Jura Vaudois), Visp region (Upper Valais), and Davos (Grisons). It is an interdisciplinary project that includes more than 40 scientists from a diverse spectrum of Swiss research institutions and scientific disciplines, e.g., the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), the Swiss Federal Institute of Technology (ETH) Zurich, and the École Polytechnique Fédéral de Lausanne (EPFL), and is financed by the Competence Center Environment and Sustainability (CCES) for 4 years (2008–2012).

Project analysis

The project anticipates the challenges that climate change brings to Swiss alpine regions up to the period 2050–2100. Challenges included declining weather conditions in snow-secure areas, the melting of glaciers and permafrost, increased natural hazards (rock-fall and landslides), and changes in forest species abundance. Climate change may have a large impact on future economic welfare, job opportunities, and overall well-being, as many of these regions are heavily dependent on winter tourism (Agrawala 2007). The goals of the project are: (1) to provide new scientific knowledge on the impacts of climate and land-use changes on ecosystem processes in three sensitive mountain regions of Switzerland; (2) an assessment of the feedback effects from changing socio-economic and political conditions to land use and adaptation to climate change using modeling techniques and stakeholder interactions; and (3) development of adapted land-use practices and innovative policy solutions in mountain regions that are ecologically effective, economically efficient, and socially feasible.

With an emphasis on forestry and agriculture, the project employed methods from both the natural and the social sciences, e.g., ecological experiments and observations, modeling techniques, formative scenario analysis, interviews, and political network analysis (Rigling et al. 2007). Stakeholder involvement in the project ranges from information (e.g., public presentations, newspaper articles, and radio programs) to consultation (e.g., stakeholder steering group meetings), and, to a lesser degree, to collaboration (e.g., workshops). Stakeholders from different sectors including forestry, tourism, nature conservation, and administration have been involved in the research process. As the project is still ongoing, further stakeholder engagement activities are currently being planned. A 1-year period of synthesis including a final stakeholder synthesis event is in planning.

The project's results cover: (1) analytical knowledge, e.g., socio-economic and ecological models (e.g., Rigling et al. 2010); (2) anticipatory knowledge, e.g., land-use scenarios (Walz et al. 2012); (3) normative knowledge, e.g., a list of sustainability criteria for the study regions; and (4) strategic knowledge, e.g., a strategy for strengthening regional cohesion (Hirschi 2010). A synthesis that would link the different results is being planned for the final year of the project. The results are being disseminated in various formats: 8 scientific articles, 22 doctoral, master, and diploma theses, 33 contributions to scientific conferences and workshops, 10 organized scientific conferences or workshops, 15 publications for stakeholders, 15 press and media articles, 13 courses and seminars for stakeholders, 10 public information events, and 6 activities at schools (Huber 2011). The societal effects of this project are yet to be determined (however, it is not planned to conduct a study on the effects due to a lack of funding).

Project evaluation

Global change is a good example of a wicked sustainability problem, as climate change has long-term, serious, and largely unforeseeable impacts on mountain regions, increased frequency of landslides and rock-fall, and on winter tourism (Agrawala 2007). Solution strategies require the integration of values and knowledge of different stakeholders and scientific disciplines, and there is high uncertainty, ignorance, and no blueprinted solution. Compared to other challenges however, life-threatening status, urgency, and interest among the people are only moderate in the study regions, indicating that the perspective of stakeholders has only partly been taken into account.

Research methods and generated knowledge types in the project have been sufficient to comprehensively address the issue and to develop solutions. When it comes to the normative knowledge, effort has been directed to building upon their own sustainability conception, largely based on a review of important political documents and expert opinions. This is a deficit, as there are already many established sustainability conceptions within scientific discourse that could have been customized to the purposes of this project. Stakeholder engagement has been, at times, collaborative and interactive. Nonetheless, stakeholder involvement should have started much earlier in the research process and could have been more intensive, interactive, and collaborative, really focusing on sustainability problems relevant to the stakeholders in the regions and to initiate strategic knowledge on how to effectively adapt to expected climate change.

The project has already yielded results that can contribute to solving the sustainability problems in the study regions (actionable knowledge). The rather low intensity of stakeholder engagement of the project makes it questionable as to whether the results will be used to initiate and establish transitions towards sustainable mountain regions. The mode of research has, rather, been extractive as to provide knowledge that may or may not be used by decision makers in the region. Global change is a large-scale problem that clearly exceeds the scope and opportunities of this project. The project is in the process of providing insights into how regions can better cope with future changes. One might argue that the focus on adaptation strategies neglects the fact that Switzerland is (along with many other states) a contributor to climate change, with an emission profile that exceeds the allocated volumes (den Elzen et al. 2011). A stronger complementary approach to mitigation strategies seems to be appropriate. The evaluation of the real-world impacts from the generated results cannot be completed at this stage, as the project is ongoing.

Recommendations

The project would have profited from employing a genuine transdisciplinary setting (Scholz 2011; Lang et al. 2012). That means that the project would start from the case (problem) and include legitimized decision makers and the public at large from the very beginning and on equal footing to jointly define and represent problems that matter to the people in the regions. Subsequently, it is about creating a pre-politicized, pre-competitive, transition arena over the entire research process. This would imply to engage stakeholders in different mutual learning processes, from information and consultation to collaboration and empowerment (Wiek 2007; Stauffacher et al. 2008; Krütli et al. 2010; Lang et al. 2012). This would enable capacity and consensus building, mediation processes, and the emergence of socially robust knowledge and orientations for transitions to sustainability (Scholz 2011).

The project would benefit from an intensified discourse about the best sustainability conceptions that the scientific literature can offer to counteract the confusion about and the arbitrariness in the meaning of "sustainability" (Schultz et al. 2008). Similar to the IPCC scenarios, which are often used as an established basis and then customized to the specific purposes (e.g., adapted to the national level), sustainability research could benefit from a pool of established sustainability concepts that scholars can customize to the specific purposes of their project.

Another improvement would be to assess the societal effects of the project, for example, changes in the knowledge, network building, trust in others, and the decision-making capacity, by means of surveys and interviews at several steps of the project (Walter et al. 2007).

Energy sustainable community in San Juan, Argentina

Basic information

The objective of the project was to develop and implement a socio-technical strategy to establish solar energy systems in a rural village in the province of San Juan in western Argentina (Parodi et al. 2000).[4] The project was situated as part of a larger program on "Autonomous Power Supplies and Mini-Grids—Rural Electrification and Water Supply" with projects in different rural areas worldwide, carried out by the Fraunhofer Institute for Solar Energy Systems in Freiburg, Germany.[5] The project was initialized in 1992 by members of the University of San Juan and later joined by the Instituto National de Agropecuaria and the Direction de Recursos Energeticos of San Juan's provincial government. Research took place in 1993–1995, as well as in 1998 and 2005 (evaluations). The project was, in part, funded through the ELDORADO program by the German Ministry of Research (1993–1994), the German Academic Exchange Service (DAAD) (1993–1995), and several in-kind services provided by the collaborating organizations.

Project analysis

The project addressed the problem of limited and inequitable access to energy sources, lack of quality of life, and resulting migration from rural to urban areas in San Juan in general and the selected village in particular. In 1993, the village had 65 inhabitants living in 14 households, generating livelihood through small-scale farming and cattle husbandry. The village had a diesel-driven water pump and used small kerosene and diesel lamps for lighting. Dry cell and car batteries supplied radios and TVs. The village was accessible by vehicle via one main connection road that was not passable all year (rainfalls). Only one car was available in the village. The distance to the next village is 20 km, to San Juan City 180 km, and to the next electricity grid connection point 120 km. The project goal was to address the problem of grid isolation through decentralized solar energy systems for electrical devices. Criteria for the energy system were fair distribution of energy services, long-term functionality with low maintenance efforts, and

[4] The selected village remains unnamed in this case study in order to protect the villagers from unsolicited contacts and impacts.

[5] See http://www.ise.fraunhofer.de/areas-of-business-and-market-areas/renewable-power-supply/autonomous-power-supplies-and-mini-grids/rural-electrification-and-water-supply/rural-electrification-and-water-supply?set_language=en&cl=en

minimum environmental impact (recycling, etc.). An additional goal was to offer development aid that empowered the beneficiaries (villagers) and allowed them to operate and maintain the energy systems independently and further developed the village sustainably. While the immediate goal of the project was to generate knowledge to establish small-scale solar energy systems in the selected village, the ultimate goal was to generate knowledge to support the transfer and upscaling of the solutions to other rural communities.

The project was structured in three phases (Parodi et al. 2000). First, in the formulation phase (1992–1993), the project team was built, the village was selected, first site visits were conducted, and the research objective and design were formulated and negotiated with the villagers. Second, in the realization phase (1994–1995), villagers' needs were elicited and analyzed, plans were produced and revised, a prototype was generated, a first demonstration solar home system was installed, a contract of utilization was formulated and negotiated, the solar systems were installed, and finally, maintenance training was provided. Third, in the evaluation phase, success and failure of the project was assessed in 1998 and 2005, recommendations were made, and adaptations executed. The research design combined methods from engineering, e.g., laboratory and field tests of solar home systems; system design, e.g., sizing of PV modules and batteries, feedback and security systems; business studies, e.g., calculations of gains/costs and payment schedules; and social sciences, e.g., interviews on how people differently valued the solar systems, anticipation of social impacts, and documentation of behavioral changes (Parodi et al. 1998, 2000). The project employed a participatory research approach and the researchers collaborated with the villagers from the beginning, conducting workshops, discussion rounds, interviews, and training units. Beyond the local level, all technical components were supplied by industries in Argentina and the federal government was informed about the project. The collaboration continued after realization, e.g., the researchers from the University of San Juan helped with the exchanging of the batteries in 2003. The participatory process was supported by a social scientist, who facilitated collaboration among researchers and villagers. The local impacts of the project were evaluated in 1998 (3 years after the realization) and in 2005 (10 years after) (Parodi et al. 1998; Schweizer-Ries et al. 2007).

The project successfully installed 14 solar home systems and a PV water pumping system, which are owned by the villagers. According to the evaluations, the systems work consistently and only minor defects have been observed (and repaired). The consistent solar power supply has changed life in the village, including: need perceptions, sleeping and working patterns, more outside visitors, less use of dry cells, no wild dumping of dry cells, extended irrigated gardens, built technical competence and literacy, enhanced self-esteem, increased happiness, brighter perceptions of the village's future, full retention of residents in the village, no intentions of moving away, and increased level of community activities (Parodi et al. 1998; Schweizer-Ries et al. 2007). General insights were gained on how to successfully conduct this type of participatory research (reflections and evaluations). The project has generated a blueprint of small-scale solar energy systems for the provision of energy (Parodi et al. 2000). Various scientific publications and academic theses resulted from this project. On the policy level, it was recognized that such solar systems could enable solar electrification of remote villages throughout Argentina. The prototype created in the realization phase of the project was visited by the Argentinean President at the time, Carlos Saúl Menem, and was used as a reference case for a Word Bank project (Covarrubias and Reiche 2000).

Project evaluation

The project addressed a sustainability problem featuring adverse long-term impacts (e.g., loss of cultural knowledge and identity and negative effects of urban growth), displays a high degree of harm and urgency (e.g., negative effects of large-scale non-renewable energy use and continuous urban growth), is highly complex (interrelated social, economic, and environmental drivers and effects of migration), and cannot be solved by simple remedies (complex socio-technical solution options). The goal of the project was to address the problem from a particular solution perspective (solar energy systems); alternative solution options were not considered or investigated. The project involved stakeholders from the beginning and stakeholders expressed a legitimate interest in solving this problem.

The project applied methods that allowed addressing the problem to some extent (not all facets of the problem were considered in the problem framing), yet, from a particular solution perspective (solar energy systems). The project employed a methodology that allowed creating different types of knowledge about the current state (e.g., energy needs, social structures, development stage, migration patterns), normative orientation (functionality and impact assessment of the solar systems), and action-oriented guidelines (systems design and implementation model) sufficient to create the solution options aspired. However, there was no future-oriented methodology (scenario construction) employed that allowed anticipating unintended consequences when transferring or upscaling the solution options. Other moderate flaws in the methodology include the lack of a comprehensive current state analysis considering all drivers; a comprehensive sustainability impact assessment (e.g., increased water extraction through the PV water pumping system); advanced "randomized" and comparative intervention research (e.g., assessment of unintended consequences); and a formal (pre-/post-) and comparative evaluation (Walter et al. 2007). The project was participatory and collaborative throughout the project phases, on high levels of intensity, and received positive feedback from the villagers. However, the engagement beyond the local and regional scale (national policy makers) was lacking meaningful stakeholder engagement, which is, on the one hand, acceptable, as it was not required for accomplishing the primary objective of the project, but led, on the other hand, to a lack of transfer and upscaling, limiting the intended larger impacts of the project.

The knowledge generated in the pilot project was sufficient for implementing a solution option and the addressed problem has been solved in the selected village (Parodi et al. 1998; Schweizer-Ries et al. 2007). The project has generated positive outcomes for the community that appear to outweigh the negative effects (e.g., increased need and wants levels; increased water consumption). However, the broader goal for rural areas in Argentina has not been achieved, due to various factors that hampered the transfer and upscaling of the results. Insufficient knowledge on how to upscale the results through technology transfer (and lack of conducting research on this question) was a major barrier, which adds an example to the failure of panaceas (Ostrom et al. 2007). This limits the success of the project, as its approach of the socio-culturally embedded introduction of technologies largely remains with the small community of project partners. A single case study does not provide enough evidence to design and fund larger programs. The need for transfer and upscaling, however, is immense, as there are rather few cases of establishing functioning solar systems in rural areas in the long run (e.g., Chakrabarti and Chakrabarti 2002; Schweizer-Ries 2011).

Recommendations

The research design and methodologies could have been improved regarding advanced future-oriented methodology, sustainability impact assessment, and comparative intervention research methodology. Moreover, a structured approach to generate transferable knowledge poses a significant improvement potential, putting more emphasis on the broader impact of the project. This transfer-oriented research would need to synthesize experiences from solar electrification projects in rural areas (in Argentina and worldwide), outline context-specific solution options for different places and communities based on the project experiences, conduct comparative studies that identify generic and specific factors of success, and build alliances to convey these insights to policy makers and development organizations.

The future of Phoenix, AZ, USA: crafting sustainable development strategies

Basic information

The project was initialized through the City of Phoenix in collaboration with the School of Sustainability at Arizona State University (ASU) (http://start.lab.asu.edu). In collaboration with city staff from different departments, an interdisciplinary research team conducted a study on urban sustainability that engaged stakeholders from across the city. The project ran for 2 years (2009–2011). The primary project objective was to develop transition strategies for sustainable development that could be incorporated into the updated General Plan, which is the city's most important guide for long-term planning. Through this research partnership, the project aimed to familiarize administrative staff and citizens across Phoenix with sustainability and anticipatory governance in the practical matter of urban planning (Wiek et al. 2010).

Project analysis

The project addressed urban sustainability problems in Phoenix. The problems ranged from energy-intense, car-dependent urban form (sprawl) resulting in high budgetary obligations for transportation and infrastructure maintenance and public transit services. The resulting persistent traffic congestion impairs economic productivity and social activities. High levels of greenhouse gas emissions, air pollution, and the urban heat island effect negatively affect local public health and climate change. Food deserts and a lack of public space for physical activities lead to adverse health impacts, such as obesity (Arizona has currently the highest rate of childhood obesity in the US). The excessive extraction and diversion of surface and groundwater (overdraft) results in degraded riparian ecosystems, land subsidence, and inequitable access to water resources. The goal of the project was to develop solution options that would, if implemented, solve and mitigate the identified problems.

The project applied a methodological framework for transformational sustainability research that integrates backcasting with foresight and intervention research methods in interactive participatory settings (Wiek et al. 2010, 2011). The framework structures research into four modules: (1) visioning for crafting a sustainable vision for Phoenix through the transfer of knowledge on sustainable systems, application of sustainability principles, and analysis of coherence; (2) historical and current state system analysis for capturing inter-linkages among key actors, activities, constraining/enabling rules and regulations, and impacts on the urban environment, economy, and society in Phoenix through system analytical approaches, including structured indicator selection, cause–effect chain analysis, and actor network analysis; (3) scenario construction for constructing non-intervention scenarios describing the future of Phoenix in contrast to the vision, through consistency and diversity analysis, visualization, and translation into narratives; and (4) backcasting of intervention and transition strategies for identifying intervention points and coordinated steps to transition from Phoenix's current state to its sustainable vision while avoiding undesirable scenarios. All methods were applied in participatory settings that allowed the mapping and reconciling of different stakeholder perspectives, values, and preferences. In collaboration with city staff, the research team conducted a series of workshops that engaged up to 115 citizens and stakeholders from across the city. A large extent of the participatory research was conducted by graduate students organized through the real-world learning programs at the School of Sustainability and the Center for Nanotechnology in Society at ASU.

The project resulted in a set of five sustainability-oriented intervention and transition strategies for Phoenix, based on vision, current state model, and non-intervention scenarios. Vision maps, narratives, and visuals were generated that integrate elicited vision statements, relative value divergence and convergence, tradeoffs, and sustainability principles. Causal systems maps were generated that reveal the dynamic structure of five "sustainability syndromes" currently playing out in the following urban domains: jobs and businesses; land use; mobility; energy; and governance and community cohesion. Each syndrome is deconstructed into detrimental effects and critical drivers through a set of indicators and direct/indirect influences and feedback loops (syndrome map). A data matrix specifies each syndrome. A set of consistent scenarios were constructed that outline what Phoenix might look like in 2050 if no deliberate action is taken to achieve the sustainability vision. For example, one scenario describes a "Phoenix Behind the Times", in which Phoenix has been resistant to the adoption of new technologies and new forms of governance to actively pursue solutions for and mitigation of existing and emerging sustainability challenges. The resulting set of five intervention and transition strategies capitalize on existing opportunities in Phoenix to address the outlined urban sustainability syndromes, avoid the undesirable future scenarios, and make progress towards the sustainability vision. For example, the Cultivating Strong Businesses strategy aims to merge existing priorities, like attracting large corporations, with others, such as creating incentives and incubators for Phoenix's growing small business sector and diversifying the urban economy. The project results have been discussed in public hearings, coaching sessions, and conferences, and have stimulated discussions among Phoenicians. The results have been used in classes in public schools in Phoenix (through ASU's NSF-funded GK-12 "Sustainable Schools" program) and in academic courses at ASU. The results have been vetted through peer reviews and have resulted in a series of academic publications. The most prominent outreach result is the incorporation into the General Plan Public Hearing Draft (December 2010), which, after further revisions over the coming year, will be presented to citizens for a public vote. The project has been recognized as an exemplary research project through the 2011 ASU President's Award for Sustainability. The project has sparked the next set of use-inspired research activities in three neighborhoods on solution options for urban food, mobility, public health, energy, and groundwater contamination (Superfund site).

Project evaluation

The addressed urban problems in Phoenix do present challenging sustainability problems, both life-threatening and urgent (e.g., greenhouse gas emissions; groundwater overdraft), with long-term impacts (e.g., childhood obesity), highly complex (interrelated social, economic, and environmental drivers and effects), and not able to be solved by simple remedies (e.g., purely technical solutions for soil and water remediation). The project goal was to develop solution options for the identified problems without favoring particular strategies or tactics. This goal was developed in collaboration with various stakeholders, including city officials, business representatives, community organizations, and citizens who expressed a legitimate interest in solving these problems. Yet, considering the representation ratio (people involved vs. people living in Phoenix), the relatively small number of people involved in the project (less than 500) can be considered a deficit.

The project employed a methodological framework that allowed addressing the identified problem comprehensively and generating knowledge about the current state (systemic syndromes), potential future developments (non-intervention scenarios), normative orientation (systemic vision), and action-oriented guidelines (transition and intervention strategies) sufficient to create solution options as aspired. As this was a combined research and teaching project, not all methodological components were developed and applied to the full extent; for instance, the systemic analysis of the syndromes lacked the full integration into a functioning model, and the intervention strategies have not been tested in simulations and pilot projects. However, the project team currently refines the results with advanced methodological approaches. The project yielded some documented evidence on its impacts (e.g., citizens' engagement and planners' capacity building), yet, an evaluation was not conducted in a formal fashion. While the project aimed to create actionable knowledge, the research team did not follow a conventional participatory action–research approach. Recognizing both the needs of stakeholders and the needs of researchers, the project facilitated negotiations in the community-based participatory research process (Wiek et al. 2010). In this vein, the project achieved relatively high levels of engagement throughout the research process. This is, in part, due to a professional support structure (e.g., professional facilitators as coaches). Nevertheless, there were some flaws in the engagement process regarding stakeholder representation due to the extent of the site (a city of more than 1 million inhabitants) and accessibility of particular social groups (e.g., children, immigrants, "working poor"). Another critical issue was the lack of follow-up capacity after the completion of the project, which precluded stakeholders from comprehensively engaging with the project results.

As the project addressed sustainability problems and employed a transformational sustainability research methodology, the results were, if not sufficient, at least a recognizable contribution towards comprehensive solution options. The project's major impact continues in capacity building, namely, in schools, in the university, and within the city administration. The results also inform subsequent research projects that specify the solution options and accompany their implementation. However, the generated results displayed some deficits. Not all results were sufficiently supported by empirical evidence (lack of resources for primary data collection) and some remained on a general level not specific enough for the neighborhood level, where they would matter to people (this insight led to subsequent projects focusing on the neighborhood level). Problematic was the focus on the city's General Plan. Considering that the General Plan is not legally binding and the relevance of long-term planning has been downgraded by recent budget decisions in the city administration, the project impacts have dissolved in political debates. Although it is recognized that the city's planning practice is an important intervention point, one has to acknowledge that the problems continue to play out in full force in Phoenix and the trajectories have not sustainably been impacted by the project. Continued efforts on all levels of decision making and across the city are necessary to change the course of urban development in Phoenix so that the subtitle of the General Plan Public Hearing Draft, "Transitioning to a Sustainable Future", becomes a reality.

Recommendations

While the research methodology represent the project's strengths, potential improvements concern the stakeholder selection, collaborative partners, and other participatory components of the project. Broader stakeholder participation from the very beginning might have resulted in a wider buy-in for the project and would have been beneficial for the implementation stage. Similarly, a broader collaborative consortium and additional alliances would possibly have allowed further developing and implementing solution options, irrespective of political debates and obstacles. Finally, the importance of coordinating and conducting such research on smaller scales (neighborhood level) enables capacity building and solution implementation where it matters to people. The research team moves forward in conducting research in Phoenix's neighborhoods.

Discussion

The five case studies reviewed in this paper cover a broad array of topics: water, bioenergy, land use, solar energy, urban development; regions: from coastal to mountainous, from rural to urban; countries: within Africa, Europe, South and North America; spatial levels: from village to country; and research approaches: methodologies, collaborating partners, funding arrangements. The selection shows a bias towards developed countries as either the projects were carried out in Europe and the US, or were led and funded by organizations from Europe and US. This bias is partly due to the lack of sustainability research and funding organizations in developing countries (Clark and Dickson 2003); yet, we also acknowledge a lack of effort to establish collaborative partnerships with sustainability researchers from developing countries.

The presented appraisals do not stem from empirical evaluative studies (except Project 4); instead, they are reflections by project leaders and participants. Considering the nascent state of such studies, this is not surprising. Nevertheless, it limits the reliability of the data presented, although the authors reviewed and revised the appraisals collectively. In particular, the identification of social impacts of the projects, which is probably the most important output variable, would greatly benefit from empirical impact studies as demonstrated in the literature (e.g., Walter et al. 2007). Moreover, comprehensive project appraisals would need to further specify, operationalize, and analyze the compliance with the criteria of saliency, credibility, and legitimacy (Cash et al. 2003; Talwar et al. 2011). This would also require studying in more detail the power constellations as well as mediation, negotiation, and facilitation processes within transformational research projects. A recent comparative study by Clark et al. (2011) concludes accordingly: "for the extremely asymmetric cases of power distribution that characterized our (and others') rural development cases, the explicit attention to managing power contained in the negotiation support formulation appears to be essential to good boundary work". Finally, more detailed project appraisals would need to scrutinize in how far the projects sufficiently analyzed the interfacing human/social systems—a deficit observable in sustainability science projects that are primarily based on bio-physical systems frameworks (Bäckstrand 2003).

Keeping these caveats in mind, the comparison across the five projects (Table 1) yields insights into the current "state-of-the-art" in transformational sustainability research:

- Each project deliberately addressed a sustainability problem, featuring, among others, long-term impacts, complexity, and urgency. However, in most of the cases, no comprehensive problem analysis was performed from a genuine sustainability perspective. This would have revealed all features of the problem constellation and prepared all parties (researchers and collaborators) for more profound and diverse solution strategies (Wiek 2011). Stakeholders did not, in all cases, confirm legitimate interest in the problem and solutions. This is a significant constraint, as stakeholder buy-in is critical for implementing solution options (see Project 1 and, in contrast, Project 4).
- All but one project formulated the goal to at least develop solution options (Project 4 even included the implementation), which indicates transformational aspirations. Despite the place-based focus of all projects (with the exception of Project 2), a significant challenge for the majority of projects was to define an adequate spatial focus for knowledge transfer and larger impact. Three of the projects (Projects 2, 4, and 5) did not meet their ambitious goals to transfer project results and impact to the continent (Africa), country (Argentina), or city level (Phoenix). It seems important to more carefully craft the project goals and to employ an adequate research methodology for evidence-based transfer and outreach.
- The variety of methodological approaches demonstrates that there is no single framework best suited for creating sustainable solution options, but several are appropriate (Jerneck et al. 2011). Despite suitable frameworks, all projects displayed deficits in particular methodological components, including sustainability assessment, synthesis, and transfer. This hints to a structural challenge for sustainability science, namely, the lack of key sustainability competencies, and the importance of team composition and internal capacity building (Wiek et al. 2011).
- Participatory research methodologies, from transdisciplinary to community-based, posed challenges to all projects regarding stakeholder selection, frequency, intensity, and quality of engagements. The more sophisticated approaches (Projects 4 and 5) did not only collaboratively conduct research, but shared control over the process and accountability for the results (Scholz 2011; Talwar et al. 2011). Critical success factors seem to be the number of legitimate stakeholders, broad coverage of different perspectives and interests, as well as competence and experience in participatory research (Lang et al. 2012). The transformational goals of sustainability science projects may also be supported through a more incisive identification, examination, and inclusion of the social agents who have the abilities, means, and power for deliberative action at multiple scales. To do so, advanced forms of stakeholder analysis and engagement need to become utilized.
- In the minority of cases, the generated results lived up to the ideal expectations of transformational research. Even if research led to actionable knowledge, deficits in applicability and synthesis undermined its value. A clear focus on small-scale (local) units and a close link to the actual implementation (as done in Project 4) are favorable factors. Yet, they do not guarantee the transferability or scalability of the solution options generated. Additional research efforts are needed to overcome applied research with one-case solutions towards the aspired transformational research that generates widely applicable solution options. This is a typical phenomenon in sustainability and transdisciplinary projects that there is a need to find a balance between (1) understanding the complexity and specificity of a case or problem in its real-life context and to work towards to its transformation, and (2) contributing to a common body of theoretical knowledge on generalizations and generic principles (Brand et al. 2012).
- As indicated above, the larger impact of all projects was rather limited. This might be due to a lack of advanced stakeholder involvement, implementation capacity, or transferability and scalability. The time periods of monitoring and evaluating impacts may also be too short. Although transformational research cannot ensure the actual implementation of results (solution options), additional efforts are needed in order to increase the likeliness of implementation and uptake.

Conclusions

Despite promising accomplishments, with respect to problem focus and basic transformational research methodology,

Table 1 Overview profiles of the sustainability science projects

Project title	Water management in the Ebro River Basin (MATISSE, Work Package 6)	Competence platform on energy crop and agroforestry systems for arid and semi-arid ecosystems in Africa (COMPETE)	Sustainable land-use practices and adaptation to global change in alpine regions in Switzerland (MOUNTLAND)	Energy sustainable communities in San Juan, Argentina	The future of Phoenix, Arizona (USA)—crafting sustainable development strategies
Basic information					
Topic	Water	Bioenergy	Land use	Solar energy	Urban development
Country/ countries	Spain	Botswana, Burkina Faso, Kenya, Mali, Senegal, South Africa, Tanzania, Zambia	Switzerland	Argentina	USA
Spatial level (no. of cases)	Region (Ebro River Basin) (1)	National/Country (8)	Region (Jura Vaudois, Visp, Davos) (3)	Village (in San Juan Region) (1)	City (Phoenix, Arizona) (1)
Lead partners	Autonomous University of Barcelona, Lund University, Maastricht University, University of East Anglia (Norwich)	Research organizations, NGOs and industry partners from Europe, Africa, Brazil, India, and Mexico (44 partners in total)	Swiss Federal Research Institute for Forest, Snow and Landscape (WSL), ETH Zurich, EPFL Lausanne	University of San Juan, Instituto National des Agropequaria San Juan, Fraunhofer ISE, University of Magdeburg	City of Phoenix, Arizona State University
Duration	2005–2008	2007–2009	2008–2012	1992–1995, 1998, 2005	2009–2011
Main funding sources	EU's 6th Framework Program	EU's 6th Framework Program	Competence Centre Environment and Sustainability (CCES), ETH Domain	German Ministry of Research, German Academic Exchange Service	Arizona State University, City of Phoenix
Project analysis					
a. Problem b. Goal	a. Water quality and quantity in Ebro River Basin, Spain b. Policy-relevant gaming tool	a. Lack of quality of life, sufficient energy access, land degradation in Africa b. Policy recommendation for sustainable bioenergy initiatives (Africa)	a. Climate change impacts on mountain regions b. Recommendations for climate adaptations (land-use and policy)	a. Lack of quality of life and migration in rural b. Implementation of reliable solar energy systems (Argentina)	a. Diverse urban problems related to energy, mobility, etc. b. Strategies for transitions and interventions (general plan)
a. Method b. Participatory process	a. Gaming tool design b. Selected stakeholders; two stakeholder meetings; consultation	a. Land mapping, impact analysis, impact appraisal, policy design b. Broad spectrum of stakeholders; meetings and workshops; consultation	a. Ecological experiments, modeling, scenario analysis, political network analysis b. Broad spectrum of stakeholders; meetings and workshops; consultation and (less) collaboration	a. Formulation (site selection, etc.); realization (planning, prototype and pilot, etc.); evaluation (1998/2005) b. Broad spectrum of local and regional stakeholders; meetings and workshops; consultation and collaboration	a. Transformational research methodology: visioning; current state analysis; scenario analysis; strategy backcasting b. Broad spectrum of local and regional stakeholders; meetings and workshops; consultation and collaboration

Table 1 continued

Project title	Water management in the Ebro River Basin (MATISSE, Work Package 6)	Competence platform on energy crop and agroforestry systems for arid and semi-arid ecosystems in Africa (COMPETE)	Sustainable land-use practices and adaptation to global change in alpine regions in Switzerland (MOUNTLAND)	Energy sustainable communities in San Juan, Argentina	The future of Phoenix, Arizona (USA)—crafting sustainable development strategies
a. Results b. Impacts	a. Agent-based social simulation model (gaming tool); initial insights into effects of using the tool; insights into success criteria for collaborative process b. –	a. Land use (change) maps, bioenergy potential maps, assessment reports (scientific publications and project reports) b. Policy documents (guidelines for assessing sustainability of bioenergy projects; "Declaration on Sustainable Bioenergy for Africa"); changes in land use strategies and zoning in selected countries	a. Land-use models, scenarios, sustainability criteria, strategy for strengthening regional cohesion (scientific publication and media) [synthesis is underway] b. [Cannot be determined as project is not completed yet]	a. Plans, prototypes and pilot/demonstration system, evaluation reports, project design blueprint (scientific publications and media) b. 14 Solar home systems and one PV water pumping system in this village; impacts on companies and policy makers in other regions	a. Maps and descriptions of urban sustainability syndromes; vision; scenarios; strategies; methodologies (scientific publications) b. Revised general plan; revised general plan is being used in the design of new policies and programs
Project evaluation					
a. Problem b. Goal	a. Yes; no clear stakeholder interest b. No, indirect contribution	a. Yes; lack of stakeholder confirmation b. Yes, but focused on one particular solution (bioenergy) and on a large region (Africa)	a. Yes, but not considered life-threatening or urgent, thus, low interest from stakeholders b. Yes, but primary focus on descriptive-analytical knowledge and on adaptation strategies	a. Yes; clear stakeholder interest b. Yes, but focused on one particular solution (solar energy) and on a large region (Argentina)	a. Yes; clear stakeholder interest b. Yes, but focused on a large entity (City of Phoenix)
a. Method b. Process	a. Not applicable; lack of clear methodology b. Deficits (number of interactions; level of participation)	a. Yes, with flaws in methodology and application (lack of rigor, follow-through, synthesis) b. Deficits (phase of interaction; level of participation)	a. Yes, but deficits regarding sustainability criteria and assessment b. Deficits (phase of interaction; level of participation)	a. Yes, with flaws in methodology (e.g., no transfer methodology); strength: self-evaluation b. Strong participatory research approach; limited stakeholder participation from national level	a. Yes with minor methodological flaws (e.g., intervention research) b. Strong participatory research approach; limited stakeholder participation from all groups
a. Results b. Impacts	a. No b. No	a. Yes, but not in all countries b. No, but initial steps have been taken (capacity built); lack of transfer	a. Yes, but not fully integrated yet [still ongoing] b. N/A, but deficits in stakeholder engagement predetermine lack of implementation	a. Yes (in this village) b. Yes (problem solved in this village); project made significant contribution to the solution; lack of transfer	a. Yes, but not for all urban syndromes b. No, but initial steps have been taken (capacity built)
Recommendations					
	– Involve broader range of stakeholders – Increase level of participation – Timely tool delivery, testing, and application	– Limit regional focus – Involve stakeholders in problem framing – Increase level of participation – Improve assessment and policy design methodology	– Include mitigation strategies into goal – Improve sustainability criteria and assessment – Involve stakeholders in problem framing – Increase level of participation	– Limit regional focus – Improve impact assessment methodology – Improve transfer methodology	– Limit urban focus – Involve *all* relevant stakeholder groups from the very beginning – Create stronger strategic alliances

there remain several challenges to comply with the impact-oriented agenda of transformational sustainability research.

A general lack of advanced methodological and process-oriented competence and experience seems to be a key factor in these challenges, which is not surprising considering the nascent state of the field. In particular, strong collaborative research processes in which scientists and stakeholders interact starting from problem framing to strategy implementation and problem transformation would advance sustainability research projects with regards to the process and impacts. Such processes show promise of building capacity, agreement, legitimacy, and socially robust orientations for initiating, establishing, adapting, and multiplying transitions towards sustainability. In such processes, it seems critically important to clarify expectations among the different actor groups (including the researchers). The challenge is to not overpromise what solution options really are, namely, they are options that still require decisions and implementation to have an impact. At the same time, the process must not get trapped in paralysis-by-analysis and the generation of knowledge that is far from being actionable. Actionable knowledge, however, can only be generated through the application of appropriate transformational research methodologies, which requires a great deal of training and experience.

In the few cases where real-world impacts were accomplished, singular case-based solutions of applied science reigned instead of the aspired transformational research generating widely applicable solution options. Advances in generalizing and transferring insights from sustainability science projects require the analysis of similarities and dissimilarities across various cases. That analysis needs to separate experiences between specific and generic features of individual cases. Further, the analysis must build typological theories that identify recurring conjunctions of mechanisms and provide hypotheses on the pathways that produce results. Finally, developed design principles built on cross-case and meta-analyses can generalize the application of case-based solutions options.

A critical background driver, not addressed in this article, are the dominant institutional structures that govern academic research, from funding schemes to promotion and tenure policies; these structures are, in the majority of cases, not conducive to this new type of research, which limits the full development and impact of transformational sustainability research. A significant shift of individual research agendas and institutions, beyond programmatic claims and calls, is necessary in order to seize the full potential of transformational sustainability research. To this end, small-capacity building networks, including research organizations from developing countries, seem to be promising venues—as the collaboration on this article demonstrates.

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