Sustain Sci (2012) 7 (Supplement 1):25–43
DOI 10.1007/s11625-011-0149-x

SPECIAL FEATURE: ORIGINAL ARTICLE

Sustainability science: bridging the gap between science and society

Transdisciplinary research in sustainability science: practice, principles, and challenges

Daniel J. Lang · Arnim Wiek · Matthias Bergmann · Michael Stauffacher · Pim Martens · Peter Moll · Mark Swilling · Christopher J. Thomas

Received: 5 October 2011 / Accepted: 12 December 2011 / Published online: 4 February 2012

Abstract There is emerging agreement that sustainability challenges require new ways of knowledge production and decision-making. One key aspect of sustainability science, therefore, is the involvement of actors from outside academia into the research process in order to integrate the best available knowledge, reconcile values and preferences, as well as create ownership for problems and solution options. Transdisciplinary, community-based, interactive, or participatory research approaches are often suggested as appropriate means to meet both the requirements posed by real-world problems as well as the goals of sustainability science as a transformational scientific field. Dispersed literature on these approaches and a variety of empirical projects applying them make it difficult for interested researchers and practitioners to review and become familiar with key components and design principles of how to *do* transdisciplinary sustainability research. Starting from a conceptual model of an ideal–typical transdisciplinary research process, this article synthesizes and structures such a set of principles from various strands of the literature and empirical experiences. We then elaborate on them, looking at challenges and some coping strategies as experienced in transdisciplinary sustainability projects in Europe, North America, South America, Africa, and Asia. The article concludes with future research needed in order to further enhance the practice of transdisciplinary sustainability research.

Keywords Transdisciplinary sustainability research · Design principles · Challenges · Evaluation

Handled by Francesca Farioli, Sapienza University of Rome, Italy.

D. J. Lang (✉) · M. Bergmann · P. Martens
Institute of Ethics and Transdisciplinary Sustainability Research, Faculty Sustainability, Leuphana University of Lüneburg, Scharnhorststr. 1, 21335 Lüneburg, Germany
e-mail: daniel.lang@leuphana.de

A. Wiek
School of Sustainability, Arizona State University, Tempe, AZ 85287-5502, USA

M. Bergmann
Institute for Social-Ecological Research, Hamburger Allee 45, 60486 Frankfurt am Main, Germany

M. Stauffacher
Institute for Environmental Decisions (IED), Natural and Social Science Interface (NSSI), ETH Zurich, CHN J74.1, Universitätstrasse 22, 8092 Zürich, Switzerland

P. Martens
International Centre for Integrated Assessment and Sustainable Development (ICIS), Maastricht University, P.O. Box 616, 6200 MD Maastricht, The Netherlands

P. Moll
Science Development, Hagenauer Str. 30, 42107 Wuppertal, Germany

M. Swilling
School of Public Leadership, University of Stellenbosch, P.O. Box 610, Bellville 7535, South Africa

C. J. Thomas
Institute of Biological, Environmental and Rural Sciences, Aberystwyth University, 3.30, Edward Llwyd Building, Penglais, Wales, UK

Introduction

Water scarcity, epidemics, climate change, natural and man-made disasters, violent conflicts, rapid urbanization—often entailing problems such as air pollution or social segregation—and many other persistent and complex challenges are threatening the viability and integrity of our global societies (Kates and Parris 2003; Rockström et al. 2009). These challenges have spawned a broad variety of societal responses from industries, universities, and civil society organizations. Academia has prominently responded through the initiation of a new field of research, namely, sustainability science, since the late 1990s (Kates et al. 2001; Clark and Dickson 2003; Swart et al. 2004; Komiyama and Takeuchi 2006; Martens 2006; Jerneck et al. 2011; Wiek et al. 2011, 2012). As a problem- and solution-oriented field, sustainability science is inter alia inspired by concepts of post-normal, mode-2, triple helix, and other science paradigms (Funtowicz and Ravetz 1993; Gibbons et al. 1994; Etzkowitz and Leydesdorff 2000) that employ corresponding research practices, such as transdisciplinary, community-based, interactive, or participatory approaches (Kasemir et al. 2003; Savan and Sider 2003; Becker 2006; Robinson and Tansey 2006; Hirsch Hadorn et al. 2006; Jahn 2008; Scholz et al. 2006; Scholz 2011). These practices have in common that they focus on research collaborations among scientists from different disciplines and non-academic stakeholders from business, government, and the civil society in order to address sustainability challenges and develop solution options. In the ground-breaking article on sustainability science by Kates et al. (2001), it reads accordingly that "participatory procedures involving scientists, stakeholders, advocates, active citizens, and users of knowledge are critically needed" (p. 641). Key arguments for this new type of research collaboration that transcends disciplinary and interdisciplinary approaches are the following: first, research on complex sustainability problems requires the constructive input from various communities of knowledge to ensure that the essential knowledge from all relevant disciplines and actor groups related to the problem is incorporated; second, research on solution options requires knowledge production beyond problem analysis, as goals, norms, and visions need to provide guidance for transition and intervention strategies; third, collaborative efforts between researchers and non-academic stakeholders promises to increase legitimacy, ownership, and accountability for the problem, as well as for the solution options (Funtowicz and Ravetz 1993; Gibbons et al. 1994; Hirsch Hadorn et al. 2006; Baumgärtner et al. 2008; Wiek 2009; Talwar et al. 2011; Spangenberg 2011).

While the field of sustainability science has been growing and gaining institutional momentum, a large body of literature on transdisciplinary, community-based, interactive, and participatory research approaches as well as empirical projects has been generated. Noteworthy, initial sets of principles, quality criteria, and success factors have been compiled for some of the aforementioned approaches (Rotmans and Van Asselt 1996; Bergmann et al. 2005; Pohl and Hirsch Hadorn 2007; Defila et al. 2006; Blackstock et al. 2007; Regeer et al. 2009; Wiek 2009; Scholz 2011; Brundiers and Wiek 2011). Yet, the literature is rather fragmented and dispersed, without providing good guidance to interested researchers and practitioners on what can be learned from the different approaches and what needs to be considered when planning and carrying out transdisciplinary sustainability research. In particular, a synthesis of experience-based guidelines that draws from various strands of the literature and practical experiences on how to do transdisciplinary research and make it possible to familiarize oneself with key components and guiding principles is missing. Such synthesis would have the additional obligation (apart from the benefit of compilation) to review and scrutinize the empirical evidence for such guidelines of transdisciplinary research (Klein 2008; Wiek 2009). It is important to recognize the significance of this question, as transdisciplinary research and similar collaborative approaches are not uncontested outside transdisciplinary research communities. Arguing from a more conventional research perspective, scientists might be skeptical with respect to reliability, validity, and other epistemological and methodological aspects of collaborative research ("credibility"). Practitioners and stakeholders, on the other hand, might be skeptical regarding the practical relevance of the results ("salience"). Experience-based guidelines that build upon demonstrated success (and failures) and satisfy all parties involved in transdisciplinary research are needed (Cash et al. 2003). Finally, transdisciplinary research in its strong version goes beyond the "primacy of science" as well as the "primacy of practice," establishing a third epistemic way (Wiek 2007; Jahn 2008). For this, guidelines are needed in order to reliably demarcate transdisciplinary research from numerous approaches that either use laypersons inputs in scientific research ("primacy of science") or provide classical decision support ("primacy of practice") (Robinson 2003; Bergmann et al. 2005). As the aim of this article is to emphasize commonalities among transdisciplinary, participatory, and collaborative research approaches rather than highlighting differences and as an in-depth elaboration on different notions of transdisciplinarity (see, e.g., Pohl and Hirsch Hadorn 2007; Thompson Klein 2010; Scholz 2011) is beyond the scope of this article, we apply a broad definition of transdisciplinarity that reads as follows:[1]

> Transdisciplinarity is a reflexive, integrative, method-driven scientific principle aiming at the solution or

[1] Adapted from Matthias Bergmann's presentation at the launching conference of the International Network for Interdisciplinarity and Transdisciplinarity (INIT) in Utrecht, The Netherlands, June 2011.

transition of societal problems and concurrently of related scientific problems by differentiating and integrating knowledge from various scientific and societal bodies of knowledge.

This definition highlights that transdisciplinary research needs to comply with the following requirements: (a) focusing on societally relevant problems; (b) enabling mutual learning processes among researchers from different disciplines (from within academia and from other research institutions), as well as actors from outside academia; and (c) aiming at creating knowledge that is solution-oriented, socially robust (see, e.g., Gibbons 1999), and transferable to both the scientific and societal practice. With regards to the latter, it is important to consider that transdisciplinarity can serve different functions, including capacity building and legitimization (Scholz 2011).

The purpose of this article is twofold: first, we provide an initial compilation of design principles for transdisciplinary sustainability research that draws from various strands of literature on collaborative research approaches as well as on practical experience; second, we want to breathe life into these principles through illustrative examples of challenges to comply with them in sustainability science as encountered in transdisciplinary projects in Europe, North America, South America, Africa, and Asia. The latter allows the reader to gain in-depth insights into the actual application of these principles in empirical sustainability research and is also a step toward empirically substantiating the design principles. In order to make the design principles as easily accessible and applicable as possible, we propose and explore them from a practice-oriented or praxeological perspective. This means the design principles are presented as close as possible to the actual research process (Bergmann et al. 2005; Bergmann and Jahn 2008; Wiek 2009), similar to a recent model of public participation (Krütli et al. 2010b) or the design principles for community-based natural resource management (Cox et al. 2010). Thus, we start with a conceptual model that structures the transdisciplinary process in three phases (see "Concept of an ideal–typical transdisciplinary research process"), then link generic design principles to these phases (see "Design principles for transdisciplinary research in sustainability science"), and, finally, explore challenges of complying with the principles in each of the three phases in elaborating on the experiences we gained in various projects in the field of sustainability science (see "Challenges of transdisciplinary research in sustainability science"). The article concludes with future research needed in order to further enhance the practice of transdisciplinary sustainability research (see "Concluding remarks").

Concept of an ideal–typical transdisciplinary research process

Key components of an ideal–typical transdisciplinary process are here presented in order to position the derived principles as accurately as possible *within* the actual research practice. We rely in this article on a slightly adapted version of an ideal–typical conceptual model (Jahn 2008), which has many similarities to other model presented in the literature (e.g., Scholz et al. 2006; Pohl and Hirsch Hadorn 2007; Wiek 2009; Carew and Wickson 2010; Krütli et al. 2010b; Stokols et al. 2010; Talwar et al. 2011). According to this model (Fig. 1), transdisciplinary research in general and in sustainability science in particular is an "interface practice": first, it initiates from societally relevant problems that imply and trigger scientific research questions; second, it relies on mutual and joint learning processes between science and society embedded in societal and scientific discourses (Siebenhüner 2004). In so doing, transdisciplinary research integrates two pathways to address "real world problems": one pathway is committed to the exploration of new options for solving societal problems (the path of problem solution, the left "arm" in Fig. 1); the other pathway is committed to the development of interdisciplinary approaches, methods, and general insights related to the problem field (the path of scientific innovation, the right "arm" in Fig. 1), which are crucial for the practical path (cf. Bergmann et al. 2010).

In the ideal–typical conceptual model presented in Fig. 1, a transdisciplinary research process is conceptualized as a sequence of three phases, including: collaboratively framing the problem and building a collaborative research team (Phase A); co-producing solution-oriented and transferable knowledge through collaborative research (Phase B); and (re-)integrating and applying the produced knowledge in both scientific and societal practice (Phase C). Thereby, a main purpose of Phase A is to integrate "the pathway of problem solution" and the "pathway of scientific innovation" to allow for collaborative research in Phase B ("integrative research pathway"), resulting in transferable knowledge that can be (re-)integrated into the societal and scientific practice in Phase C. Though the model might indicate a rather linear process, individual phases and the overall sequence often have to be performed in an iterative or recursive cycle, also highlighting the need for reflectivity in transdisciplinarity (see, e.g., Spangenberg 2011). In this article, we slightly adapt the original model by: (a) changing the terminology to match the international discourse in sustainability science and related fields and (b) underlining the need for a deliberate design of the collaboration between actors from academia or other research institutions and actors from practice.

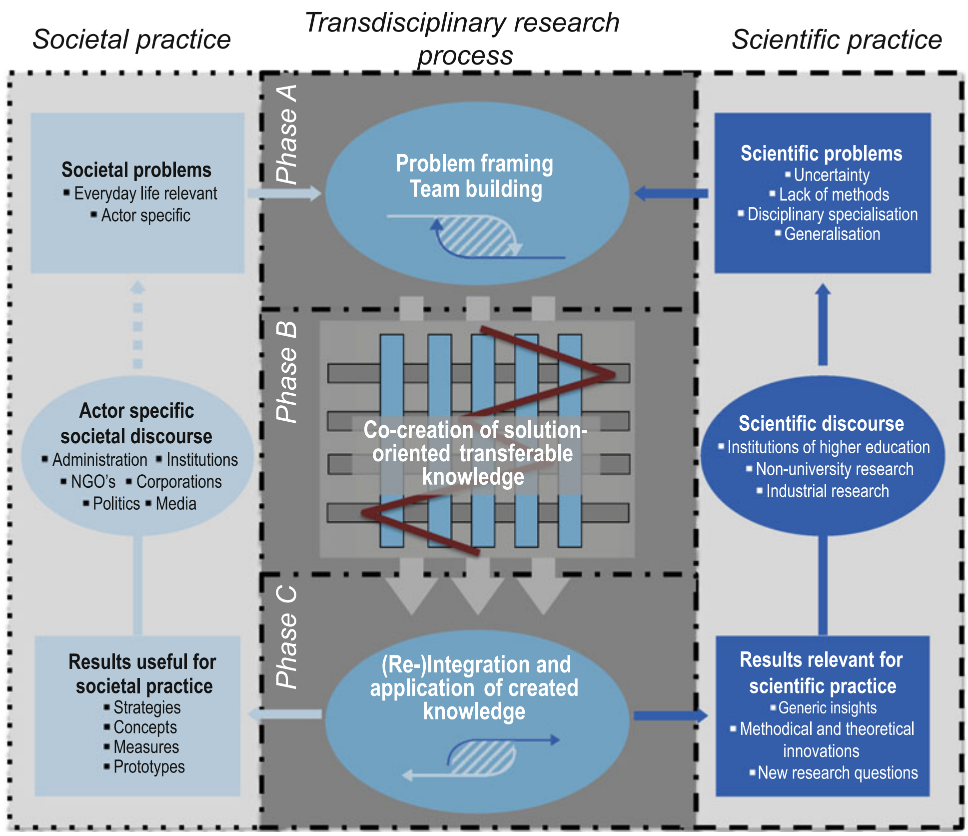

Fig. 1 Conceptual model of an ideal–typical transdisciplinary research process (adapted from: Bergmann et al. 2005; Jahn 2008; Keil 2009; Bunders et al. 2010; there are several models which outline transdisciplinary research process in a similar way: e.g., Scholz et al. 2006; Pohl and Hirsch Hadorn 2007; Wiek 2009; Carew and Wickson 2010; Krütli et al. 2010b; Stokols et al. 2010; Talwar et al. 2011)

Phase A: Collaborative problem framing and building a collaborative research team

This phase orients, frames, and enables the core research process. It consists of several activities: identification and description of the real-world problem; setting of an agreed-upon research object, including the joint formulation of research objectives and specific research- as well as societally-relevant questions; the design of a conceptual and methodological framework for knowledge integration; and the building of a collaborative research team. Essential in this phase is that the real-world problem is translated into a boundary object (see, e.g., Clark et al. 2011) that is both researchable and allows for the re-integration of the insights into societal implementation as well as the scientific body of knowledge.

Phase B: Co-creation of solution-oriented and transferable knowledge through collaborative research

This phase is the actual *doing* of the research. In this phase, a set of integrative (scientific) methods is adopted, further developed, and applied to facilitate the differentiation and integration of the different bodies of knowledge coming together in the process. Concomitantly, a collaborative research design allows for goal-oriented collaboration among different disciplines, as well as between researchers and actors from outside academia, in a functional and dynamic way. For each step of the research process, it needs to be defined who contributes what, supported by which means and to what end (Krütli et al. 2010a, b). Thereby, it is important to consider different levels of stakeholder involvement in the research process (Wiek 2007; Stauffacher et al. 2008; see the (red) zigzag line in the center of Fig. 1).

Phase C: (Re-)integrating and applying the co-created knowledge

This phase is the process of using, applying, and implementing the research results. As different perspectives, world views, values, and types of knowledge are integrated over the course of the entire transdisciplinary research process, this phase is not a classical form of knowledge transfer from science to practice (van Kerkhoff and Lebel 2006; Talwar et al. 2011). It is, instead, a (re-)integration of the results into: (a) the societal practice (e.g., implementation of the evidence-based strategies and action programs generated during the research) and (b) the scientific practice (e.g., comparison, generalization, and incorporation of results into the scientific body of literature). Apart from the tangible products (e.g., strategies), the transdisciplinary process, if designed accordingly, might also lead to less tangible but equally important outcomes, such as enhanced decision-making capacity of the practice actors involved (Wiek et al. 2006; Walter et al. 2007). Likewise, a transdisciplinary project can trigger an intense learning process. It can empower and motivate stakeholders to contribute more actively to the implementation or related decision processes. Especially in the field of sustainability science, the centralized steering idea has to be questioned and, in many cases, be replaced by the metaphor of an ongoing learning process (see, e.g., Laws et al. 2004).

Design principles for transdisciplinary research in sustainability science

In the following, we synthesize insights from different strands of the literature as well as from experiences in transdisciplinary projects over the past 10 years into a comprehensive and practice-oriented set of design principles for transdisciplinary sustainability research (e.g., Siebenhüner 2004; Bergmann et al. 2005; Blackstock et al. 2007; Pohl and Hirsch Hadorn 2007; Regeer et al. 2009; Wiek 2009; Bergmann et al. 2010; Brundiers and Wiek 2011; Scholz 2011). We, thereby, also draw from various articles focusing on particular quality criteria of transdisciplinary (sustainability) research, such as the mitigation of conflicts and negotiation (van den Hove 2006) or balancing control and accountability (Talwar et al. 2011). We are fully aware that our synthesis does not always do full justice to the specific underlying theoretical assumptions, fields of application, and other features of the respective contribution from which we are drawing insights. However, we follow this pathway with the intention to bridge different communities of collaborative research in order to further develop the field and make these principles accessible to as many interested researchers and practitioners as possible.

The set of design principles is structured into the three phases of a transdisciplinary research process introduced in the previous section (Table 1). We have formulated those principles close to the actual research practice and as tasks that can be assigned to specific actors (researchers, stakeholder, facilitators, etc.) along the three phases of the research process. There is no fixed rule on who should take the lead with regards to which task; yet, it is important to assign responsibilities right from the beginning of the project (see the principles of *team building* and *assignment of appropriate roles*). To make the design principles as well as the phases more tangible, a transdisciplinary "model project" is presented along the principles in Table 2.

Phase A: Design principles for collaborative problem framing and building a collaborative research team

- *Build a collaborative research team*. Identify scientists from relevant disciplines/scientific fields and "real-world actors" who have experience, expertise, or any other relevant "stake" in the problem constellation pre-identified for the research project (Pohl and Hirsch Hadorn 2007). Apply transparent criteria and justifications for who should and who should not be included in the research project and why. Often, this is a recursive process when expanding the team with additional experts or real-world actors representing specific interests, expertise, or experiences *after* the initial problem description. Facilitate explicit team-building processes (*Selecting* team members and *building* a collaborative team are two different steps in the overall process.). Furthermore, it is crucial to establish an organizational structure in which responsibilities, competencies, and decision rules are clearly defined. In many cases, a good strategy is to establish balanced structures between researchers and practice actors on all organizational levels including a joint leadership (see, e.g., Scholz et al. 2006). Make sure to contract in advance professional facilitators who can support the team at critical stages of the research process. A key aspect of building a collaborative team is to develop a "common language" among all team members. This is a joint effort that builds capacity and prevents misunderstandings and roadblocks for collaboration at later stages of the research process. This effort cuts across the subsequent activities (problem definition, etc.) and continues into Phase B. Key components in this respect are, first, to commonly define those terms that play a central role in the problem field and/or are used differently in collaborating disciplines and, second, to build a joint understanding of key concepts relevant in the research process (Stokols et al. 2010).
- *Create joint understanding and definition of the sustainability problem to be addressed*. Define the sustainability problem as a societally relevant problem that implies and triggers scientific research questions. Justify that this is, in fact, a sustainability problem and not just any kind of complex problem (Siebenhnüner 2004; Wiek et al. 2012). Make sure all team members (scientists and practitioners) are involved in the problem definition. Facilitate the process in a way that integrates and balances "contradicting normative scientific and political claims of importance and relevance" (Bergmann and Jahn 2008, p. 92). This sub-principle ensures that any subsequent research task departs from this common reference point and, thus, contributes to the overarching project goal.

Table 1 Design principles for transdisciplinary research in sustainability science and related guiding questions

Design principle	Guiding question
Phase A	
Build a collaborative research team	Does (did/will) the project team include all relevant expertise, experience, and other relevant "stakes" needed to tackle the sustainability problem in a way that provides solution options and contributes to the related scientific body of knowledge?
Create joint understanding and definition of the sustainability problem to be addressed	Does the project team reach a common understanding of the sustainability problem to be addressed and does the team accept a joint definition of the problem?
Collaboratively define the boundary/research object, research objectives as well as specific research questions, and success criteria	Is a common research object or guiding question, with subsequent specified research object and questions, formulated, and does the partners agree on common success criteria?
Design a methodological framework for collaborative knowledge production and integration	Does the project team agree upon a jointly developed methodological framework that defines how the research target will be pursued in Phase B and what transdisciplinary settings will be employed? Does the framework adequately account for both the collaboration among the scientific fields and with the practice partners?
Phase B	
Assign and support appropriate roles for practitioners and researchers	Are the tasks and roles of the actors from science and practice involved in the research process clearly defined?
Apply and adjust integrative research methods and transdisciplinary settings for knowledge generation and integration	Does the research team employ or develop methods suitable to generate solution options for the problem addressed? Does the team employ or develop suitable settings for inter- and transdisciplinary cooperation and knowledge integration?
Phase C	
Realize two-dimensional integration	Are the project results implemented to resolve or mitigate the problem addressed? Are the results integrated into the existing scientific body of knowledge for transfer and scaling-up efforts?
Generate targeted products for both parties	Does the research team provide practice partners and scientists with products, publications, services, etc. in an appropriate form and language?
Evaluate scientific and societal impact	Are the goals being achieved? What additional (unanticipated) positive effects are being accomplished?
General Design Principles (cutting across the three phases)	
Facilitate continuous formative evaluation	Is a formative evaluation being conducted involving relevant experts related to the topical field and transdisciplinary research (throughout the project)?
Mitigate conflict constellations	Does the researchers/practitioners prepare for/anticipate conflict at the outset, and are procedures/processes being adopted for managing conflict as and when it arises?
Enhance capabilities for and interest in participation	Is adequate attention being paid to the (material and intellectual) capabilities that are required for effective and sustained participation in the project over time?

The precise formulation of the design/evaluative guiding questions depends on the specific type of evaluation, e.g., ex-ante assessment, formative evaluation during the research process, or ex-post evaluation (internal or external)

- *Collaboratively define the boundary/research object, research objectives as well as specific research questions and success criteria*. Collaboratively formulate the overall object and objective(s) of the research process in order to be able to track progress and realign research activities during the research process (Defila et al. 2006; Blackstock et al. 2007). The boundary/research object can be formulated in a guiding question (Scholz et al. 2006) and often needs to be further specified in a set of sub-questions. The definition of the research objective(s) requires explicitly accounting for the different interests of scientists and practitioners collaborating in the project (Wiek 2007). While synergistic, both parties pursue ultimately *different* objectives (extending the body of scientific knowledge vs. solving/transforming the real-world problem), and it is advantageous for the process to make these differences transparent. Still, especially the roles of scientists will become multiplied and potential role conflicts need to be reflected upon. Subsequently, the boundary/research

Table 2 Compliance with design principles in the project: "Sustainable Urban Mobility—Strategies for an Environmentally and Socially Sound, and Economically Efficient Development of Transportation in Urban Regions" funded by the German Federal Ministry of Education and Research, 1994 to 1998 (Bergmann and Jahn 2008)

Principle	Realization
Phase A	
Build a collaborative research team	Team built from an environmental research network of independent research institutes and complemented by additional partners; therefore, most team members were used to collaborate in cross-disciplinary, problem-oriented integrative research projects. City departments (transportation and urban planning, finance) of Freiburg and Schwerin, both in Germany, which served as model cities
Create joint understanding and definition of the sustainability problem to be addressed	Clear distinction between the societal, real-life problem and the research object. Description of the societal problem: "The dramatic increase in motorized transportation services has led to a number of environmental problems, impaired the quality of life in urban areas and constrained opportunities for urban development. Exclusively technical solutions directed at vehicles or infrastructure do not result in the envisioned improvements" (English translation of Bergmann et al. 2010)
Collaboratively define the boundary/research object, research objectives as well as specific research questions, and success criteria	Main research object (guiding question): "How can mobility be decoupled from its prevailing form of realization, namely, auto-mobility?" To facilitate the access for different disciplines, mobility was deconstructed into the three dimensions physical, social-spatial, and social-symbolic mobility Research questions were not formulated along the participating disciplines but, along aspects of the societal problems, acknowledging the necessity of developing cross-disciplinary methods: • How to combine data on mobility behavior, the symbolic dimension of transportation behavior, means of transportation, and the citizens' lifestyles? ⇨ New method developed: mobility style analysis • What are the interdependencies between planning and transportation, including the spatial allocation of housing, workplaces, transportation routes, and transportation demand? ⇨ Development of a computer-aided learning model for city/transportation planners • How to realize a sustainable urban transportation system that is economically sound in times of low budgets in communities? ⇨ Development of an accounting system "Least Cost Transportation Planning" integrating all (internal and external) investment and subsequent costs
Design a methodological framework for collaborative knowledge production and integration	Strong coupling between the research questions and the method development ⇨ Collaboration and integration during the entire research process
Phase B	
Appropriate roles for practitioners and researchers	Citizens surveyed and engaged in writing mobility diaries were involved as everyday experts; team members from the city departments served as planning experts (part of the research team)
Apply and adjust integrative research methods and transdisciplinary settings for knowledge generation and integration	See methodological framework and the integrative research questions above. Mentors principle was developed (Mentorship pairs are formed of two team members from different disciplines. They mutually review and comment on each others' products to enhance their comprehensibility for extra-disciplinary participants and the connectivity between all products)
Phase C	
Realize two-dimensional integration	Two-dimensional (re-)integration through key questions. Answers refer to the respective research results and provide: (a) integration of concepts and methods into the body of scientific knowledge; (b) integration of local implementation strategies (planning guide for local community actors)
Generate targeted "products" for both parties	Planning guide for communities containing a 'Sustainable mobility management scheme' was published. Book on "Sustainable urban mobility" was written for sciences and reported on the newly developed methods

Table 2 continued

Principle	Realization
Evaluate scientific and societal impact	The mobility-style analysis, the LCTP procedure, and the computer learning model became regular research tools in the official transportation and city planning procedures. A formal ex-post evaluation on specific scientific and social impacts was not conducted
Facilitate continuous formative evaluation	Workshops with and without external reviewers were conducted as evaluative, reflexive milestones (formative evaluation) throughout the project
General Design Principles (cutting across the three phases)	
Mitigate conflict constellations	No conflicts occurred within the core team due to the fact that team members were used to collaborating in transdisciplinary projects and that most stakeholders agreed on the relevance of the topic. The conflict between the research team and external researchers responsible for collecting quantitative national transportation data, who were hesitant to adopt the new policy-oriented method, had to be moderated by officials from the Federal Ministry of Education and Research
Enhance capabilities for and interest in participation	Consultant provided professional facilitation within the research network and between scientists and actors from practice

object and the objectives needs to be further specified into operationalized research questions, which is a crucial step for developing an integration model, and facilitates designing the methodological framework. Outline the success criteria, which will be used to evaluate whether the objective(s) was/were met or not.

- *Design a methodological framework for collaborative knowledge production and integration*. Agree on the set of methods and transdisciplinary settings to be applied in Phase B and develop a concept for integrating the research results throughout the project (see, e.g., Scholz et al. 2006; Wiek and Walter 2009; Talwar et al. 2011). Existing methodological compilations for transdisciplinary research should be consulted (see, e.g., Scholz and Tietje 2002; Weaver and Rotmans 2006; Bergmann et al. 2010). The latter concept should also employ evidence-based templates for collaboration, such as the functional–dynamic model of participation proposed by Stauffacher et al. (2008). Such a framework allows a structured collaboration and synthesis across all team members and project phases. The framework might have to be adjusted during the project, but it provides a common orientation for all team members from the beginning (Defila et al. 2006; Scholz et al. 2006).

Phase B: Design principles for co-creation of solution-oriented and transferable knowledge through collaborative research

- *Assign and support appropriate roles for practitioners and researchers*. Assign in each research effort appropriate roles and responsibilities for scientists and practitioners in a transparent process, accounting for inertia, reluctance, and structural obstacles (Maasen and Lieven 2006; Wiek 2007). Base the assignments on the overall framework outlined in Phase A and make sure that they comply with the predefined organizational structure of the project. For scientists, balancing societal relevance with scientific rigor becomes a key challenge and asks for particular attention. Ensure facilitation that allows compliance with the assigned roles and responsibilities as well as attaining to the aspired levels of participation (van Kerkhoff and Lebel 2006; Wiek 2007). Furthermore, leadership related to cognitive (providing a means to integrate the different epistemics of the actors involved), structural (addressing the needs for coordination and information exchange), and procedural (resolving conflicts during the process) tasks facilitates successful transdisciplinary processes (Gray 2008).
- *Apply and adjust integrative research methods and transdisciplinary settings for knowledge generation and integration*. According to the methodological framework developed in Phase A, make use of and further develop appropriate methods for transdisciplinary sustainability research. Use tools to support teamwork and collaboration such as the *advocate principle*, the *tandem principle* 2, or the *mentors' principle* (see Table 2) (Bergmann et al. 2010). Such instruments provide the research team with valuable support for inter- and transdisciplinary quality control and help to make research results better accessible for practice partners. The team might also utilize their collaborative potential and further develop existing or develop novel methods for transdisciplinary knowledge production and integration.

Table 3 Empirically derived challenges of transdisciplinary research in sustainability science and outline of some exemplary coping strategies

Design principles	Challenges			Exemplary strategies
	Title	Description	Sources	
Phase A				
Joint problem framing	Lack of problem awareness or insufficient problem framing	Issues are not perceived as being problematic	Trutnevyte et al. (2011), Dunn et al. (2011), Ng'ang'a et al. (2009)	Conduct primarily study to build problem awareness
Collaboratively defining the boundary/research object	Unbalanced problem ownership	Dominance of scientists or actors from practice in defining the joint boundary/research object and research objectives	Krütli et al. (2010b), Gatzweiler (2005)	Joint leadership
Team building	Insufficient legitimacy of the team or actors involved	Underrepresentation of relevant actor groups in the research process	Scholz et al. (2009), Keller (2011), Tavener-Smith (2012)	Stakeholder mapping (expertise and interest); creating structures that enable participation
Phase B				
Application of methods and settings for integration	Conflicting methodological standards	Conflict between scientists and researchers regarding suitable methods	Wiek et al. (2010), Talwar et al. (2011)	Systematic comparison of methods; use demonstration projects
Application of methods and settings for integration	Lack of integration	Lack of integration across knowledge types, organizational structures, communicative styles, or technical aspects	Jahn (2008), Bergmann et al. (2010), Walz et al. (2012)	Application of structured and formative knowledge integration methods
Appropriate roles Capabilities for participation (cross-cutting principle)	Discontinuous participation	Barriers for researchers and partners from practice to participate in transdisciplinary processes	Zajíkovà and Martens (2007), Wiek et al. (2012)	Design project with low thresholds for and appropriate levels of participation
Application of methods and settings for integration	Vagueness and ambiguity of results	Different interpretations of results conceal potential conflicts	Trutnevyte et al. (2011)	Specification and explicit conflict reconciliation
Capabilities for participation (cross-cutting principle) Application of methods and settings for integration	Fear to fail	Pressure leads to retreat to pre-packaged solutions Knowledge-first trap blocks solution-oriented progress	http://www.sdinet.org/country/malawi/	Initialize actions first to stimulate researching-/learning-by-doing
Phase C				
Two-dimensional integration	Limited, case-specific solution options	Lack of transferability and scaling-up of results (insufficient reintegration)	Parodi et al. (1998), Wiek et al. (2012)	Comparative studies to derive generalizable results

Table 3 continued

Design principles	Challenges		Sources	Exemplary strategies
	Title	Description		
Two-dimensional integration Scientific and societal impact	Lack of legitimacy of transdisciplinary outcomes	Friction between transdisciplinary projects and political processes	Stauffacher (2010), Scholz (2011), van Zeijl-Rozema and Martens (2011)	Take into account existing socio-political context in the design
Targeted "products" Scientific and societal impact	Capitalization on distorted research results	Results are misused to legitimate actions that were not intended	Hyman (2011), Cape Higher Education Consortium (CHEC) et al. (2011)	Establish ongoing collaborative and reflexive discourse
Targeted "products" Scientific and societal impact	Tracking scientific and societal impacts	Difficulties to assess scientific and societal impacts due to characteristics of transdisciplinary research	Walter et al. (2007)	Employ advanced evaluation methodologies

Phase C: Design principles for (re-)integrating and applying the created knowledge

- *Realize two-dimensional (re-)integration*. Review and revise the outcomes generated in Phase B from both perspectives separately, i.e., the societal and the scientific practice. Likewise, the mutuality of the learning process becomes visible. It is important to employ different criteria for revision and rendering, as both perspectives adhere to quality criteria such as scientific credibility or practical applicability (saliency) differently (Wiek 2007; Jahn 2008).
- *Generate targeted "products" for both parties*. Provide the scientific actors and the practice partners with appropriate products (cf. Defila et al. 2006) that present and "translate" the results of the project in a way that the actors can make use of—as a contribution to real-world problem-solving/transformation or to scientific progress/innovation (Pohl and Hirsch Hadorn 2007).
- *Evaluate societal and scientific impact*. Evaluate the project at different stages after completion of the project to demonstrate impact and generate lessons learned for future project design (Walter et al. 2007). For both scientific as well as societal impacts, an important reference point is the success factors defined in Phase A, which might have been adapted in the course of the project.

General design principles cutting across the three phases

- *Facilitate continuous formative evaluation*. Formative evaluation throughout the transdisciplinary sustainability research project by an extended peer group (comprising experts from science and practice) allows reviewing progress and reshaping the subsequent project steps and phases if necessary (Bergmann et al. 2005; Walter et al. 2007; Regeer et al. 2009).
- *Mitigate conflict constellations*. Transdisciplinary research is characterized by continuous interaction between scientists from different disciplines and different practice actors. The context that existed at the outset of the process can rapidly shift as new actors become involved, actors change roles or attitudes, new insights are being revealed, and so forth. In order to prevent conflicts, reflexive meetings, open discussion forums, explicit and mediated negotiations as well as adapted agreements should accompany the transdisciplinary research process over the entire course of the project (van den Hove 2006; Wiek 2007). This means that the learning process inherent in a transdisciplinary project needs to be carefully designed and followed.

- *Enhance capabilities for and interest in participation*. It cannot be assumed that all actors have the capacity or continuous interest to participate in a given transdisciplinary research project that might continue over several years. Some actors might underestimate the time and energy necessary to participate in a meaningful way, while others might not have the means to become involved from the outset. For continuous stakeholder participation it is inter alia important: to select locations that are easily accessible for stakeholders; to schedule meeting times that allow maximum participation; to facilitate discussions in several languages (as necessary); to involve stakeholders through a high level of interactivity that allow participants not only to articulate their perspectives, but also to engage in meaningful discussions, deliberations, and negotiations; and to incorporate visual products and media, for instance, by visual designers during the activities in order to allow for meaningful interactions across different languages, levels of literacy, and educational backgrounds (Stokols et al. 2010).

The purpose of the design principles formulated above is to practically guide transdisciplinary research processes and facilitate an effective and efficient research process for all actors involved. The principles present ideal–typical guidelines rather than instructions that can be applied in any given context. Like the conceptual model, the design principles represent a generic transdisciplinary research process. In the context of sustainability science, each phase and principle might take a particular shape that reflects the specificities of the transformational character of sustainability science, the specific features of sustainability problems in each context, and the unique ways in which non-academic actors are involved in each phase (including their capacities for effective participation).

Challenges of transdisciplinary research in sustainability science

In order to exemplify the role of the design principles in sustainability science and to raise awareness for critical aspects, we present and discuss exemplary challenges and outline coping strategies as experienced in transdisciplinary sustainability research projects over the past 10 years (see Table 3).[2]

[2] Not all of the projects we draw from used the term "transdisciplinary" nor did all of the projects meet all design principles; however, the basic intention of all projects was (explicit or not) to comply with the requirements of the above definition of transdisciplinary research.

Specific challenges in collaborative problem framing and team building (Phase A)

Lack of problem awareness or insufficient problem framing

The principle to start from a joint problem definition can be challenged by a lack of problem awareness and the resulting lack of agreement on the problem. In one case, a research team approached the mayor of a Swiss municipality with whom they had collaborated in previous transdisciplinary projects (Scholz et al. 2006; Scholz and Stauffacher 2007). The offer was to initiate a project on innovative community-based energy strategies. The mayor replied that the community would not be aware of the relevance and urgency of this issue and claimed that the initial goal should be to raise awareness on issues of energy production, shortage, and impacts. Thus, the research team and the mayor jointly defined a guiding question that provocatively asked if the community needs an energy strategy at all (Cloos et al. 2010). In this case, the actual problem definition was the main project result and required a relatively laborious process, in which the community eventually realized the need for an energy strategy and structured energy planning (Trutnevyte et al. 2011). This example speaks to the general challenge of overcoming reluctance and inertia on both sides, science and society alike, to leave their respective "comfort zone" and engage in a truly mutual and joint problem-framing process (Bergmann and Jahn 2008). In other cases, the problem definition might run against one-sided perceptions, established practices, or institutional inertia. For example, across Africa, the distribution of insecticide-treated bed nets (ITNs) forms a major part of many national and international malaria control programs with the goal of universal coverage over the next decade. Though they are effective, poor uptake rates and improper use of ITNs is a major impediment to their success. This is widely perceived as a users' problem that can be fixed by top-down education and marketing schemes. In a recent participatory study of ITN use in southern Tanzania, Dunn et al. (2011) revealed that there are numerous "nuanced and inter-related socio-cultural and economic explanations for non-use, which interplay with the everyday ways in which people live their lives" and that there is an urgent need "to move beyond explanations of 'non-compliance' at the individual and household level to an appreciation of how malaria-related behaviours map onto the 'reality' of rural livelihoods" (p. 415). The importance of local cultural, social, and economic factors in determining effective bed net use highlights that a transdisciplinary approach, integrating knowledge from different disciplines related to these factors as well as experiential knowledge from actors in the cases under investigation, will be required to establish sustainable malaria control (Ng'ang'a et al. 2009). This is, in general, true for public health, which is a key aspect of sustainable development. Yet, this is often at odds with the established modes of operation and funding schemes of international aid organizations.

Unbalanced problem ownership

The initiative for transdisciplinary research projects is rarely taken jointly by partners from science and practice. Though there are cases where partners from practice approach researchers with regards to societal problems, in the majority of cases, scientists approach partners outside academia to get them involved in transdisciplinary research projects (Siebenhüner 2004; Wiek et al. 2007; Talwar et al. 2011). In one case, a research team was interested in conducting a study on what defines a fair and transparent site selection process for nuclear waste disposal in Switzerland (Krütli et al. 2010a). The team encountered tremendous reluctance and resistance from potential partners outside academia due to the contested nature of the topic and a long-standing history of fierce debates in Switzerland. Although the transdisciplinary research project got realized, unbalanced problem ownership continued over the course of the project and led to several difficulties. Diverging starting points are not problematic per se. Yet, they become a major challenge if the divergence is not narrowed or bridged in the problem-framing phase of the project. An organizational project structure that establishes joint leadership as well as shared rights and obligations from the outset is conducive to developing balanced problem ownership (see design principle "build collaborative research team"). Unbalanced problem ownership can be prevented through a project setting that closely links knowledge production and implementation interests, as demonstrated in a project on the conservation and use of wild populations of "Coffea arabica" in the montane rainforests of Ethiopia (Gatzweiler 2005; Schmitt et al. 2010). Two success factors in this project were as follows: first, the project was initiated through an Ethiopian scientist who conducted his PhD on the rainforest loss in his home region with the intention to create knowledge applicable to conservation efforts; second, the non-profit Ethiopian Coffee Forest Forum was founded in the first phase of the project and worked as an intermediary (or boundary) organization between research and implementation during the remainder of the project.

Insufficient legitimacy of the team or actors involved

Legitimacy is an important quality criterion for transdisciplinary research or boundary work for sustainable development in general (Cash et al. 2003; Clark et al. 2011). Compliance with this principle requires the selection of a sufficient number and diversity of stakeholders with a legitimate stake in the process, be it, for instance, because they are negatively affected by the problem or because they are responsible parties. This poses a twofold challenge: first, in the majority of projects, it is only possible to involve a relatively small number of actors due to limited resources and methodological reasons; second, it is very tempting to rely on the network of "usual suspects", namely, people who have been involved in previous projects or are generally interested in participatory and civic engagement processes—but by no means represent all or even the most relevant stakeholder groups. In one project on the future of the Swiss waste management system, the team conducted a criteria-based stakeholder and expert selection that relied on a set of predefined expertise and interests, which were informed by the initial problem framing (Scholz et al. 2009). Despite the comprehensive and elaborated stakeholder mapping, this explicitly sustainability- and future-oriented research project still faced the challenge of how to involve representatives of future generations. This is particularly important in infrastructure projects that create path dependencies for one or more generations. In response to this challenge, there are novel approaches emerging, for instance, the appointment and involvement of "guardians for future generations" (Skagen Ekeli 2006). Another challenge related to the selection and involvement of legitimate stakeholders is the lack of knowledge on who the relevant stakeholders actually are. This challenge is, for instance, prevalent in many developing country contexts going through extremely rapid urbanization processes. In such situations, there can be very serious problems, such as homeless people living in illegal informal settlements, but without formalized stakeholder or recognized leadership groups to represent them. Quite often, the leadership groupings are informal and even make an effort to hide themselves to avoid repressive state action. In Stellenbosch, South Africa, researchers engaged, for instance, with a community of 6,000 people called Enkanini who had illegally occupied a piece of public land (Keller 2011; Tavener-Smith 2012). Not only did government officials refuse to be seen to be "entering" this community, there was also no identifiable leadership to work with. The result was a prolonged process over several months of engaging with individuals, staying for days or weeks at a time in the community to become part of everyday life, working with individuals on their problems, and then slowly making contact with community leaders as trust was built. This highlights the fact that problem formulation might be a prolonged social process involving interactions with many individual actors rather than an event involving established formations.

Specific challenges in co-producing knowledge through collaborative research (Phase B)

Conflicting methodological standards

Transdisciplinary sustainability research is a research practice and, as such, needs to adhere to quality standards, in particular, when it comes to adopting and applying research methods (Wiek et al. 2012). However, quality standards in transdisciplinary research are, as indicated above, not as clear-cut as it might be the case in other academic fields. Apart from scientific credibility, the criteria of saliency and legitimacy demand equal attention in transdisciplinary sustainability research, even though scientists in the present academic system are still primarily judged by the former. This might lead to conflicts between scientists and practice partners, who might have different expectations and enforce different quality standards, in particular, when using methods for which both practical and scientific approaches exist. In a transdisciplinary project in Sri Lanka, this challenge became so serious that the success of the overall project became jeopardized. The project objective was to develop a culturally sensitive, practically applicable, and, nevertheless, scientifically sound planning framework for sustainability-oriented long-term recovery after the 2004 tsunami in the Indian Ocean (Wiek et al. 2010). While researchers insisted on employing and integrating advanced scenario construction and multi-criteria assessment methods into the framework, partners from local NGOs and international aid organizations opted for rather pragmatic tools. The conflicts were never fully resolved but mitigated through increased internal facilitation and mediation. Systematic and criteria-based comparisons between the different methodological options seems to be a promising way to go (Savan and Sider 2003); yet, in this particular case, it was difficult to realize because of time constraints.

Lack of integration across knowledge types, organizational structures, communicative styles, or technical aspects

Several integration challenges might be encountered when conducting transdisciplinary research that can be differentiated into cognitive-epistemic, social and organizational, communicative, and technical challenges (Jahn 2008; Pohl 2011). These challenges can be exemplified through a transdisciplinary scenario study (Walz et al. submitted), which was part of a research project on ecosystem services in Swiss mountain regions.[3] The scenarios were inter alia intended to provide inputs for ecosystem models as well as for framing policy options. A cognitive-epistemic integration challenge is, for instance, highlighted by the fact that the ecosystem models considered timeframes of several decades, while the policy and decision-making analyses considered much shorter timeframes. A technical integration challenge occurred because the models provided and needed quantitative data, whereas for policy and decision-making analyses also qualitative aspects played an important role. Differently interpreted definitions of key aspects among team members posed an additional communicative integration challenge. The methodology of formative scenario analysis provided a helpful means to cope with these integration challenges (Scholz and Tietje 2002; Wiek et al. 2006; Spoerri et al. 2009). Using such integrative methodologies can serve as a means to tackle various types of integration challenges (Bergmann et al. 2010).

Discontinuous participation

Continuous interest and participation is a critical success factor for transdisciplinary sustainability research. Yet, there are critical factors that can undermine continued participation. For instance, in a project related to regional sustainable development in the Slovak Republic, researchers faced a low and steadily decreasing level of participation, inter alia, due to a general lack of civic engagement in this post-communist country. This might be a consequence of citizens' increasing opportunism and growing mistrust in public institutions (Zajíkovà and Martens 2007). To cope with this challenge, research was designed in a way such that participation was generally affordable and associated with as little effort as possible; for example, questionnaires were directly distributed to potential respondents through peers serving as "promoters" of the project. Another example stems from a transdisciplinary research project on urban sustainability in Phoenix, Arizona (Wiek et al. 2012). Ironically, the project had a similar starting point as the previous one from the Slovak Republic because the last formal public engagement process related to urban planning in Phoenix dated back to the 1970s. Despite this lack of familiarity with civic engagement in urban planning, the interest and participation in the transdisciplinary research activities was profound. The challenge was, instead, on side of the research team trying to keep up with and follow up on all citizens' and organizations' requests and offers to continue and even extend their participation. Because of a lack of handling capacity, interest and participation in the project decreased or was, at least, not fully utilized over the course of the project. This indicates the need for finding the right level and scale of participation that is manageable and can be maintained over the entire life-span of the project.

[3] See: http://www.cces.ethz.ch/projects/sulu/MOUNTLAND. See also Wiek et al. (2012).

Vagueness and ambiguity of results

The co-production of knowledge in transdisciplinary projects is confronted with the potential pitfall of creating results that are approved of by the collaborating parties only because they are kept vague and ambiguous. An example is the creation of sustainability visions, which play an increasingly important role in transdisciplinary sustainability research projects (Kim and Oki 2011; Wiek and Iwaniec 2011). Visions are usually articulated and documented in images, narratives, or metaphors. Such visions are often generic and ambiguous, and, thereby, might conceal potential conflicts, due to their interpretative flexibility (Berkhout 2006; Raven et al. 2009). To cope with this challenge, different strategies have been developed. In a project on regional energy strategies in Switzerland, for each energy vision, a number of specific scenarios were collaboratively developed to reveal what concrete actions the visions implied. In so doing, the visions became tangible and made a more in-depth deliberation and co-production possible (Trutnevyte et al. 2011). Similarly, in a visioning project on sustainable urban development in Phoenix, Arizona, the research team conducted a large-scale workshop to identify, deliberate, and reconcile conflicts in different urban visions (Wiek and Iwaniec 2011).

Fear to fail

There are several potential shortcomings and flaws which transdisciplinary sustainability research has to navigate, one of the most critical ones being the fear to fail. This might lead to retreating to pre-packaged (technical) solutions without facilitating a process that allows involved practice partners, such as communities, to understand the rationale of the solution options, or it might lead to endless collaborative research that continuously postpones the ultimate step of releasing the outcomes (knowledge-first trap). An alternative is to actively perturb the system by quickly putting knowledge into action and embracing the notion of "researching-by-doing" (like learning-by-doing). This is what happened in a project in Lilongwe, Malawi.[4] Instead of spending time developing a comprehensive vision which presumes that action flows from fully fledged images of the future, researchers helped train homeless women to use adobe bricks to build houses that did not need to be fired in a charcoal-burning kiln. Within a period of 6 months, 800 houses were built on land donated by the municipality. Many things went wrong that a more thorough research process would have averted, for instance, inappropriate low-density layout, standalone rather than semi-detached units, and single-storey buildings, but the learning from this action–reflection process is what led to improved outcomes during the second phase of the project. Action created the space for learning-by-doing—an iterative cycle based on the audacity to fail (at the beginning).

Specific challenges in (re-)integrating, transferring, and applying the created knowledge (Phase C)

Limited case-specific solution options

A key principle of transdisciplinary research is the (re-) integration of the generated knowledge into scientific and societal practice. While real-world implementation of the solution options to the sustainability problem is critically important, it is equally important to integrate the generated knowledge into the existing body of scientific knowledge. A major reason is that, thereby, this knowledge becomes transferable and applicable to other cases and other problem constellations. However, the generalization of case study results poses a major challenge to transdisciplinary sustainability research that has been experienced in numerous projects. This can be illustrated with the example of a transdisciplinary study on the mitigation of rapid urbanization and fostering rural energy independence in Argentina (Parodi et al. 1998). The project successfully created actionable knowledge that was used to install solar home systems and a PV water pumping system in a rural village. All systems have consistently worked for more than 10 years and are owned and maintained by the villagers. The project has generated several positive outcomes. However, the project was lacking in terms of reintegrating the generated knowledge with similar studies that would allow transferring, multiplying, and scaling up the solution options that are possibly viable for many other rural communities (Wiek et al. 2012). This limits the success of the project as its transdisciplinary introduction of technologies largely remains with the small community of project partners. While a single case study does not provide enough evidence to design and fund larger programs, the need for transfer and scaling up in this particular case is substantial, as there are rather few successful cases of establishing functioning solar systems in rural areas in the long run.

Lack of legitimacy of transdisciplinary outcomes

Another challenge emerges from the question of what role the results of a transdisciplinary research project ought to play in relation to "official" political processes (e.g., legal resolutions). Transdisciplinary sustainability projects aim to generate actionable knowledge for collective action in order to mitigate or resolve sustainability problems. This

[4] Personal observations; project documentation available at: http://www.sdinet.org/country/malawi/.

process and its outcomes might interfere with legitimized procedures and official politics. In a project on urban sustainability in the northeastern part of Switzerland, this challenge became apparent through the continuous and productive controversy between researchers and practice partners (urban planning department) about the status and potentially disruptive impact of the research results. This challenge refers back to the challenge of coping with the legitimacy of the team and the partners, or the lack thereof (Phase A). In another project, a transdisciplinary study on measuring sustainable regional development in the Netherlands (Province of Limburg), the results generated in the project were not adopted and implemented, in part, due to the fact that the research team had partnered with experts who "had no political mandate for defining sustainable development in this regional context because [they were] neither representative of the population nor an elected body with delegated powers from the residents of Limburg" (van Zeijl-Rozema and Martens 2011, p. 202). Coping strategies have to be applied early in the process (Phases A or B) and include transparent deliberation of roles and expectations, as well as ensuring complementarity between the transdisciplinary project and ongoing political processes (Wiek 2007; Stauffacher 2010; Scholz 2011).

Capitalizing on distorted research results

The co-production of knowledge in transdisciplinary sustainability research projects requires the sharing of rights and responsibilities between scientists and practice partners (Talwar et al. 2011). However, even a carefully conducted transdisciplinary research project might not always lead to results that satisfy both parties. Even worse, the results might be (re-)integrated into either domain, science or society, in ways not approved of by the collaborating partner. This might lead to situations where, for instance, researchers find themselves unwittingly "supporting" an application of the generated knowledge which they might strongly disagree with. A good example for this challenge is a transdisciplinary research project from Cape Town creating a strategy for a large-scale sustainability-oriented rejuvenation of the Central Business District. The study was undertaken by a consortium of researchers from the three Cape Town-based universities, representatives of government, and representatives of the property development industry (Cape Higher Education Consortium [CHEC] et al. 2011; Hyman 2011). Jointly initiated by the researchers and the government, the research extended over a period of 6 months and included joint workshops, meetings, and discussions. The end result was a policy-oriented, research-based document that fundamentally redefined the future of the Central Business District by proposing a comprehensive economic development strategy based on social inclusion and sustainability. However, over the course of the year that followed the adoption of the approach by the government, government officials slightly twisted the results to emphasize financial returns on investment rather than the comprehensive approach. When faced with opposition, they legitimized their strategies by referring to the fact that the universities helped to co-author the framework. To counteract this, the universities established a broad stakeholder forum to review the specific strategies against the overall approach of the initial document. In summary, the reintegration and knowledge transfer became an ongoing and contested process.

Tracking scientific and societal impacts

Besides formative evaluation, which is a crucial part of sound transdisciplinary research practice, evaluating the societal as well as the scientific impacts of a transdisciplinary project is important for legitimizing the additional resources and time invested (compared to "normal" research). While there are fairly robust and standardized approaches to evaluate scientific impact (bibliometric and citation metrics), these approaches are not sufficient for appraising the contribution of the individual project to sustainability science's core questions (Kates et al. 2001) and grand challenges (Reid et al. 2010). Yet, it is even more challenging to accurately track societal impacts of transdisciplinary research. Such impacts often occur with significant delays; causal relations between a project and its impacts are often difficult to establish because of the complexity of the problems addressed and the complexity of the solution options adopted; impacts might include effects that are important but not easily measurable, such as increased decision-making capacity (Pregernig 2007; Walter et al. 2007; Talwar et al. 2011). These challenges were also encountered in a transdisciplinary research project in Switzerland on sustainable transition strategies for traditional branches of a regional economy (e.g., dairy, saw mill, textile industry; see Scholz et al. 2006; Scholz and Stauffacher 2007). The evidence for increased decision-making capacity was rather inconclusive, in part due to a lack of a rigorous evaluation methodology. The research team, therefore, developed a methodology (including a social effect index) and conducted a comprehensive ex-post evaluation 3 years after the completion of the project. The evaluation revealed a significant correlation between project involvement and increased decision-making capacity (Walter et al. 2007).

Concluding remarks

Societies face sustainability challenges that entail a multitude of different problems with specific characteristics.

Coping with these problems in an efficient and effective way requires selecting the research approach and principles that fit best. As sustainability science is a problem-driven and solution-oriented field that follows a transformational agenda, transdisciplinary research is, in many cases, a promising choice, as it aims at bridging the gap between problem solving and scientific innovation. But this does not undermine the relevance of disciplinary or interdisciplinary approaches. Spangenberg (2011) suggest the distinction between science for sustainability (rather monodisciplinary) and science of sustainability (inter- and transdisciplinary), the latter having gained much less attention than the former. In contrast to other reviews, the objective of this paper is neither to focus on differentiating features of transdisciplinary, participatory, and collaborative research approaches, nor to highlight differentiating characteristics of sustainability science as compared to other research fields applying transdisciplinary approaches. The goal is, instead: to formulate a set of principles for guiding transdisciplinary research in sustainability science based on the literature and empirical research experience; to present exemplary challenges faced in concrete transdisciplinary research projects in the field of sustainability science; and to outline some possible strategies to cope with these challenges. In linking the principles to an ideal–typical conceptual model of a transdisciplinary research process, they should offer a framework for practically designing, conducting, and evaluating transdisciplinary research. Nevertheless, the presented challenges provide clear evidence that this framework should not be understood as "a recipe" applicable in any given context. In contrast, as transdisciplinary sustainability research is in general embedded in specific contexts, the compiled principles need to be specifically adapted for each project. Thus, to further strengthen transdisciplinary sustainability research, more emphasis needs to be put on better understanding context conditions across various cases. One of the fascinating experiences made while co-authoring this article was to realize fundamental differences among transdisciplinary research projects conducted in different cultural contexts; yet, it was interesting to see that the design principles derived from projects in specific contexts seem also to be generally applicable in most of the other contexts. These specificities might require adopting and developing different and specific methodologies. However, the community needs to strive for enhanced collaboration and cohesiveness with respect to these methodologies. In fact, mutual learning among the different researchers needs to be established and learning processes beyond the boundaries of individual projects must take place. If the field of transdisciplinary sustainability research is soon about to reach a stage of maturity, existing conceptual, methodological, and empirical knowledge needs to be better synthesized and consolidated, while future research agendas need to be better coordinated. Along those lines, a critical step will be to turn the proposed set of design principles, which is entirely based on the literature and personal experiences, into an evidence-based set of principles. This calls for evaluative qualitative and quantitative meta-studies to make use of the widespread experiences and evidence. Thereby, it seems critical to also learn from other research fields, for instance, program evaluation research or intervention research (Fraser et al. 2009), in which transdisciplinary research is being conducted with an emphasis on demonstrating evidence of research–impact relations. Furthermore, it is necessary to better understand the various roles which scientists take in such projects and the respective role conflicts this might bring about.

As mentioned in the introduction, there is an ever-increasing call for transdisciplinary approaches to tackle fundamental societal challenges, especially those related to sustainability, both from society and the scientific community. In Germany, for instance, transdisciplinary research is considered to be key for the fundamental sustainable energy transition enacted by the Federal Parliament of Germany in Summer 2011. This new level of awareness and commitment is a tremendous opportunity to seize the potential of transdisciplinary research for societal (sustainability) transformations. However, it also bears the risk of leveling this research practice, using it as a remedy for any kind of research or problem-solving activity. The latter would neither contribute to the transformational agenda of sustainability science, nor would it help to strengthen sustainability science as a research field. The present article intended to navigate the space between opportunity and risk. Living up to the high expectations in transdisciplinary sustainability research will, however, require continuous structural changes in the academic system in order to build capacity for transdisciplinarity among students and researchers, as well as among stakeholders and decision-makers outside academia (Russell et al. 2008; Schneidewind et al. 2011).

Acknowledgments We would like to thank the four anonymous reviewers for their helpful comments on previous versions of this article. Furthermore, we want to thank Christopher Lüderitz and Rob Cutter for their helpful assistance. We acknowledge the feedback from the participants in the session on "Solution-oriented transdisciplinary research for sustainable development" at the 2nd International Conference on Sustainability Science (ICSS 2010), Sapienza University Rome, Italy, June 23–25, 2010, on critical issues discussed in this article. Arnim Wiek acknowledges support through the Swiss National Science Foundation grant PA0011-115315.

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