



Transdisciplinary co-production of knowledge and sustainability transformations: Three generic mechanisms of impact generation

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ABSTRACT

Transdisciplinary co-production of knowledge is widely credited with producing knowledge that can contribute to sustainability transformations, but there is little empirical evidence showing to what extent and through what mechanisms it is actually advancing sustainability. This article analyses how 31 transdisciplinary projects conceptualised the link between transdisciplinary co-production of knowledge and sustainability transformations, and as part of an institutional learning process explores what experiences projects garnered while implementing their theories of change. The research identified three generic conceptualisations of impact generation mechanisms: a) promoting systems, target, and transformation knowledge for more informed and equitable decision-making, b) fostering social learning for collective action, and c) enhancing competences for reflective leadership. It also identified seven different strategies through which the studied projects implemented these three generic mechanisms to induce sustainability transformations. Exploring potentials and limitations of the different mechanisms, the article concludes that the question is not which mechanisms or strategies are better than others, but in what situation and combination they might be most promising.

1. Introduction

The endorsement of the UN 2030 Agenda for sustainable development in 2015 reinforced the call for a form of science actively contributing to sustainability transformations. In other words, science should not only focus on better understanding human–nature interactions, but also seek to encourage changing these interactions along more sustainable trajectories (Kates et al., 2001). Sustainability scientists increasingly agree that the required changes need to be fundamental, rapid, and include a reflection on worldviews, beliefs, and power structures underpinning unsustainable development (Fazey et al., 2018). This in turn requires new research strategies that rethink how science and society relate to each other and how relevant knowledge is produced. In this context, transdisciplinary co-production of knowledge (TD) is considered a promising approach, because it focuses on real-world challenges, enables collaborations among various scientific disciplines and societal actors, and calls for self-reflectiveness (Fazey et al., 2018; Schneider et al., 2019b).

However, while TD receives much credit for producing knowledge that can contribute to sustainable development, there is little empirical evidence showing to what extent and through what mechanisms it is

actually advancing sustainability transformations (Bell et al., 2011; Kaufmann-Hayoz et al., 2016; Polk, 2014; Wiek et al., 2014). This makes it difficult for researchers and academic institutions to reflect on and enhance the contributions of science to sustainable development in a systematic way.

Existing studies investigating the link between TD and sustainability transformations use various frameworks usually consisting of a series of stages such as inputs, research processes, direct outputs, and further outcomes, which are connected through various feedback loops (Binder et al., 2015; Kaufmann-Hayoz et al., 2016; Mitchell et al., 2015; Wiek et al., 2014). But the process of impact generation is highly complex (Bornmann, 2013; Kaufmann-Hayoz et al., 2016) and existing frameworks still struggle to account for this complexity (Godin and Dore, 2005). Recent studies in the field of research impact evaluation have found that multiple pathways lead to societal impacts. Muhonen et al. (2019), for example, identified 12 different pathways from research to societal impact, ranging from the classical pipeline approach, to public engagement, commercialisation, and building of new epistemic communities. All of these pathways represent different forms of productive interactions between scientists and societal actors (Molas-Gallart and Tang, 2011; Spaepen and Van Drooge, 2011).

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Table 1
Characteristics of the projects that participated in the study.

Geographical context	Themes	Funding scheme	Project duration
Asia (10)	Sustainable land management (7)	International organisations (5)	< 1 year (1)
Africa (10)	Sustainable water governance (2)	European funders (2)	1–3 years (11)
Latin America (6)	Food sustainability (3)	National Science Foundation (12)	4–6 years (11)
Europe (16)	Large-scale land acquisitions (4)	National governments (21)	> 7 years (8)
Global (9)	Human-wellbeing and poverty reduction (6)	Foundations (5)	
	Ecosystem services and biodiversity (5)	NGO/CSO (3)	
	Sustainable regional/mountain development (5)	University (5)	
	Sufficient lifestyles (3)		
	Sustainable rural employment (2)		
	Policy coherence for SD (1)		
	Learning for sustainability (4)		
	Effectiveness of TD research (2)		
	Global sustainability - 2030 Agenda (1)		

N = 31. In brackets are the number of projects that fall into each category. Multiple attributions are possible.

In transdisciplinary co-production of knowledge, productive interactions are not only relevant for bringing the generated knowledge to fruition, but also for the very generation of new knowledge. It is assumed that the collaborative nature of the research approach itself, including joint framing of problems and goals, is constitutive for triggering transformative change (Lang et al., 2012). Relational outcomes such as increased trust, motivation, joint understanding, and network building are seen as mediators (Walter et al., 2007). Beyond these findings, little agreement exists on what are effective and desirable pathways to impact, partly because of lack of research, partly because TD proponents' views differ regarding the role that science can or should play in society. Some stress the academic character of TD endeavours transcending disciplinary boundaries to solve complex problems for society (Mittelstraß, 2018). Others highlight the need to link societal and scientific perspectives to create more relevant and robust knowledge (Hirsch Hadorn et al., 2006; Jahn et al., 2012). And others again conceptualise TD as an overall societal process where scientists and societal actors engage in joint learning and action (Krohn et al., 2019).

Whatever the approach, agreement exists that TD should entail self-reflexive processes (Fazey et al., 2018; Schneider et al., 2019b) and formative evaluation (Lang et al., 2012). For this purpose, scholars recently started to apply theory of change thinking, an approach for dealing with the highly complex process of impact generation through sustainability science (Heiskanen et al., 2018; Oberlack et al., 2019).

Theory of change thinking originated in the field of programme planning and development cooperation. It aims to enhance learning for effectiveness of societal interventions through designing and regularly scrutinizing pathways to impact. A theory of change outlines an intervention's working hypotheses about how its activities might trigger changes and continuously refines it through cycles of action and reflection. In doing so, it acknowledges that societal transformations are complex and contested processes that rarely unfold in linear ways (Dhillon and Vaca, 2018; Vogel, 2012). Understanding a TD project as an intervention at the science–society interface means exploring basic assumptions about how societal transformations unfold, as well as defining what role scientists and academic knowledge should play in this process, and how specific knowledge-related activities can induce transformative change (Green, 2016; Taplin and Rasic, 2012; Thornton et al., 2017). As theory of change thinking has only recently entered academic institutions, few reviews exist on TD projects' theories of change, and systematic learning exercises are lacking to reflect on assumptions regarding how change is achieved, what kind of transformations projects aspire to, why the transformations originally envisioned in TD projects are sometimes different from achieved changes, and what are advantages and disadvantages of different project approaches.

To address these two gaps, we designed an institutional learning

process at our own academic competence centre to jointly analyse our projects' theories of change and capitalize on experiences with distinct pathways from TD co-production of knowledge to sustainability transformations. Our aim was to advance our own understanding of how TD projects aiming to contribute to sustainability transformations can become more effective, and to contribute to the broader debate on effectiveness of TD projects. The present paper explores the following three research questions: 1) How do TD projects conceptualise the link between TD and sustainability transformations, and what strategies do they use? 2) What were their experiences with implementing their strategies and theories of change? And 3) what lessons can be drawn more broadly from this theory of change assessment for enhancing the effectiveness of TD for sustainability?

2. Methodology

2.1. Context and study design

Our study is embedded in the University of Bern, Centre for Development and Environment's (CDE) 2018–19 institutional goal process. CDE induced a centre-wide reflection and learning process on how it can enhance its effectiveness in contributing to sustainability transformations through its projects, which range from research to teaching and practice. CDE employs around 100 people from 17 disciplines. It has activities in five regions of the global South as well as in Switzerland and Europe, and is currently implementing over 80 projects. We drew a purposive sample of 31 TD projects for this study. As we aimed to identify generic impact generation mechanisms and induce learning from and between very different TD projects, sampling was driven by the following criteria: a) maximum variation of project types in terms of geographical contexts, themes, funding schemes, and project durations (Table 1), differing transdisciplinary methodologies, and differing theories of change at CDE; b) inclusiveness regarding staff involvement (most of CDE's staff were involved in at least one of the 31 selected projects); and c) willingness of project representatives to contribute to the study.

2.2. Methodological approach

Our research was based on the understanding that TD helps to co-produce actionable knowledge. All participants in the study were TD practitioners; hence, our research is guided by what Burawoy (1998) calls a “reflexive model of science”, which embraces engagement with, rather than detachment from, the object of analysis as the broad road to knowledge. In this mode of research, reflective practitioners (Schön, 1983) complement structured methods for self-reflection and formative assessment with established methods and approaches of social sciences (Lang et al., 2012; Schneider et al., 2019a). We consider this

Generic mechanisms for impact generation

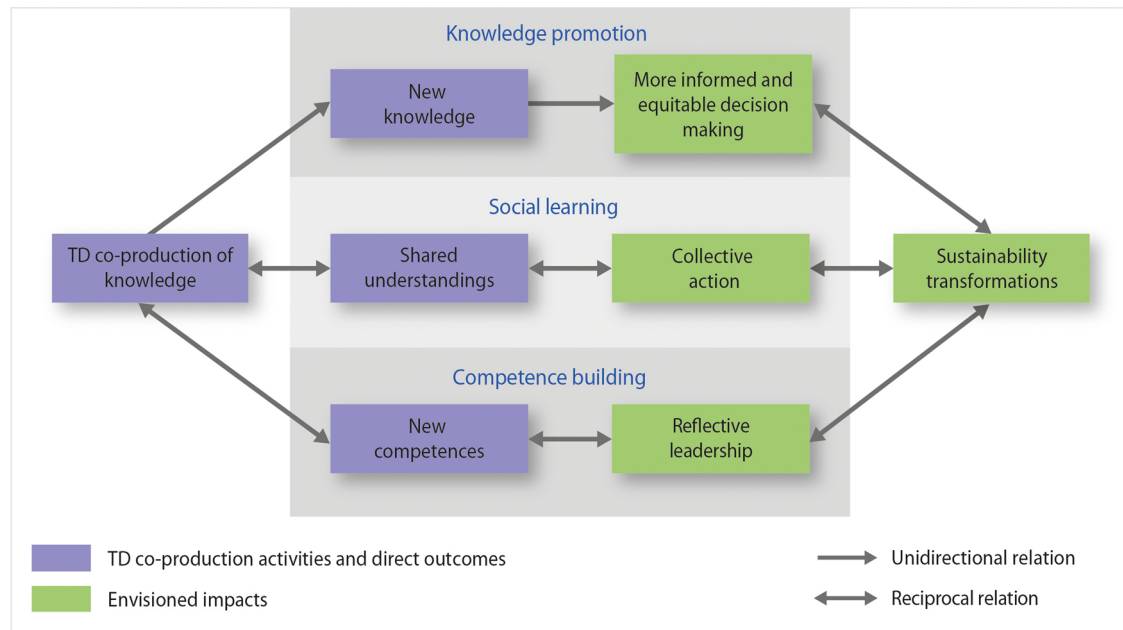


Fig. 1. Overview of three generic mechanisms of impact generation.

understanding of scientific practice as highly suitable to achieve our goals, as it allows for in-depth analysis of the TD projects' change theories and experiences, while at the same time fostering learning among the participating projects and beyond, with a view to enhancing the potential of TD research to contribute to sustainability transformations (Nowotny et al., 2001; Schneider et al., 2019b). The advantage of such an informed and self-reflexive TD approach is that the research team is deeply knowledgeable about the investigated practices and intrinsically motivated to unravel impact mechanisms that allow them to become more transformative. The team is also interested in sharing insights with a broader community of practice. But the approach also bears the disadvantage of possible blindness to alternative interpretations.

The TD approach informing this paper included regular meetings of a core group, a one-day workshop with all project representatives, group work in project teams, and an online survey. We – the co-authors of this article, junior and senior project representatives of the CDEs' thematic clusters interested in or experts on the topic – formed the core group. We designed and governed the overall research process and conducted the in-depth analyses. First meetings of the core group served to find common ground on the topic by exploring the change theories of our own projects. Based on the insights gained and a literature review, we developed a study design, which included workshop guidelines and a follow-up survey questionnaire.

The one-day workshop enabled the CDE's TD projects to reflect on their explicit or implicit change theories and to jointly explore lessons learned during this process. Group exercises alternately took place in mixed and project teams. Participants clarified how they understood transformation, how they saw their role and contributions as academics, what might be appropriate and relevant project goals, what approaches they used to support transformations (if they did), in what kinds of contexts, and how their change theories could be improved. The discussions were documented on flip-charts and later summarized by the co-authors. Participants were also encouraged to provide documented change theories (including pathways to impact or societal relevance statements in proposals).

Several project teams continued this reflection and documented it after the workshop. A subsequent online survey with open and closed

questions based on the workshop results enabled participants to capture their projects' original and adapted change theories as well as implemented activities, experiences, observed impacts, and lessons learnt.

Survey results and collected project documentations were assessed using qualitative content analysis (Flick, 2005). In a first step, we established a table with project profiles by combining data from the survey and documented change theories. We then inductively identified main strategies of impact generation that the projects employ to trigger change. Subsequently, we explored the assumptions underlying these strategies, to filter out generic (ideal type in the sense of Weber (1949)) mechanisms of impact generation. These analyses were based on an iterative process of concept identification and comparison to identify recurrent patterns of similarities and differences. We started with the project profiles containing explicit change theories and assumptions, and step by step included the available descriptions and survey answers of the other projects, asking whether the strategies and underlying assumptions of these projects corresponded to the former, or provided new ideas regarding how TD might foster transformation. In case of ambiguity – in particular when theories of change were not explicit – we rediscussed the identified attributions with the concerned projects and adapted them if necessary. In a final step, we used qualitative content analysis again to identify lessons learned on implementing theories of change in TD co-production of knowledge.

3. Results

Analysis of the 31 projects' theories of change showed that each theory was unique in how it depicted the detailed pathways to impact of TD co-production of knowledge. But meta-level comparison of projects' assumptions allowed us to identify three distinct generic mechanisms of impact generation (Fig. 1): a) promoting systems, target, and transformation knowledge for more informed and equitable decision-making, b) fostering social learning for collective action, and c) enhancing competences for reflective leadership. These three generic mechanisms were activated by seven recurrent strategies that the studied projects used to contribute to sustainability transformations (Table 2). The three mechanisms of impact generation and the seven associated strategies represent ideal type constructions for analytically

Table 2
Three generic mechanisms of impact generation, seven generic strategies, and related assumptions.

Generic mechanism	Main strategies	Assumptions		Key mechanism of impact generation
		Understanding of TD	Understanding of sustainability transformations	
Knowledge promotion	1 Access to information	Cognitive process leading to new systems, target and transformation knowledge that can subsequently be taken up by societal actors for decision-making	Changes in narratives, practices and policies fostering sustainability	TD knowledge is a substance to be transferred from the project to other people, where it will trigger changes in action through more informed and equitable decision-making
	2 Advice and training			
Social learning	3 Public debates	Social learning process enhancing the participants' collective agency and potential for joint action towards sustainability through knowledge sharing, deliberation of values and joint practices	Changes in practices, institutions and power relationships needed to jointly learn and act towards sustainability.	TD knowledge is an emergent property of interactions and situated in coordinated actions. Change is triggered through the joint actions of the actors involved in TD collaborations
	4 Multi-stakeholder groups			
Competence building	5 North-South partnerships	Self-transformative process leading to new, individual competences for reflective leadership through joint experimentation and self-reflection, learning edges and mirroring feedbacks.	Radical changes in practices, institutions and power relationships require embodied transformations of the potential change agents themselves, including values and competences.	When potential change agents engage in TD work, they develop competences that enable them to better tackle sustainability challenges and opportunities in their life and work
	6 Transformative education			
	7 Communities of practice			

disentangling the assumed pathways to impact. However, they do not exist in isolation. Indeed, we found that projects usually combined several of the related assumptions in a single theory of change, though one assumption was generally dominant. We also found that some of the associated strategies could also contribute to one of the other two mechanisms (e.g. multi-stakeholder processes were attributed to the social learning mechanism, but they might also contribute to enhancing competences for leadership).

In the following, we first present the three mechanisms and seven strategies, then we analyse achievements and challenges involved in their implementation, and the lessons learned. We also refer to the projects' own framing of their terminology and assumptions about impact generation mechanisms within specific literature, and discuss each identified impact generation mechanism in the context of other scholars' work exploring similar mechanisms.

3.1. Mechanisms and strategies to contribute to sustainability transformations

3.1.1. Promoting systems, target, and transformation knowledge for more informed and equitable decision-making

The first generic mechanism is rooted in the assumption that transdisciplinary co-production of knowledge is a cognitive process leading to new knowledge, understandings, and perspectives that subsequently can be used to inform societal actors for decision-making (Table 2). The generated knowledge was seen as a substance to be transferred from the project to other people, where it would trigger action. Though TD was expected to create knowledge of a different quality than disciplinary knowledge, spread of this knowledge was conceptualised according to classical knowledge utilization models such as Landry et al.'s (2001), however without explicitly referencing them. From this perspective, to contribute to sustainability transformations TD researchers need to ensure, first, the quality of the generated knowledge, and then its promotion.

The projects defined the different quality of knowledge as more relevant, robust, holistic, legitimate, innovative, or actionable. We found varying beliefs about whether, when, and how societal actors should be involved. But there was a widespread, shared vocabulary referring to an existing TD discourse (e.g. Hirsch Hadorn et al., 2006; Wuelser et al., 2012) that TD research generates not only systems knowledge, but also target and transformation knowledge. Systems knowledge refers to descriptive and explanatory knowledge about the problem situation (e.g. status, causes, and consequences of resource degradation), target knowledge to norms and values related to the desired future development (e.g. for defining sustainability visions, indicators, and thresholds), and transformation knowledge is about how to make change from the current to the target status happen (e.g. measures and tools, governance mechanisms, pathways to impact).

The projects named three different strategies to promote the generated systems, target, and transformation knowledge. They diverged on how they thought knowledge is spread and what changes it might trigger.

1) *Improved access to relevant information for societal actors* is seen as precondition for more informed decision-making, because actors such as government staff and extensionists can gain more accurate and holistic understanding of the sustainability problems and their drivers and consequences, as well as a repertory of solutions and best practices to choose from. Moreover, proponents of this strategy often refer to values of equity and data transparency. In this case, improved access to knowledge is seen as a means to empower different actors, including civil society organisations, to participate in inclusive and equitable decision-making. Proponents assume that more informed and equitable decision making will in turn lead to changing practices and policies. Access is enhanced through technical publications, data visualisations and open access, online

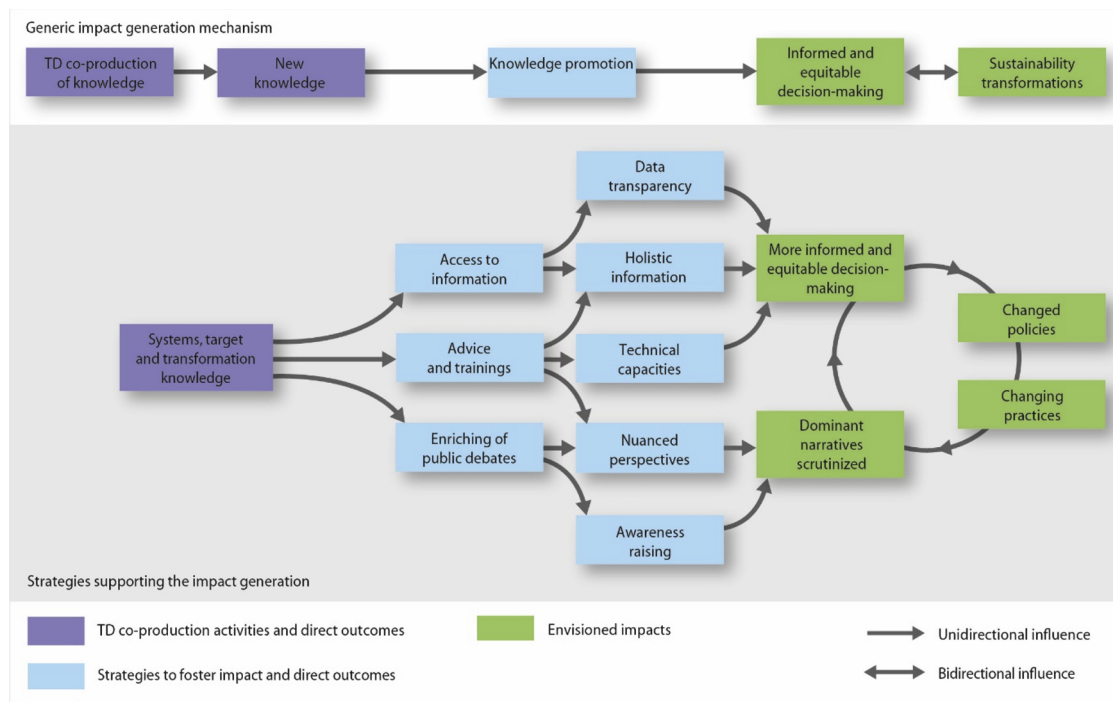


Fig. 2. Idealised pathways to impact from the perspective of knowledge promotion (the upper part shows the generic impact generation mechanism. The lower part outlines the identified strategies and related outcomes and envisioned impacts).

databases on various topics such as existing land use changes, large-scale land acquisitions, or sustainable land management technologies.

- 2) Research-based *advice and trainings* are expected to bring knowledge to fruition through collaboration with actors requesting scientific expertise or capacity building. Contributions can involve thematic and/or methodological contributions, e.g. regarding how to assess complex relationships between different sustainable development goals on a national scale. In countries of the global South, trainings are often combined with the access-to-information strategy to support actors in using the information provided (e.g. through GIS training), and in integrating it in overall decision-making procedures such as up-scaling sustainable land management.
- 3) Enriching *public debates* through nuanced or alternative perspectives is sought to enhance education and awareness, democratic deliberation, and transformation of dominant but unconstructive world-views and narratives that hinder sustainability transformations. This strategy was often reported by projects in which issues were of interest to the broader public or when factual and normative questions were highly interrelated, such as in the case of gender issues, sustainable lifestyles and consumption, working conditions, and regional development. Means to promote knowledge included publications, public lectures, newspapers, radio and television broadcasts, and social media (Fig. 2).

3.1.2. Fostering social learning for collective action

The second generic mechanism features TD as a social learning process that enhances the participants' collective agency and potential for joint action towards sustainability. As the actors jointly search for solutions to sustainability problems, they build trust, mutual understanding, and the systems, target, and transformation knowledge helping them to move forward. In other words, TD knowledge is conceived as the emergent property of interactions and is situated in coordinated actions, rather than as a substance that can be removed from the social context where it was created and transferred to another (as assumed by the knowledge promotion mechanism). Projects underscoring this understanding of TD are often inspired by literature in the

field of natural resource management, organisational learning, and science studies (Bouwen and Taillieu, 2004; Bruckmeier and Tovey, 2008; Nowotny et al., 2001; Rist et al., 2007; Schneider et al., 2009). While this understanding of TD does not necessarily contradict the one described under the knowledge promotion mechanism, it highlights a different dimension and possible pathway to impact: Here, change is triggered through the (joint) actions of the actors involved in co-producing new knowledge. Hence, from this perspective, to contribute to sustainability transformations, TD researchers need to engage with social actors involved in the sustainability challenges at stake, to share knowledge, deliberate values, and jointly learn their way forward. The projects mentioned two main strategies to foster social learning and collective action for sustainability transformations:

- 1) *Multi-stakeholder processes* are expected to enhance knowledge sharing and deliberation of values through joint practices between societal actors with different backgrounds, perspectives, and priorities. It is assumed that this leads to increased levels of mutual understanding regarding meaningful systems, target, and transformation knowledge needed for (joint) action towards sustainability transformations, in particular in the field of natural resource management, agriculture, and food systems. Some projects highlighted the need for equal involvement of all actors concerned by an issue, to jointly deliberate and search for practicable pathways in the sense of democratic and reflective governance (Voss et al., 2006). Others rather aim to strategically foster network building among sustainability conscious actors to increase their power for action.
- 2) *North–South partnerships* between researchers and other actors of the global North and South are expected to foster trust, mutual understanding, and the competences and experiences needed to jointly implement meaningful TD research projects. The assumption is that strong and long-term partnerships are a precondition for the generation of knowledge that is relevant, legitimate, context-specific, and actionable in countries of the global South. Moreover, it is assumed that partnerships enhance ownership and agency to collaborate effectively with various further societal actors such as local governments, business actors and research institutions, thereby

Fostering social learning for collective action

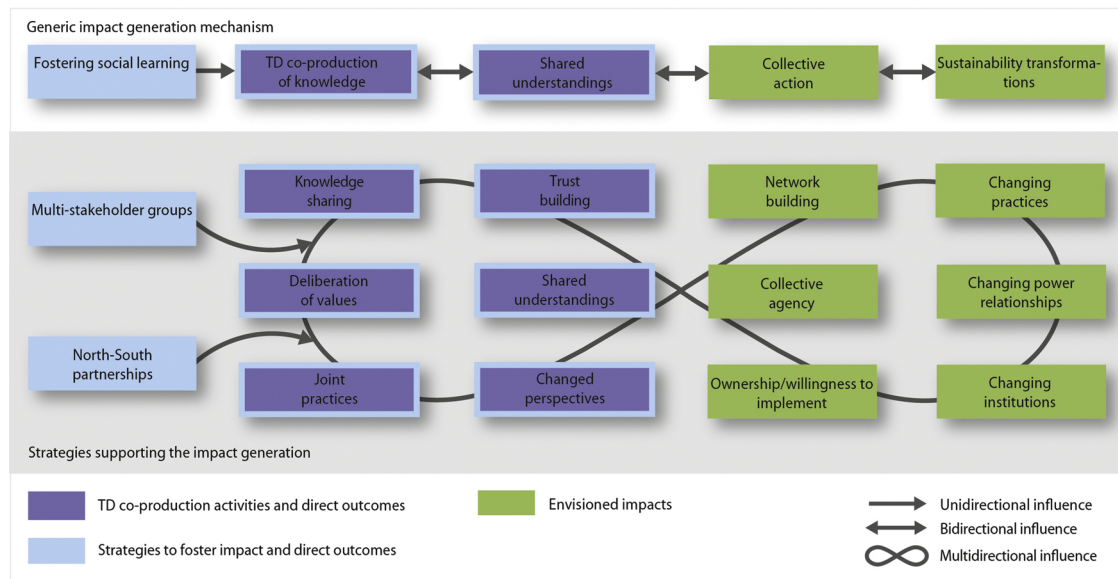


Fig. 3. Idealised pathways to impact from a social learning perspective.

contributing to more informed decision-making in settings where power disparities tend to prevail (this understanding is outlined in Stöckli et al., 2012; Upreti et al., 2012) (Fig. 3).

3.1.3. Enhancing competences for reflective leadership

The third generic mechanism of impact generation conceptualises TD as a self-transformative process leading to new competences for reflective leadership. The underlying assumption is that when potential change agents engage in TD work including joint experimentation, learning, and self-reflection, they develop competences (knowledge, skills, values, and attitudes) that enable them to better tackle sustainability challenges and opportunities in their life and work. Similar to the other two mechanisms, knowledge is conceived as being co-constructed in TD settings, but in this case the focus is on knowledge as part of personal and embodied competences of the participating change agents. This understanding of TD is close to notions that see TD as an educative or transcending process by which people become a more complex self as they engage in TD work (McGregor, 2015; Nicolescu, 1996). Through this self-transformation, change agents can apply the generated and embodied knowledge also in other situations and contexts. Hence, as in the social learning mechanism, participants in TD research themselves are seen as part of the pathway to impact. From this perspective, to contribute to sustainability transformations, TD researchers need safe spaces that enable change agents to experience personal learning processes through TD knowledge co-production.

The following two strategies applied by our studied projects aim to enhance competences for reflective leadership:

- 1) *Transformative education* builds on the assumption that fostering students' competences for reflective leadership will enable them to act as effective change agents in their private and professional life. Radically changed practices and institutions and deeper sustainability transformations are the long term goal (this understanding is outlined in Trechsel et al., 2018). This strategy is employed by undergraduate and graduate programmes run by CDE, with learning edges explicitly staged in teaching-and-learning settings that aim for more than the acquisition of knowledge and include TD knowledge co-production situations. Relevant competences are related to systems thinking, anticipation and imagination, critical (self)-reflection, dealing with normative questions, interpersonal relations, and strategic planning as well as practical skills as introduced by

Rieckmann (2012); Wiek et al. (2011), and Wilhelm et al. (2019).

- 2) Shared learning in *communities of practice* (Wenger, 1998) is believed to enhance the participants' competences for reflective leadership and provide room for manoeuvre to contribute to sustainability transformations in situations where knowledge is limited. Communities of practice are groups of people who share a common concern or passion and who want to improve their competences and practices through sharing experiences, reflecting on own practices and values, and engaging in or learning from research. TD researchers can have different roles in this strategy: they can create reflective spaces by connecting interested actors, enhance reflectivity by mirroring their practices and presenting alternative perspectives, or help actors to better understand the context they are working in or causal relations they are not aware of (Fig. 4).

3.2. Experiences with implementing different change theory strategies

Reflecting on the actual experiences with implementing their theories of change, the involved projects drew various lessons for their individual project work, both for improving their current practices, as well as for adapting underlying assumptions. While some of the reported learnings were rather project-specific, others were more generic. In the following we present generic learnings drawn from comparing the different projects' experiences.

3.2.1. Promoting systems, target, and transformation knowledge for more informed and equitable decision-making

Projects fostering promotion of systems, target, and transformation knowledge reported that they were successful in establishing holistic and transparent information databases, enhancing the technical capacities of key actors, and enriching debates with more innovative concepts or nuanced perspectives. This was visible in download rates, media coverage, citations in scientific and policy reports, as well as in feedbacks from training course participants and partners. For example, the UN Special Rapporteur, Philip Alston, quoted the *Social Economic Atlas of the Lao PDR* (2018) developed together with the Lao statistics bureau as a basis of his critique regarding extreme poverty and human rights violations in Lao.

Effects with regard to more informed and equitable decision-making and changes in dominant narratives on a broader governance level were also visible, but to a more limited extent and mostly in longer projects

Enhancing competences for reflective leadership

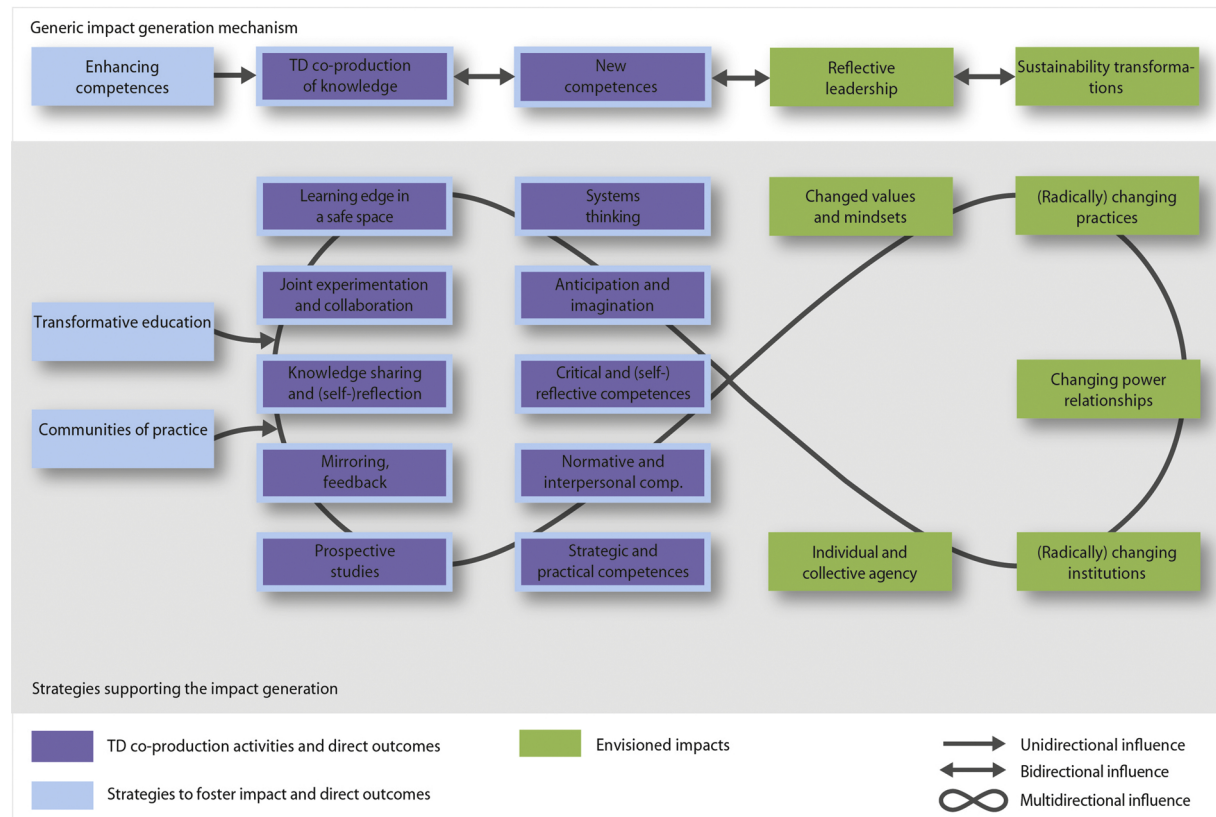


Fig. 4. Idealised pathways to impact from a competence building perspective.

(6 years and more). For example, the WOCAT programme aiming to support innovation and decision-making concerning sustainable land management (SLM) established an open access database featuring effective SLM technologies and approaches that were identified together with local land users worldwide (www.wocat.org). In addition, they have been training stakeholders to enhance their capacity to work with this database and select promising technologies and approaches for up-scaling in their contexts. Through these activities SLM gained recognition amongst different national institutions and the provided knowledge was used in decision-making.

However, many projects concluded that knowledge promotion activities – to be successful – need to be combined with other strategies aiming to foster trust and joint understanding among different actors, or changes in individual competences or institutional cultures. Indeed, several projects with more visible effects on decision-making and governance processes had been collaborating with concerned societal actors over many years. Nevertheless, they concluded that in future more emphasis should be placed on social learning and competence building strategies, which belong to the other two impact generation mechanisms. For example, the DECIDE project that has worked with the Lao government for many years on fostering inclusive decision-making for sustainable development by making socio-economic and ecological information accessible concluded that more efforts in trust building and learning among government institutions is needed to foster further change.

3.2.2. Fostering social learning for collective action

Projects emphasising the importance of social learning for collective action and institutional change reported that trust and joint understanding could be increased between various actors involved and that this was crucial for successfully co-producing knowledge (e.g. regarding sustainability assessments, joint future visions, or identification of best

practices for sustainable land management). This was stated for both North-South partnerships and multi-stakeholder processes. Moreover, in several cases emerging collective actions were observed. In some cases, these actions were initiated and facilitated by the projects: For example, the OneMap Myanmar project set up a multi-stakeholder platform to help resolve land disputes related to large-scale oil palm concessions bringing together actors from the government, civil society, companies, and ethnic armed groups who did not work together before. The participants engaged in joint deliberation, data generation, and verification through mapping land uses and concessions. These activities informed governmental decision-making, leading to revisiting land use planning in concession areas. In other cases, projects connected with ongoing transformation initiatives. For example, the project r4d Food connected with local food initiatives and supported them in assessing the sustainability of the local food systems and identifying room for improvement. Identifying weaknesses in the legal system related to successful commercialisation, they subsequently developed lobbying strategies for inducing change. In any case, most projects that reported collective action outcomes also mentioned having substantially adapted their approach according to the needs of the stakeholder process (e.g. for new topics coming up or changing contexts).

Interestingly, in many cases, to foster trust, commitment, and joint understanding the projects integrated knowledge promotion strategies in the collaboration process. For example, they provided trainings, elaborated attractive visualisations of latest scientific insights of high interest to the participants, or involved participants in scientific activities such as drone flying or satellite image interpretation. In several cases, scientific inputs served as entry point for discussions, catalysing joint learning and often helping to rationalise contested situations.

However, several challenges were also mentioned, e.g. difficult contexts (political instability, corruption, illegal networks, financial profits), conflictive perspectives and priorities, negative impacts and

increased conflicts, insufficient adaptation to the needs of the stakeholders involved, and the general observation that North-South partnerships are still heavily steered by Northern partners, leading to insufficient ownership by Southern partners. Cultural and political characteristics of authoritarian countries often shut down the potential for open dialogue and social learning between hierarchically distinct actors. Moreover, it was difficult to assess to what extent collective actions continued after the projects ended or to what extent they could be attributed to a project. For example, in the MontanAqua project, after a 2-year interaction process, stakeholders of a Swiss Alpine region with originally very different perspectives co-created a joint future vision for sustainable water governance that included increased collaboration between communes and renegotiation of water rights. But one key stakeholder – the president of the water-richest commune – vetoed the agreement, apparently because he could not defend the result with his commune, and the joint activities came to an end. However, a few years later several communes merged and decided to combine their water governance institutions after all.

In summary, projects reconfirmed the crucial importance of relational activities and long-term partnerships, but highlighted the need to increase attention to power relationships, financial incentives, and other factors that might hinder emergence and translation of social learning outcomes into effective collective actions towards sustainability.

3.2.3. Enhancing competences for reflective leadership

Projects aiming to foster competence building for reflective leadership usually indicated that participants in respective events showed high satisfaction with their learnings. They were very engaged and willing to jointly reflect and self-reflect, and had a high desire to improve their practices and make change happen. Depending on participants' experience levels, they rather enjoyed learning through striking new experiences, or by jointly reflecting on one another's existing experiences. An example of the first is a project for developing a teaching format where students from different disciplinary backgrounds engaged in TD case studies to learn how to jointly frame and tackle sustainability problems by integrating many different perspectives. An example of the second is a community of practice where representatives of different TD research funding programmes met to share their experiences with governing these funding programmes. They also jointly reflected on how to improve their effectiveness in contributing to sustainability with future funding programmes. In both cases, it was felt to be important that participants experienced self-efficiency and solution finding, but also that they challenged one another to create deeper learning with regard to underlying values and their own potentials and limitations.

Making changes in competences and reflective leadership visible and assessing them, however, is challenging. While increases in cognitive and practical competences can be measured more easily, this is more difficult for social and normative ones and in particular for tracking their effects. Moreover, defining what competences for fostering sustainability transformations are relevant depends entirely on the context. For example, a researcher involved in several of the investigated projects gained considerable competences in reflective leadership that helped to successfully govern follow-up projects. However, in two actual projects these competences seemed not to be equally suitable to deal with the different social and cultural constellations.

Competence building through experimentation and self-reflection also has its limitations. Several projects reported about moments of frustration when the group process became stuck. For example, when differences in perspectives led to circular discussions around values or priorities, or participants felt that they could not learn from the other participants' experiences because they were too far away from their own thinking. Some projects succeeded in overcoming such obstacles, using the frustration experienced as a learning edge. Interestingly, this often occurred either through the existence of or the investment in strong relational bonds, or through tailored knowledge inputs that were valued by participants and stimulated further debate and motivation.

4. Discussion and conclusion

In this paper, we reported insights from an institutional learning process aiming to enhance a university competence centre's effectiveness in contributing to sustainability transformations in research, teaching, and practice. Exploring the 31 involved TD projects' theories of change, we identified three generic ways in which the projects conceptualised impact generation: through a) promoting systems, target, and transformation knowledge for more informed and equitable decision-making, b) fostering social learning for collective action, and c) enhancing competences for reflective leadership. Each impact generation mechanism was informed by strategies for fostering sustainability transformations; we identified seven altogether, none of which was used on its own. Our research confirms insights from other studies which demonstrate that there are multiple pathways to societal impact (Maru et al., 2018; Muhonen et al., 2019).

Our study embraced a very high heterogeneity of different TD approaches. This allowed us to unravel and compare quite distinct theories of change. The three identified impact generation mechanisms and the associated strategies represent ideas that are widely discussed in the broader literature but often in disparate fields, or with one claimed as superior to the others in validity and usefulness. For example, authors using a situated learning approach to TD tend to question the transferability of the generated knowledge (Westberg and Polk, 2016), and authors stressing knowledge promotion as pathway to impact sometimes disregard the impact potential residing in the participating actors themselves and their increased agency. Our research on the projects' experiences with implementing their theories of change showed that these theories all had promise in specific situations, particularly when combined with each other.

In addition, we found that all theories of change also had limitations. In general, independently of the assumed mechanism of change, most projects were successful in reaching their envisaged immediate outcomes (e.g. data transparency, creation of trust and mutual understanding, self-reflection) and some projects also reported effects regarding further envisaged changes (e.g. changes in policies, mindsets, or practices). But open questions remained regarding, first, the validity of the identified impact generation mechanisms under different contexts and second, to what extent true sustainability transformations were triggered. Similar findings have also been reported by Polk (2014), who found that TD processes do produce societally robust knowledge, but that this does not necessarily translate into sustainability transformations beyond the project's scope. This is partly due to the difficulty of tracing impacts beyond projects' immediate sphere of influence (Wiek et al., 2014), partly because of the wickedness and ambiguity of societal challenges and the complexity of societal transformation processes (Polk, 2014), where knowledge is only one among several influencing factors (Reed et al., 2018).

Indeed, most projects at CDE encountered many challenges, including disturbing external influences (e.g. shifting debates and priorities, political unrest, illegal structures and corruption, power games) and a tendency to overestimate what they could achieve through a TD project. On one side of the spectrum, we found those projects that heavily invested in knowledge promotion and learning activities, but without sufficiently scrutinizing how more informed decision-making might effectively contribute to sustainability transformations or taking into account how broader societal, economic, and political processes might affect knowledge-based transformations. On the other side of the spectrum, projects elaborated sophisticated societal transformation theories, but without clear ideas about how their own activities as TD research projects might contribute to transformation.

As a consequence, the chosen impact generation strategies did not always fully fit the purpose. Interestingly, projects highlighting one impact generation mechanism often stressed that more effort would be needed in the realm of another of the two identified at generic level. Indeed, our research provides evidence that most promising pathways

to impact are long-term, adaptive processes that combine elements of the three mechanisms of impact generation in parallel or over time. Hence, we conclude that the question is not which mechanisms or strategies are better than others, but in what situation and combination they might be most effective. Future research could therefore further contextualize our generic impact generation mechanisms and investigate whether specific patterns between impact generation mechanisms, contexts and transformation goals can be detected. Further investigation into the extent and depth of transformation that has been achieved would also be necessary as part of such a self-reflective exercise. Do the observed impacts involve fundamental and rapid transformations of deeper leverage points such as world views and power structures (Fazey et al., 2018)?

The fact that we covered a broad range of different TD understandings and practices explored at CDE ensures a good degree of relevance of the identified mechanisms for impact generation for many other TD projects. However, it is very likely that inclusion of additional TD approaches such as real-world laboratories (Heiskanen et al., 2018) might reveal additional mechanisms, including different understandings of transformation. This is particularly true when aiming to identify more contextualised theories of change, e.g. for achieving transformations regarding particular topics such as sustainable land management or sufficient lifestyles. Additional inclusion of non-academic societal actors involved in TD projects will be key to further refine, and maybe challenge, the present findings. We encourage TD projects aiming to contribute to sustainability transformations to further explore different pathways to impact inspired by the different mechanisms of impact generation, but also to be realistic and regularly scrutinize their assumptions against the background of reflected experiences, academic theories, and monitoring insights. In the same way, we argue that future research should increase efforts to empirically investigate different pathways to impact (EASSH, 2019), neither limiting themselves to simplified models of knowledge utilization and transfer, nor neglecting the very option of knowledge transferability. Last but not least, we urge science policy practice institutions to acknowledge the importance of change theory thinking for enhancing and tracking impact, also ensuring consideration of pathways to impact that do not produce easily quantifiable results.

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Declaration of Competing Interest

None.

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