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Sustainability Science for Meeting Africa's Challenges

Transdisciplinary research for systemic change: who to learn with, what to learn about and how to learn

Dirk J. Roux[1,2] · **Jeanne L. Nel**[2,3] · **Georgina Cundill**[4,5] · **Patrick O'Farrell**[3,6] · **Christo Fabricius**[2]

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Abstract A key aim of transdisciplinary research is for actors from science, policy and practice to co-evolve their understanding of a social–ecological issue, reconcile their diverse perspectives and co-produce appropriate knowledge to serve a common purpose. With its concurrent grounding in practice and science, transdisciplinary research represents a significant departure from conventional research. We focus on mutual learning within transdisciplinary research and highlight three aspects that could guide other researchers in designing and facilitating such learning. These are: "who to learn with", "what to learn about" and "how to learn". For each of these questions, we present learning heuristics that are supported by a comparative analysis of two case studies that addressed contemporary conservation issues in South Africa but varied in scale and duration. These were a five-year national-scale project focusing on the prioritisation of freshwater ecosystems for conservation and a three-year local-scale project that used ecological infrastructure as a theme for advancing sustainability dialogues. Regarding the proposed learning heuristics, "who to learn with" is scale dependent and needs to be informed by relevant disciplines and policy sectors with the aim of establishing a knowledge network representing empirical, pragmatic, normative and purposive functions. This emergent network should be enriched by involving relevant experts, novices and bridging agents, where possible. It is important for such networks to learn about the respective histories, system processes and drivers, values and knowledge that exist in the social–ecological system of interest. Moreover, learning together about key concepts and issues can help to develop a shared vocabulary, which in turn can contribute to a shared understanding, a common vision and an agreed way of responding to it. New ways of group learning can be promoted and enhanced by co-developing outputs (boundary objects) for application across knowledge domains and creating spaces (third places) that facilitate exchange of knowledge and knowledge co-production. We conclude with five generic lessons for transdisciplinary researchers to enhance project success: (a) the duration, timing and continuation potential of a project influences its prospects for achieving systemic and sustainable change; (b) bridging agents, especially if embedded within an implementing agency, play a critical role in facilitating transdisciplinary learning with enhanced outcomes; (c) researchers need to participate as co-learners rather than masters of knowledge domains; (d) purposeful mixed-paradigm research designs could help to mend knowledge fragmentation within science; and (e) researchers must be vigilant for three pitfalls in mutual learning initiatives,

Handled by Alexandros Gasparatos, IR3S, University of Tokyo, Tokyo, Japan.

✉ Dirk J. Roux
dirk.roux@sanparks.org

1 Scientific Services, South African National Parks, Private Bag X6531, George 6530, South Africa

2 Sustainability Research Unit, Nelson Mandela Metropolitan University, Private Bag X6531, George 6530, South Africa

3 Council for Scientific and Industrial Research, Natural Resources and the Environment, P.O. Box 320, Stellenbosch 7599, South Africa

4 Department of Environmental Science, Rhodes University, P.O. Box 94, Grahamstown 6130, South Africa

5 International Development Research Centre, P.O. Box 8500, Ottawa K1G 3H9, Canada

6 Percy FitzPatrick Institute of African Ornithology, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa

namely biases in participant self-selection, perceived superiority of scientific knowledge and the attraction of simple solutions to wicked problems that retain the status quo.

Keywords Bridging agent · Boundary objects · Engaged science · Learning heuristics · Transdisciplinary learning framework

Introduction

Science and technological innovation were spectacularly successful drivers of social and economic development during most of the twentieth century. These drivers have helped humans to achieve their current position of dominance on Earth, to the extent that the actions of people have become a threat to the planet's biophysical support base (Barnosky et al. 2012; Rockström et al. 2009). As a result, there is a call on science to respond to one of the most pressing issues of our time, namely to understand the interdependent relationship between human well-being and diverse, functioning ecological systems, and to guide humanity towards a more sustainable relationship with nature (Lubchenco 1998). Furthermore, relevant knowledge should be produced in ways that help overcome the divide between science and practice (Van Kerkhoff and Lebel 2006; Cornell et al. 2013; Clark et al. 2016) to create a complementary interplay between scientific knowledge production and institutional innovation (Woodhill 2010).

The above challenge is at least in part being met by the emergence and increasing prominence of a number of research and management approaches focussed on addressing complex social–ecological issues. Management approaches include adaptive management and adaptive co-management (Armitage et al. 2008), while research approaches include post-normal science (Funtowicz and Ravetz 1993), sustainability science (Clark and Dickson 2003) and transdisciplinary research (Hirsch Hadorn et al. 2008). These approaches are not necessarily mutually exclusive; for example, transdisciplinarity has been identified as a key aspect of sustainability science (Komiyama and Takeuchi 2006; Kates 2011). Here, we largely draw upon, and build on, the concept of transdisciplinary research.

The aim of transdisciplinary research is for actors from academia, policy and/or practice domains to co-evolve their understanding of a social–ecological issue, reconcile their diverse perspectives and co-produce appropriate knowledge to serve a common purpose (Hirsch Hadorn et al. 2010; Lang et al. 2012; Young et al. 2014). Such an engaged research approach can expose participants to multiple perspectives regarding the pressing issues in social–ecological systems, creating an enriched picture of such issues and potentially uncovering complementarities across diverse knowledge systems (Polk 2014; Tengö et al. 2014). A requirement of transdisciplinary research is to enable mutual learning processes among researchers representing different disciplines as well as actors from outside academia (Russell et al. 2008; Stauffacher et al. 2008; Mobjörk 2010).

However, learning across diverse knowledge systems is challenging and often characterised by misunderstanding, power plays, disagreement and tension (Cook et al. 2013). For knowledge to disperse, it is necessary to make knowledge domains (and their boundaries) more permeable, while maintaining the functional integrity of the contributing knowledge system. Such "boundary work" (Guston 2001; Mollinga 2010; Van Kerkhoff and Lebel 2006) is enabled by bridging agents. These individuals can "make it happen" and have been variously named boundary spanners, intermediaries and institutional entrepreneurs. They have been linked to a variety of skills and competencies such as developing social networks and building trust, legitimacy and social capital (Harris and Lyon 2013; Westley et al. 2013). Bridging agents are skilled at social facilitation and can create specialised interfaces between external knowledge sources, research teams and various participating actors. They can also translate knowledge and facilitate bidirectional transfers across relevant knowledge boundaries.

Facilitating transdisciplinary research to improve society's capacity to learn about (and respond to) a changing world sounds like a noble purpose. However, with its concurrent grounding in practice and science, transdisciplinary research represents a significant departure from conventional research. Academics and practitioners alike tend to believe in the superiority of their knowledge, especially when supported by hard data or personal experience (Berbés-Blázquez et al. 2016), creating a significant obstacle to mutual learning. It may not be intuitive for unversed researchers to prepare themselves to participate in, or facilitate, the mutual learning processes that are part of transdisciplinary research. Creating such transdisciplinary environments for effective learning can be important in order to address the significant sustainability challenges in African contexts, but the need for capacity and resources to achieve this must be recognised (Reyers et al. 2010).

In this paper, we explore the role that researchers can play as bridging agents in designing and maintaining systemic learning processes (spanning relevant actors of a particular social–ecological system) as part of their transdisciplinary endeavours. We use a novel transdisciplinary learning framework that draws from two case studies in South Africa to reflect on three questions that we consider foundational to learning in transdisciplinary research: "who to learn with", "what to learn about" and "how to learn". We conclude by presenting generic insights for consideration in the design of similar research initiatives in other parts of Africa and beyond.

Methodology

Research approach

This paper draws on two transdisciplinary research projects that addressed contemporary conservation issues in South Africa. The two projects are used as case studies to extract important insights for learning in transdisciplinary settings. They were chosen based on the authors' direct involvement with them (i.e. two authors were involved with both projects and three authors with one of the projects each), their marked variation in scale and duration, well-documented project specifications and achievements to draw on, and their respective transdisciplinary research designs (see below).

As transdisciplinary researchers we co-learned with other actors and at the same time influenced the evolution of the "group story" (Hampton, 2004), and thus the ways of relating to and understanding the relevant social–ecological systems and issues (Paschen and Ison 2014) in the respective case studies. As bridging agents we were also compelled to learn about project design criteria that could influence learning proficiency and equitable participation.

We asked three questions to reflect on our learning through these transdisciplinary experiences: who to learn with, what to learn about and how to learn? Based on our observations and experiences in the two projects, a number of answers (or rather learning heuristics) emerged for each of the questions. These heuristics were refined through ongoing reflections that happened informally and opportunistically during the course of (as well as subsequent to) the respective projects, spanning a period of 10 years. Early heuristics helped to inform the design of the second case study, and in this way, heuristics and design modifications emerged through iterative refinement.

For this paper, we select two heuristics for each question based on their perceived robustness for each case study project, relative novel contributions to the transdisciplinary literature, and potential for generic application. The selected heuristics are not mutually exclusive (as can be expected from complex learning processes) nor are they intended to be all inclusive. Rather they serve as "rules of thumb" or a starting point to support transdisciplinary learning. The questions and selected heuristics are presented as a framework for transdisciplinary learning (Fig. 1). We then used the framework to inform a comparative analysis of the case studies. The resulting insights are grounded in theories and concepts from a broad spectrum of research fields, including stakeholder engagement, social learning and knowledge co-production.

Case studies

National Freshwater Ecosystem Priority Area (NFEPA) project

Systematic conservation planning provides a widely accepted approach for identifying and prioritising ecosystems for protection (Kukkala and Moilanen 2013; Margules and Pressey 2000). The systematic approach to conservation planning focuses on conserving a representative suite of biodiversity, often driven by quantitative targets (Carwardine et al. 2009). Such targets can, for example, be to effectively conserve 17% of Earth's terrestrial and inland water ecosystems by 2020, as specified by the Convention on Biological Diversity's Aichi Targets (CBD 2011). While 30 years of refinement has made systematic conservation planning a sophisticated tool, effective implementation of the resulting conservation plans remains a challenge (Knight et al. 2008).

Implementation of conservation plans could benefit from a number of institutional enablers, including political endorsement of conservation targets, a conducive policy environment and mandated agencies with awareness, sense of ownership and appropriate capacity to achieve conservation outcomes (Roux and Nel 2013). In addition to the technical approach of identifying priority areas for biodiversity conservation, an implementation orientation requires enhancing the "absorptive capacity" (i.e. ability to identify, assimilate, transform and apply valuable external information) of knowledge implementers (Cohen and Levinthal 1990).

This was explicitly attempted during the design of a freshwater conservation plan for South Africa (Murray et al. 2011). The multi-year (2006–2011) NFEPA initiative had dual aims to: (1) identify spatial conservation priorities (referred to as Freshwater Ecosystem Priority Areas or FEPAs) in a scientifically credible manner and (2) develop an institutional basis for the effective conservation and management of these FEPAs (Roux and Nel 2013).

Unlike earlier freshwater conservation plans for South Africa, the national-scale NFEPA initiative achieved significant traction with intended users (Roux and Nel 2013). In the relatively short time since their publication in 2011 (Driver et al. 2011; Nel et al. 2011a), the FEPA products have enjoyed remarkable uptake in policy and management tools for freshwater ecosystems (Nel et al. 2016). This has contributed to a systemic and notable change in the

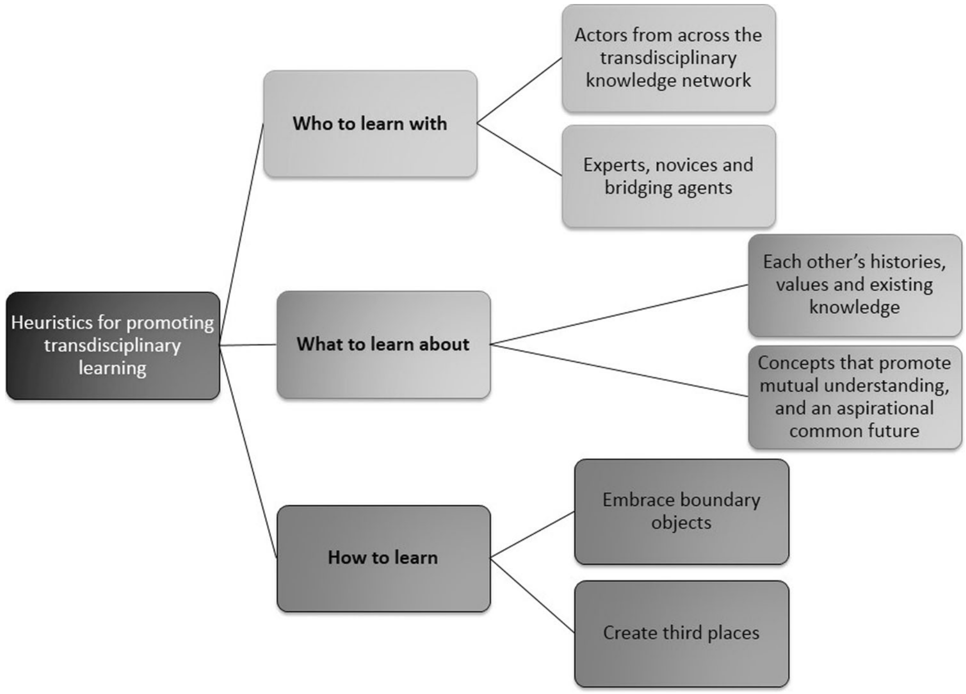

Fig. 1 Summary of the transdisciplinary learning framework that emerged from the case studies and was used for their comparative analysis. The various learning heuristics can be used as principles to strive for in the design and execution of transdisciplinary research initiatives

discourse on the management and protection of freshwater ecosystems.

The NFEPA initiative has played out, partly by design and partly by serendipity, as a transdisciplinary research process (Audouin et al. 2013; Cundill et al. 2015; Funke and Nienaber 2012; Nel et al. 2016). The project team consisted of members from various national agencies including end-users of the ultimate products (Table 1). Team members fulfilled the role of bridging agents and facilitated mutual learning across multiple institutional boundaries spanning national and provincial government as well as water, conservation and land-use planning sectors (Nel et al. 2016).

Wilderness ecological infrastructure project

Ecological infrastructure refers to functioning ecosystems that deliver valuable services to people. Examples of ecological infrastructure include strips of riparian vegetation that filter pollutants from water (Kemper 2001), wetlands that slow down flood waters (Kemper 2001), or coastal and estuarine ecosystems such as salt marshes and foredunes that can contribute to erosion control or absorb the impacts of sea storms (Barbier et al. 2011). When neglected or eroded by human activity, ecological infrastructure declines slowly and unnoticeably until a surprise event such as a flood, coastal surge, fire or drought occurs, which makes the decline instantaneously relevant, due to the associated debilitating economic, social and political impacts (Dobson et al. 2006; MA 2005). In South Africa, ecological infrastructure has been introduced into the development and policy domains as a term for engaging with infrastructure development, where it is framed as the nature-based equivalent of built infrastructure (Driver et al. 2012).

Typically, the benefits/contributions of ecological infrastructure are not easy to quantify. Furthermore, they are not well studied and therefore somewhat obscure in the minds of decision-makers (Reyers et al. 2015). Yet, its relation to other forms of infrastructure (such as built infrastructure) may make the concept of ecological infrastructure sufficiently compatible with existing knowledge at local levels of governance to aid its adoption.

The 3-year Wilderness project aimed to use ecological infrastructure as a theme for exploring how decision-makers and landscape managers understood and responded to new scientific understanding, environmental change and sustainability challenges (Table 1). The project focussed on a small drainage basin along the south coast of South Africa (Wilderness River Basin), which contain wide-ranging land uses including a dairy farming community, Ramsar wetlands, a coastal village and parts of a national park (O'Farrell et al. 2015).

Because the Wilderness project aimed to promote social–ecological transformation towards a more sustainable future in the Wilderness River Basin, it was designed with a transdisciplinary research process in mind. The project team consisted of researchers from a national research council and a university and relied heavily on the contributions of postgraduate students.

Table 1 Characteristics of the two case studies

	NFEPA project	Wilderness project
Duration	5 years (2006–2011); relationships had already been built with several relevant agencies through basin-scale projects that preceded NFEPA	3 years (2012–2015)
Scale	National (South Africa)	Local—relatively small drainage basin (Wilderness Lakes and Touw River)
Funding mechanism	Consortium of funders: WRC, CSIR, SANBI, WWF, DWS. SANParks, DEA and SAIAB contributed in kind (salaries). Project coordinated through WRC mechanisms and steered through both advisory and technical Reference Group meetings at major project milestones.	WRC, based on annual call for funding of unsolicited research proposals. Steered through annual meetings of a Reference Group (constituted by the funder) against pre-defined and pre-scheduled deliverables (although the funder was open to negotiating mid-course adaptations)
% of budget allocated for transdisciplinary engagement	60	47
Main actors involved	Researchers (CSIR, SAIAB and universities) Water resource managers (national and provincial government departments) Conservation agencies (national and provincial) Environmental consultants	Researchers (CSIR, NMMU) Commercial resource users (dairy farmers and foresters) Recreational users (conservancy) Subsistence users (local community) Civil society (ratepayers and residents association) Service delivery (municipality and conservation agency)
Bridging agents	Fairly senior project team with established networks and social capital in both the water and conservation communities, including members from national government departments and conservation agencies	University staff on the project team including senior professor and students residing in the study area (i.e. "community-embedded" researchers)
Forums for transdisciplinary engagement (mutual learning)	Five sub-national workshops (3 days each) in regional city centres Three basin-level pilot studies (chosen on representation and user readiness) Biodiversity Planning Forum (conservation planning community of practice) Freshwater Ecosystem Network (community of practice to connect managers in the water and the environmental sector) One national workshop Training workshops in three regional centres	Local community forums Focus group meetings Dialogues Local media
Main products	Atlas of FEPAs (Nel et al. 2011a) Implementation manual (Driver et al. 2011) Technical report describing science (Nel et al. 2011b) Data and information portal (http://bgis.sanbi.org/Projects/Detail/48) Papers and presentations (e.g. Nel et al. 2016; Roux and Nel 2013)	Project report (O'Farrell et al. 2015) Newspaper and popular science articles Student dissertations (Buckle 2016; Crisp 2015; Mc Culloch 2016; Roos 2015)
Desired outcomes	A new narrative in regulatory agencies Management impact Policy impact	New knowledge network New narrative in the Wilderness community New practices

CSIR Council for Scientific and Industrial Research, *DEA* Department of Environmental Affairs (previously *DEAT* Department of Environmental Affairs and Tourism), *DWS* Department of Water and Sanitation (previously *DWAF* Department of Water Affairs and Tourism), *NMMU* Nelson Mandela Metropolitan University, *SANBI* South African National Biodiversity Institute, *SAIAB* South African Institute for Aquatic Biodiversity, *SANParks* South African National Parks, *WRC* Water Research Commission, *WWF* Worldwide Fund for Nature

Results and discussion

Who to learn with?

Deciding which actors are eligible and essential for participation in a particular transdisciplinary learning process (as well as involving them in such a process) can be daunting. Important considerations include breadth of invitation, timing, extent and duration of involvement, techniques used to involve the different actors, and equitability, including a consideration of the imperative to empower marginal groups (Armitage et al. 2008; Krütli et al. 2010; Mobjörk 2010). Here, we focus on two actor-selection heuristics to facilitate long-term and systemic learning and avoid selection bias.

Actors from across the transdisciplinary knowledge network

Jantsch (1972) classified university knowledge into a four-level hierarchy. Max-Neef (2005) depicted these levels as a transdisciplinary hierarchy of knowledge (Fig. 2a). Empirical disciplines at the base of the pyramid describe knowledge that exists, disciplines at the pragmatic level describe what can be done, disciplines at the normative level describe what is desired and disciplines at the purposive level reflects socially embedded values that define what should be done (see Fig. 2a).

We used these levels, and also mobilised non-academic knowledge, to identify relevant actors for the NFEPA (Fig. 2b) and Wilderness (Fig. 2c) projects, respectively. Transdisciplinary learning would then strive to connect individuals vertically and horizontally across these levels and disciplines into a learning network (Reyers et al. 2010).

Funke and Nienaber (2012) state that the NFEPA project represented a significant departure from "business as usual" research because the project team "consistently grappled with issues of transdisciplinarity". These authors highlight the diversity of experts who were involved in producing the research as well as the manner in which perceived research end-users participated throughout the research process—from problem framing to completion. Co-learners included actors that had (a) empirical-level expertise in political science, social ecology, aquatic ecology, conservation biology, ichthyology, environmental chemistry and geographic information systems (from research organisations as well as embedded in national and provincial government agencies and departments); (b) pragmatic-level expertise in environmental management, systematic conservation planning and water resource management (national and provincial government departments as well as consultants); and (c) normative-level expertise in planning and policy across environment and water sectors (national and provincial government departments) (Fig. 2b). At the purposive level, the values underpinning the study were rooted in cross-sector policy objectives (Roux et al. 2006) which, in turn, were strongly influenced by legislation from particularly the water and biodiversity sectors. Importantly, the participatory process used to derive cross-sector policy objectives for freshwater conservation (Roux et al. 2008) helped to build inter-organisational relationships even before the inception of the NFEPA project (Audouin et al. 2013). Indeed, many of these organisations became funders and co-designers of the NFEPA project (Nel et al. 2016). This multiple institutional ownership of the NFEPA project undoubtedly served as a catalyst for the widespread dissemination and uptake of the project outputs.

In the Wilderness project, members of the project team represent various empirical-level disciplines from across the natural and social sciences, including conservation biology, systems ecology, aquatic ecology, communication and social–ecological resilience (Fig. 2c). At the pragmatic level, the team engaged agriculture (mainly dairy farmers) and civil society (e.g. Seven Passes Initiative, Touw River Conservancy, Wilderness Ratepayers and Residents Association). At the normative level, co-learning occurred with decision-makers from government entities (SANParks and Eden District Municipality) as well as the project steering committee. The purposive level included the Water Research Commission (directing the scope of research) as well as sustainability principles from national policy documents and scientific literature (O'Farrell et al. 2015).

Max-Neef's hierarchy of knowledge (Fig. 2a) was a useful guide for mapping out the expertise and functions required to achieve the aims of each case study. It helped to consider the systematic representation across the transdisciplinary hierarchy, both vertically and horizontally (see Fig. 2b, c). However, we found it more useful to view the two-dimensional hierarchy as a knowledge network that is inextricably linked to (and dynamically shaped by) the development of relationships among diverse actors. In instances where actor linkages are not well developed or understood, an explicit focus on "network weaving" may be helpful. This involves social network mapping and analysis to help strategically identify non-communicating stakeholders with whom mutually beneficial links could be established (Vance-Borland and Holley 2011).

Ultimately, the two-dimensional hierarchy depicted in Fig. 2a will only deliver on transdisciplinary learning and systemic change if populated by actors with appropriate agency, i.e. those who have the capacity to participate in the learning process, relay messages over space and time and act on new knowledge within their mandates. Establishing linkages takes time and is often mediated by

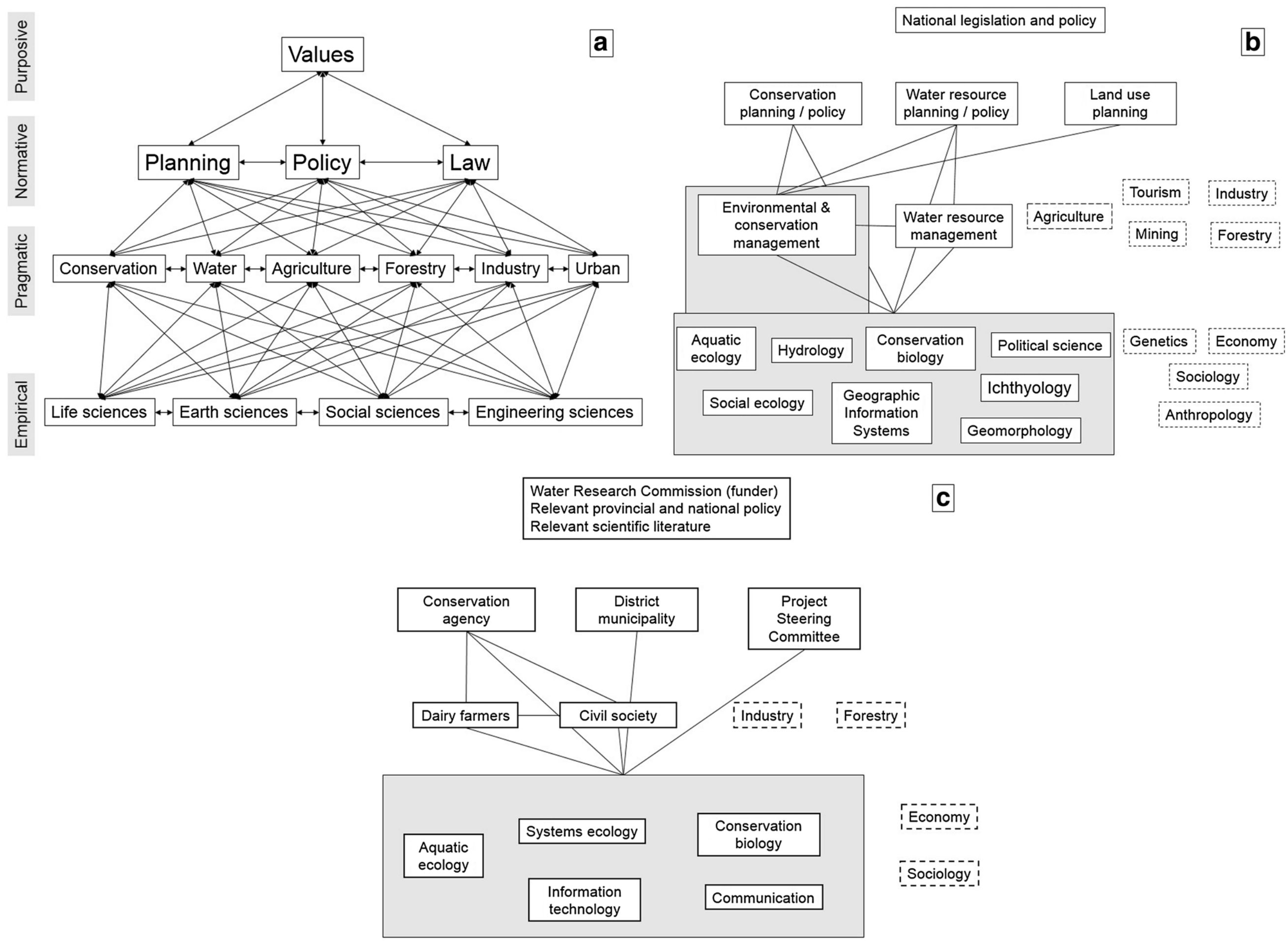

Fig. 2 Hierarchies of knowledge based on the literature (**a**) and applied for the two case studies (**b**, **c**). A hierarchy of knowledge based on Jantsch (1972), Max-Neef (2005) and Reyers et al. (2010) (**a**) was used to map relevant transdisciplinary actors for the NFEPA (**b**) and Wilderness (**c**) projects, respectively. In **b** and **c**, the *grey shading* indicates the knowledge domain of the project team members, some of whom also acted as bridging agents. *Boxes with solid outlines* indicate actor groups that were successfully engaged and *boxes with dotted outlines* indicate actor groups that were deemed important to the respective studies but who were not successfully engaged within the duration of these projects. *Connecting lines* are used to indicate the actors between whom mutual learning occurred

serendipity. For example, in the Wilderness project a discussion with an official at a school sport event helped to overcome an impasse in setting up a formal meeting. The reality is that in an emerging democracy such as South Africa, stakeholder capacities are uneven, which is one of the root causes of inequity. To promote more equitable participation remains a challenge, which we strived to overcome through a number of strategies. These included to (a) comprehensively analyse social networks in advance, especially in the Wilderness project (Roos 2015), (b) use community workers and community-based organisations as intermediaries to link the research team with historically neglected stakeholders, (c) advertise knowledge-sharing events in unusual places such as the local post office and schools, (d) use accessible bridging objects such as simple maps and participatory mapping exercises (see section on boundary objects below) to level the playing field and (e) organise knowledge-sharing events at or close to participants' places of work and residence (see section on third places), to enter their comfort zones instead of inviting them into ours.

Experts, novices and bridging agents

A balance of seasoned professionals and novices can facilitate mentoring, succession and a constructive and complementary tension between more established and more open mindsets (Bransford et al. 2003). Following Bransford et al. (2003), we use "experts" to refer to experienced professionals who have acquired extensive knowledge that enhances their ability to interpret information, reason and solve problems. The competence credibility of these individuals lends trustworthiness to the projects in which they are involved, and in most cases, they are sought-after mentors or supervisors for less experienced workers.

Novices on the other hand are eager to learn new things and do not have the restrictions of overly conditioned "habits of understanding" (sensu Ison (2010)), deeply entrenched beliefs or overburdened work schedules. They might be in a position to "see" new opportunities or solutions and to adopt "new ways of doing" in the workplace. At least some of the experts and novices should also be bridging agents, in this context referring to people skilled at connecting key individuals from different knowledge domains across the transdisciplinary knowledge network (Fig. 2).

The NFEPA project team included experts, novices and bridging agents, spanning key national government departments, agencies and research facilities. However, relatively few experts and bridging agents came from provincial government departments. While the NFEPA project gave considerable attention to developing end-user readiness for its products (e.g. through facilitating participatory case studies within selected provinces), none of the nine provinces in South Africa had the full suite of aquatic and conservation expertise (Driver et al. 2011) to enable them to effectively discharge their mandates regarding freshwater conservation and management. Those provinces with relevant capacity (see Impson 2016) were markedly more active in the NFEPA engagement processes, which generally translated into stronger adoption of project outputs. Some provinces lacked the basic freshwater and conservation expertise required to effectively "absorb" the new information (Impson 2016). While we would suggest that transdisciplinary learning provides a platform for increasing the "absorptive capacity" (see Murray et al. 2011) of participants, there seems to be a minimum threshold of prior knowledge that enables participation in the first place and over which the transdisciplinary project has limited control.

In the Wilderness project, the research team consisted of a number of established scientists (experts) as well as MSc/MA/MTech- and PhD-level students (novices). Some of the team members were also natural bridging agents, and the project drew extensively on existing relationships between researchers and actors from across the transdisciplinary knowledge network (Fig. 2c). However, the same presence of experts and novices was not achieved within all stakeholder groups. For example, the dairy farmers and officials from the District Municipality appeared to be mostly established career experts, while the lack of novices in these groups might challenge their future institutional memory regarding lessons learned from this project. The Seven Passes Initiative, on the other hand, was represented mostly by young people from the Touwsranten community, and we had to actively recruit senior community members with historical knowledge. Engagement dynamics were further enhanced by natural networkers or "connectors" (sensu Gladwell 2000) both in the farming community and civic society groups. However, the project team was unable to find and engage such individuals within government, which no doubt hampered uptake of the project outcomes in these agencies. So while one may have an idea of who to learn with, finding these people can prove impossibly difficult and potentially impact the outcomes of transdisciplinary research.

What to learn about?

Individual learning proficiency is highest when learning about things that the individual already knows a lot about (Bransford et al. 2003). Furthermore, it is convenient to learn about these things with and from others who share the same language, belief, education and socio-economic status, because such similarities support effective communication (Rogers 1995). These two learning principles help to reinforce disciplinary focus and knowledge fragmentation in science.

An important point of departure in transdisciplinary learning is to learn about things that will help to overcome perceived differentness (among the spectrum of actors/co-learners that have been identified in the previous section) and work towards shared interest. Below we present two such learning themes.

Each other's histories, values and existing knowledge

People's perceptions of and responses to social–ecological change are likely to be context specific and grounded in place-based histories, social networks, cultural norms and institutional structures, and involve a variety of actors at all levels of society (Paschen and Ison 2014). To foster a better appreciation of the diverse perspectives that exist across a transdisciplinary knowledge network, actors should also learn about the perspectives of fellow actors in their social–ecological system. A starting point is to learn about each other's histories, existing knowledge and realities.

In the NFEPA project, actors from across the transdisciplinary network mostly had similar levels of education (tertiary) but displayed differences in work cultures (e.g. science, management, policy functions). From project inception, an effort was made to understand relevant policy contexts and to be reflective of the key policy issues (e.g. that NFEPA products should align with existing legislation and avoid spatial congruence with areas prioritised for economic development). Similarly, the project enabled interaction with conservation practitioners and the team endeavoured to understand their implementation realities, e.g. regarding resource limitations. The sociopolitical history of South Africa featured in many discussions and the need to balance conservation aspirations with socio-economic priorities was acknowledged.

The Wilderness project was characterised by substantial dissimilarity among actors in terms of both education and work cultures. Dairy farmers, scientists, local government officials, residents of low-cost settlements and subsistence fishers are not naturally "members of the same flock". In this project, the research team made a dedicated effort to listen first (especially during the first year of the project) and to offer their perspectives only when asked. Initially, the dairy farmers did not see enough relevance in the project to commit their time. Through attending some of their meetings as observers (e.g. around a farmer's kitchen table over coffee), the interest and commitment of the farmers grew to the point of becoming a key participant group by the end of the project. The fact that staff and students from the local university were part of the project team contributed to trust building. Some of the MSc/MA/MTech students integrated narrative enquiry in their research approach (e.g. Roos 2015; Buckle 2016; Mc Culloch 2016). These student researchers and other actors became co-learners, as opposed to investigators and subjects, participating in a mutual process of reflection and sense making. One MSc thesis focussed on synthesising historical events that played a significant role in shaping the social–ecological system of the Wilderness Basin (Roos 2015). Various stakeholders were surprised to learn how these events affected fellow stakeholders, and that they were all linked to some degree as inhabitants of the same basin.

A general characteristic of both case studies was that scientists respectfully and empathetically listened to their transdisciplinary learning partners. Such listening helped to remove social distance and build trust among participants. Learning about each other also provided a deep understanding of the receiving environment for the project outputs. This helped to translate the new transdisciplinary insights into relevant and useful products.

However, some of the actor groups, including public-sector departments and agencies, were ill-prepared to collaborate and learn with other actors. Reasons may include (a) prejudices (not able to "hear" views contrary to established beliefs), (b) capacity limitations (more specifically depth and breadth of project-related knowledge) and (c) inability to navigate power inequalities among actors. In such situations, which are particularly prevalent in developing countries, mutual learning and knowledge co-production processes are likely to be slower than what researchers or funders desire (Reyers et al. 2010). However, in our experience, learning about each other's worlds and realities contributed significantly to relationship building and subsequent willingness to engage in mutual learning on the theme of the particular project.

Concepts that promote mutual understanding, and an aspirational common future

Concepts represent generalisations or abstractions of how things work. In transdisciplinary research, shared concepts can help to steer mutual learning and foster common understanding. Acknowledging that people construct new understanding based on what they already know and believe (Bransford et al. 2003), the same concept may lead to different interpretations by different transdisciplinary actors. This diversity of perspectives contributes to a rich knowledge base from which a desired common future can be jointly articulated.

In the NFEPA project, scientists summarised consensus, uncertainties and disagreements from the literature on systematic conservation planning and freshwater ecology. These were presented to policy officials and resource managers in a form that was relevant to their respective policy contexts and work mandates (see Roux et al. 2008). Through the resulting science–policy–management dialogue, concepts such as conservation targets, biodiversity representation, planning for efficiency and free-flowing rivers became part of the NFEPA narrative. These concepts facilitated sense making and exploration of mutual understanding. New terms such as "Freshwater Ecosystem Priority Areas (FEPAs") and "implementation-driven planning" emerged from the transdisciplinary learning process and helped to establish a sense of broad ownership through shared vocabulary. The project was directed by a national goal, namely "to conserve a sample of the full variety or diversity of inland water ecosystems that occur in South Africa… for present and future generations". This goal was itself the outcome of deliberations with policy officials across various sectors. It was widely "owned" and collectively disaggregated into five subordinate policy objectives and several implementation principles and recommendations (Roux et al. 2006), including a quantitative target of conserving 20% of all freshwater ecosystem types. The latter became influential and served as an aspirational vision for guiding the spatial delineation of FEPAs.

The Wilderness project team used various engagements (e.g. sustainability dialogues) as opportunities to introduce selected concepts to stakeholders. These concepts included ecological infrastructure, ecosystem services, Anthropocene, co-management, stewardship and water quality. Learning about ecological infrastructure and ecosystem services helped a local government department to reconceptualise the links between their environmental management mandate and societal benefits. Dairy farmers could relate to the risk that toxic cyanobacteria pose to their cows and hence the dangers associated with nutrient enrichment of farm dams. It was also rewarding to learn that, following one of the dialogues, a farmer had sourced further reading on the tragedy of the commons and that the concept has helped him to better understand social–ecological challenges in the area. During the third year of the project, actors from the Wilderness project identified the need for a common vision, articulating it as: “A healthy river system and healthy community through collective effort, beyond our own back yards” (O’Farrell et al. 2015).

In both case studies, we found that most of the identified actors were open to (and interested in) learning about new concepts from science, especially those concepts that were also of direct relevance to their worlds. We found the skilful introduction of shared [scientific] concepts of interest to be an important catalyst for transdisciplinary learning.

How to learn [together]?

“How to learn” relates to designing interventions to ensure true co-learning and empowering actors to participate equally in the knowledge production process (Mobjörk 2010). We found that knowledge co-production was a useful yardstick to aim for, defined by Armitage et al. (2011) as “the collaborative process of bringing a plurality of knowledge sources and types together to address a defined problem and build an integrated or systems-oriented understanding of that problem”. Below we present two ways for facilitating learning that promoted knowledge co-production in our case studies, namely the use of boundary objects and third places.

Embrace boundary objects

Several academic communities recognise the importance of boundary objects but view and use the concept differently (Star and Griesemer 1989). Examples of boundary objects include models (White et al. 2010), indicators (Turnhout et al. 2007) and maps (Nel et al. 2016). Co-production of these objects can establish shared interest and at least overlapping understanding across multiple knowledge domains. Star and Griesemer (1989; page 393) suggest that boundary objects are useful “in developing and maintaining coherence across intersecting social worlds”.

In the NFEPA project, a national and several sub-national maps of FEPAs served as tangible tools and shared boundary objects to promote multi-agency cooperation in conserving freshwater biodiversity. These maps were collectively envisioned during the project’s initiation phase and were co-produced by diverse stakeholders through a series of interactive workshops. During these workshops, more than 450 individuals representing >1000 years of collective experience contributed knowledge to help design, revise and improve the maps (Fig. 3a, b) (Nel et al. 2016). This resulted in the broad ownership and utility of the FEPAs, which have found application in both national policy and decision-making processes, as well as local management in the water and biodiversity sectors (Nel et al. 2016). Examples of uptake include a national water resource strategy (DWS 2013), a national biodiversity assessment (Driver et al. 2012), water catchment management strategy and plans (Inkomati 2013) and a management plan for a national park (Roux et al. 2016).

In the Wilderness project, maps depicting built and ecological infrastructure were used as boundary objects. Stakeholders were asked to partake in participatory mapping exercises (similar to focus group meetings, see Chambers 2006), typically with 4–5 individuals from a single actor group at one time. A list of prompts was used to guide the conversation and participants indicated their “answers” on the printed map using various colour pens to differentiate between ecological infrastructure, built infrastructure, and threats to those infrastructures, among other issues.

Create “third places”

A certain public space (also referred to as the *agora*) is required for scientists and practitioners to meet, share experiences and learn together (Nowotny et al. 2001; Pohl et al. 2010; Polk 2014). For both projects, we were inspired by a related concept that is relatively new to the transdisciplinary literature, namely Ray Oldenburg’s “third place”. A third place refers to a social environment, other than home or the workplace, that provides a neutral ground for engagement, conversation and community building, and for establishing feelings of a sense of place (Oldenburg 1989). In a transdisciplinary sense, a third place represents a learning space at the interface between academia and practice, where academics and non-academics can have an equal voice when they engage to find common ground regarding particular social–ecological issues.

In creating third places, there are some physical considerations. For example, using accessible yet attractive locations, and seating arrangements that encourages interaction. There are also non-physical design features such as creating a space where disciplinary boundaries become less clear and less intrinsically acceptable (e.g. through the careful use of language).

Conversation or dialogue is the main activity taking place at third places. During the dialogue, it is likely, and perhaps desirable, that a third position will emerge, which is not an academic, traditional, management or policy position, but rather acknowledges and reflects the values and beliefs of all the relevant actors. It might not be

Fig. 3 Use of boundary objects and a third places in the two projects. Maps used as boundary objects in the NFEPA project served to facilitate stakeholder engagement (**a**) and evolved into spatially explicit conservation plans (**b**). In the Wilderness project, various actor groups could relate to ecological as well as built infrastructures on maps of their local areas (**c**), and the village school hall was a good third place for dialogues (**d**)

possible for any one actor group to imagine this third position without the rich interaction of all the positions during iterative issue framing, knowledge production and knowledge application. We propose that transdisciplinary work does not start once the third position emerges. Rather, the third position is a product of transdisciplinary engagement.

The interactive workshops that characterised the NFEPA project were commonly held at a meeting facility in a botanical garden. The relatively neutral setting contributed to free and equal communication among policy officials, conservation practitioners, scientists and resource planners. These workshops were characterised by participants being fully engaged around a table covered with maps rather than sitting in a hall listening to presentations (Fig. 3a).

The most notable third places that were created during the Wilderness project were in the form of "sustainability dialogues" following the World Café method (Oelofse and Cady 2012). This method facilitates group learning through multiple mini-dialogues that encourage participant interaction around questions formulated in a way to stimulate reflection and access the collective intelligence of the group as a source for innovative thinking (Brown and Isaacs 2008). Dialogues were held on the local university campus and in the hall of a local primary school (Fig. 3d). Care was taken to create a welcoming and open ambiance and to facilitate inclusive participation. For example, seating arrangements and refreshments mimicked a coffee shop rather than a lecture hall. Technical information was translated and shared in common English and Afrikaans (the local vernacular), often using metaphors, such as comparing a catchment to the human body when explaining its complex connections. Convenience, accessibility and neutrality were important considerations in selecting the venues and timing for dialogues. For example, several dairy farmers attended the dialogue in the school hall after dropping their children for school. The children helped arrange tables and chairs before school and farmers felt comfortable to attend with their work clothes. From the feedback of participants, these events were learning highlights.

Lessons for transdisciplinary researchers

In both our case studies, explicit efforts were made to involve actors from across the transdisciplinary knowledge network (Fig. 2). Retrospectively, we emphasise the value of a representative spread of experts and novices throughout the network including some skilful bridging agents. This was fulfilled by the respective project teams, who instilled an ethos of listening to (and learning about) transdisciplinary learning partners, to the point where there was sufficient social cohesion among actors to jointly formulate a common vision. Complementary learning about concepts of shared interest (e.g. conservation planning and stewardship of ecological infrastructure) helped to inform the vision. Boundary objects and third places were helpful mechanisms for facilitating transdisciplinary learning.

Yet, when assessed against the systemic change achieved, the outcomes of the two case studies were different. The NFEPA project demonstrates how transdisciplinary learning and the associated emergence of co-produced and practice-based knowledge can fundamentally shift an institutional group story (in this case related to the conservation of freshwater ecosystems), with the NFEPA concepts and vocabulary now seemingly well entrenched in relevant policy, management plans and environmental practices (Nel et al. 2016). In the Wilderness project, enthusiastic participation and signs of an evolving group story did not translate into a systemic shift in institutional arrangements. The project team was not successful in securing a follow-on project, and the gains made during the Wilderness project seem vulnerable to regression.

While we acknowledge that findings from case studies in social–ecological systems cannot be easily generalised due to the uniqueness of the setting, some insights from our case study experiences could act as lessons to other transdisciplinary researchers. Through applying the learning framework to our case studies, and reflecting on their different outcomes, we have distilled five generic lessons for transdisciplinary researchers.

First, the duration, timing and continuation potential of a project influences its prospects for achieving systemic and sustainable change through transdisciplinary learning. At least six years of co-learning in the relevant science, policy and practice domains preceded the NFEPA project. A further five years of knowledge co-production served to consolidate and entrench the new knowledge. On the other hand, the Wilderness project was a newly initiated project. Although it served to establish conditions suitable to foster transdisciplinary learning, three years were insufficient to anchor the new knowledge systemically in this social–ecological system. This highlights a challenge for individual research projects and postgraduate studies that are framed as transdisciplinary research. Conventional funding arrangements and postgraduate studies offer limited opportunities for problem co-framing and knowledge co-production with transdisciplinary actors (Esler et al. 2016), and limited scope for mid-course adaptations based on context-specific factors. It might be more realistic to conceive transdisciplinary research as a programme consisting of a number of complementary research projects that converge towards a common, but dynamic, goal (Roux et al. 2010).

Second, bridging agents play a critical role in the social facilitation required for transdisciplinary learning. They migrate horizontally and vertically across the transdisciplinary knowledge network to connect different functions and domains, act as conduits for knowledge flows and reduce knowledge fragmentation. Our findings also indicate that the role of bridging agent should be embedded within an institution that has a primary interest in implementing the envisaged change. While excellent bridging agents may exist in academic institutions (e.g. universities, science councils), these institutions are not ideally placed for the long-term role of a bridging agent. During the NFEPA project, staff from the national biodiversity institute (SANBI) played a strong bridging role between national and provincial spheres of government, water and biodiversity policy sectors, and science and policy functions. SANBI could maintain its own NFEPA drive after the project concluded. At the same time, it is an influential policy institute that has been instrumental in entrenching NFEPA principles in various national policy developments. In the Wilderness project, the staff and students of the local university were successful bridging agents in that they were perceived as neutral and with a genuine interest in local issues. While they manage to facilitate dialogue among transdisciplinary actors, a lack of an institutionalised bridging agent hindered post-project sustainability. Some of the actors are now asking when the next meeting will take place, and without a related project this leaves the university bridging agent in a somewhat embarrassing position.

Third, transdisciplinary learning holds the potential to put researchers, decision-makers and other knowledge users on equal footing. It challenges the notion of a researcher as the "expert" who "produces" knowledge that is "transferred" to users (Rogers 2006). Transdisciplinary researcher will need to expand their scope from being skilled at mastering a knowledge domain to also being skilled at participating in open learning systems and from participating in knowledge co-production to also being involved with its translation to action (Cornell et al. 2013).

Fourth, transdisciplinary learning that is underpinned by mixed-paradigm research could help mend knowledge fragmentation within science. Our main focus in this paper was on learning across science–stakeholder knowledge domains. However, learning across academia's natural and social science cultures is also relevant. In the Wilderness project, postgraduate theses used narrative, empirical and action research designs (Buckle 2016; Crisp 2015; Mc Culloch 2016; Roos 2015). Complementarity, and indeed synergy, of results was facilitated by an overall project aim and regular dialogues. Students (and supervisors) from across social and biophysical subject areas interacted with remarkable ease and were generally appreciative of the broad exposure. We believe that a transdisciplinary approach with purposeful mixed-paradigm design could contribute to opening up new synergies between traditional divides of qualitative and quantitative research as well as inductive and deductive reasoning in science.

Fifth, transdisciplinary researchers must constantly guard against three wicked pitfalls in mutual learning initiatives. The first is biases in participant self-selection as educated and wealthy participants have easier access to information, respond and interact faster, and nominate themselves more readily than those from disadvantaged backgrounds. The second is the perceived superiority of scientific knowledge and empirical ("hard") data that is common among many types of stakeholders. Participants with experiential and informal knowledge struggle to legitimise their "data" and may withhold such information for fear of being ridiculed or looked down upon. The third is the "fatal attraction" of simple solutions to wicked problems. Participants who confidently propose (or impose) simple solutions gain traction and appeal. However, such solutions may often favour the status quo instead of innovation. We believe that our approach to mutual learning, while not being a silver bullet to the wicked problem of collaborative ecosystem management, can help guard against such pitfalls.

Conclusions

The global science community is more connected and learning faster than ever before. Governments and society in general are overwhelmed with rapid changes and frequent surprises and increasingly operate in a reactive mode. It is inherently challenging to maintain two-way knowledge flows between these two domains. Transdisciplinary research is an approach tailored to address this challenge.

Although transdisciplinary research has a relatively long history of academic discourse, agreement on standards for its practice is still lacking. The development of such standards will depend on publishing insights that emerge from across diverse transdisciplinary research settings. Attention should also be given to the social processes (such as mutual learning) that form an inevitable part of transdisciplinary research. However, social processes introduce context-specific nuances, may change in dynamic and unpredictable ways, cannot be controlled or fully known, and on the whole may not be reproducible. A challenge to the advancement of transdisciplinarity is that it is difficult to convey the full richness of such processes, especially in mainstream publication formats that are largely optimised for the more established hypothetico-deductive method of scientific inquiry.

In this paper, we address some of the social dynamics of transdisciplinary research as experienced in two case studies that took place in South Africa. We focused on a component that has received relatively scant attention, namely how to enable mutual learning processes among relevant actors. Based on the comparative analysis of our case studies, we present a transdisciplinary learning framework consisting of six learning heuristics (Fig. 1). These proved useful across the scales of the respective case studies (i.e. national and local). Although our learning heuristics emerged from specific case study contexts, we believe that they provide generic utility for both reflecting on and designing the learning components of transdisciplinary research initiatives.

Other novel contributions that emerged from our analysis include (a) a modification of Jantsch and Max-Neef's hierarchy of disciplines to include non-academic knowledge and its application to identify relevant actors; (b) emphasising the value of including both experts and novices in transdisciplinary work; (c) distinguishing between the effectiveness of bridging agents who are embedded within an implementation agency and those who are not; (d) using Oldenburg's (1989) third places to characterise the public space for transdisciplinary learning; and (e) highlighting the potential of mixed-paradigm research designs within a programme of study to help mend scientific knowledge fragmentation.

Based on our observations and findings, we frame transdisciplinary research as a process of mutual learning, which is directed by a desired sustainability outcome, is semi-bounded by a scale-dependent social–ecological system and is practiced by a transdisciplinary network of actors whose intention is to produce and apply relevant knowledge. Finally, we suggest that practicing transdisciplinary research with attention to who to learn with, what to learn about and how to learn can promote systemic learning and possibly catalyse institutional change.

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