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Perspective

Characteristics, potentials, and challenges of transdisciplinary research

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SUMMARY

Resolving the grand challenges and wicked problems of the Anthropocene will require skillfully combining a broad range of knowledge and understandings—both scientific and non-scientific—of Earth systems and human societies. One approach to this is transdisciplinary research, which has gained considerable interest over the last few decades, resulting in an extensive body of literature about transdisciplinarity. However, this has in turn led to the challenge that developing a good understanding of transdisciplinary research can require extensive effort. Here we provide a focused overview and perspective for disciplinary and interdisciplinary researchers who are interested in efficiently obtaining a solid understanding of transdisciplinarity. We describe definitions, characteristics, schools of thought, and an exemplary three-phase model of transdisciplinary research. We also discuss three key challenges that transdisciplinary research faces in the context of addressing the broader challenges of the Anthropocene, and we consider approaches to dealing with these specific challenges, based especially on our experiences with building up transdisciplinary research projects at the Institute for Advanced Sustainability Studies.

INTRODUCTION

The rapid and vast transformations that global human societies and the environment are undergoing in the Anthropocene[1] result in numerous, closely linked societal and environmental challenges, such as increasing urbanization, growing energy and mobility demands, non-sustainable production and consumption patterns of food and consumer goods, loss of biodiversity, climate change, and pollution of air, water, and soils.

Academic research—both natural and social sciences, along with the humanities—has historically provided and continues to provide insights about these challenges. This knowledge has often been valuable in support of policymaking process aimed at developing regulations, incentives, and other mechanisms for addressing these challenges, as well as for social advocacy striving for more extensive political and societal responses to known threats. Knowledge has played a key role in many societal transformations, and it is increasingly doing so in modern societies.[2] There is active research on understanding how this actually occurs, for example how social learning arises and how this in turn leads to change.[3]

Traditionally, policy advice has largely consisted of investigating and communicating the consequences of specific policies and actions, along with developing future scenarios and solution pathway options. These are often stated in if-then relationships: "if this option is followed, then this result can be expected," striving to find pathways that would be particularly effective or optimal for some specific goal. While this form of science-based policy advice can be highly effective for many decisions with relatively little ambiguity, e.g., where to place measurement devices to provide effective environmental pollution monitoring for a specific regulation, it becomes considerably less effective in the context of increasingly complex and interconnected societal and environmental challenges, such as climate change and pandemics like COVID-19. Although academic research can still provide very valuable insights into complex challenges, such as into the costs (social and economic) and implications of policy measures, it is not able to provide clear assessments of if-then relationships, let alone determining solutions or optimal pathways, due to the multi-faceted nature of such challenges. At the pinnacle of complexity for societal challenges are so-called *wicked problems*[4] (see Box 1), which are so complex and interconnected that they cannot really be *solved*, rather only *resolved* in multiple ways, with differing costs and benefits for those involved.

In light of this, extensive consideration has been given to understanding how the science-policy nexus can more effectively support sustainability-oriented transformations and address wicked problems and other complex societal challenges,[13,14] for example by proactively involving the various societal actors who are or will be directly affected by these transformation processes.[15,16] A major step in this direction has been the

Box 1. Wicked problems: major incentives for developing transdisciplinary research

The concept of a wicked problem emerged in the late 1960s and early 1970s based on experiences with the complex interrelationships between various social and environmental aspects of city planning.[4] The term "wicked" is not intended in the moral sense of being "evil"; instead, it is in the sense of being malignant. Thus wicked problems are much more difficult to address than more benign problems; although these can nevertheless still be extremely complicated, traditional scientific methods are generally effective for them, for example determining to a high degree of certainty the structure of some unknown organic molecule.[4]

Ten key characteristics of wicked problems were defined in the seminal work by Rittel and colleagues.[4] These are paraphrased in a recent study on climate change as a wicked problem,[5] which fits well to the context of this Perspective. Here, we have only modified this description slightly for readability:

1. Wicked problems have no definitive formulation.
2. Wicked problems have no ends to their causal chains—"no stopping rule" (i.e., one is never completely "done" dealing with the wicked problem).
3. Wicked problems do not have "true-false" solutions, rather "good-bad" or "better-worse" ones.
4. Wicked problems offer no "immediate" or "ultimate" tests for a solution.
5. Wicked problems mean that every attempt at a solution is consequential, i.e., there is no opportunity to innocuously learn by trial and error since every attempt counts significantly.
6. Wicked problems do not have an "exhaustively describable" set or series of solutions.
7. Every wicked problem is unique—having at least one "distinguishing property that is of overriding importance."
8. Every wicked problem points to other wicked problems—each also being a symptom of the other.
9. The discrepancies that characterize a wicked problem can be explained in multiple ways, and the choice of explanation affects how the wicked problem will be approached and possibly resolved.
10. Wicked problems pose particular difficulties for those aiming to resolve them (or as Rittel and Weber originally stated it: "The planner has no right to be wrong").

Although this list is already relatively exhaustive, various other characteristics have also been ascribed to wicked problems over the years. For example, wicked problems are often accompanied by significant pressure due to urgency and their often vast implications or "high stakes."[6,7] Some studies have proposed the category of "super-wicked problems,"[8] which have further characteristics, especially the absence of a well-defined central authority when a coordinated division of responsibility is imperative. As a consequence of several of these characteristics, Rittel and Weber[4] point out that it is not really appropriate to consider *solutions* to wicked problems, rather only a range of possible *resolutions,* and Funtowicz and Ravetz[6] even noted that for such challenges, "the term 'problem,' with its connotations of an exercise where a defined methodology is likely to lead to a clear solution, is less appropriate." There are many well-known contemporary wicked problems, such as climate change,[5,9] which involves numerous complex aspects to consider in addressing the sources and impacts of climate forcers. Another contemporary wicked problem is the rapid growth of digital technologies; among its many implications is the challenge of supporting sustainable development in urban regions without disproportionately compromising security and privacy,[10] which ironically closely relates to the challenges that originally led to the development of the concept of wicked problems. And of course, the COVID-19 pandemic[11,12] exemplifies the characteristics of a wicked problem, with the wide range of perspectives and approaches to balancing the trade-offs between the immediate and the long-term health, social, cultural, and economic impacts.

development of transdisciplinary research (TDR), which has a long history[17–22] and has branched into numerous understandings and approaches (only some of which directly involve societal actors in the research process). An introduction to the concept of transdisciplinarity, including various definitions and schools of thought, is given in the next section. Throughout this Perspective, we apply the term "transdisciplinary" to specifically imply a form of research. It is also legitimate to apply the term as an adjective in other contexts, such as a "transdisciplinary group" or a "transdisciplinary meeting," in which "disciplines are transcended" by involving non-academic societal actors together with academics from various disciplines. It is worth noting upfront that in our viewpoint, and that of many transdisciplinarity scholars,[22,23] TDR is intended to augment—rather than to replace—research conducted using long-standing disciplinary and interdisciplinary scientific methods. This also applies to traditional policy advice formats based on disciplinary and interdisciplinary scientific knowledge, which should also be augmented, not replaced, by transdisciplinary approaches.

The emphasis on TDR in large community programs like *Future Earth*[24] and in journals like *One Earth* and *Earth's Future* has contributed to a growing interest in the topic, especially among researchers working on sustainability-oriented topics in more traditional disciplinary and interdisciplinary academic settings. A thorough understanding of transdisciplinarity is in principle readably attainable—though with considerable effort—through reading the many reviews and extensive handbooks that have been published on the topic.[21–23,25–29] In particular, Lang et al.[30] provide a targeted, specialist overview, specifically from the sustainability science perspective, considering design principles for carrying out TDR. However, it can be quite daunting to even get started into such extensive reading, and for many researchers it would be adequate to have a good general understanding of transdisciplinarity without delving into such details. To our knowledge, there is not yet a paper that is specifically designed to serve this purpose.

This Perspective aims to fill this gap by providing an accurate and adequately comprehensive yet easily readable scientific overview of the characteristics and challenges of TDR, particularly

Box 2. A brief history of transdisciplinary research

The terms ‘‘transdisciplinary’’ and ‘‘transdisciplinarity’’ have a 50-year history, being primarily attributed to a conference on interdisciplinarity in 1970 and follow-up publications by Piaget[19] and Jantsch,[17,18] along with a little-known PhD thesis titled ‘‘Toward transdisciplinary inquiry in the humane sciences’’[20] that independently introduced the term at the same time.[22] However, the general developments leading to the concept of transdisciplinarity have much earlier roots in discussions (e.g., Brunswick[35]) about the need for new forms of interdisciplinary collaboration to address wicked problems and other societal challenges.

Interestingly, although the concepts of transdisciplinarity and wicked problems were both introduced in the early 1970s, they were not really connected closely until the early 1990s. Klein[36] has attributed this connection especially to the 1992 UN Earth Summit (in Rio de Janeiro), which resulted in a significantly increased awareness of the need for more effective interaction between the academic and policy communities to support societal transformations. Other factors also certainly played a role, especially the ‘‘growing realization that globalization was not necessarily a good thing’’,[22] evidenced through tragedies like the AIDS pandemic. This all led to the seemingly explosive development of different TDR concepts and practices over the last three decades, and to a concept of transdisciplinarity that generally ‘‘prioritizes the interface between science, society, and technology in the contemporary world’’.[22,37]

During this time, the First World Congress of Transdisciplinarity took place in 1994, which resulted in the ‘‘Charter on Transdisciplinarity’’ (http://ciret-transdisciplinarity.org/chart.php#en) and the ‘‘Manifesto of Transdisciplinarity’’ by Nicolescu,[38] which included a clear orientation toward the common good, stating: ‘‘Shared knowledge should lead to a shared understanding based on an absolute *respect* for the collective and individual Otherness united by our common life on one and the same Earth’’. However, the works of Nicolescu and of several others[39–41] were also in contrast to the more pragmatic focus of developing and applying TDR in the context of societal challenges like wicked problems; instead, this school of thought focused on conceiving ‘‘…transdisciplinarity as a theoretical unity of all of our knowledge’’.[21] This builds on the work of the transdisciplinarity scholars of the early 1970s, who shared a vision of a ‘‘purpose-oriented integration of knowledge to grasp the complexity of problems in the life-world’’.[21] The work of Nicolescu and others was especially fueled by their frustration over the increasing specialization of science, which Nicolescu[42] expressed very pointedly: ‘‘In 1950, we already had 54 disciplines. … In the year 2000 we had more than 8,000 disciplines.…[based on] a very serious poll made by the National Science Foundation. … 8,000 disciplines means 8,000 ways to look for reality. It means a catastrophe for knowledge in some sense, because it means there is no more unity of knowledge.’’ However, it is important to emphasize that Nicolescu did not want to abolish distinct disciplinary work, rather find ways to bridge the silos of disciplinary work toward more unified knowledge perspectives.

These very different perspectives characterizing the long-standing interest in transdisciplinarity have resulted in a plethora of definitions, along with various approaches for putting TDR into practice. About a decade ago, Nicolescu[33] lamented that the resurgence of interest in transdisciplinarity ‘‘provoked, around 1990, a more or less violent war of definitions. This war is not yet finished.’’ Jahn et al.[23] pointed out shortly afterward that ‘‘a universally accepted definition is not available, even after 40 years of intensive scholarly discourse,’’ and more recently Thompson et al.[34] asserted: ‘‘While there is a growing body of literature on such approaches, there remains no widely-accepted definition, concrete framework, or empirical strategy for how to carry out a transdisciplinary project.’’

While there are clearly many different definitions associated with the rather different schools of thought about what transdisciplinarity is and encompasses, it is worth noting that – as in many academic endeavors – the boundary between these schools of thought is not quite as sharp as suggested by Figure 1, with the two schools having a common history and some shared characteristics, beyond the common feature of building on disciplinary, multi- and interdisciplinary research. In particular, although it does not appear explicitly in any of the "social engagement" transdisciplinarity definitions included in Figure 1, the roots in the "unity of knowledge" discussions were historically nevertheless implicitly fundamental for many of those researchers whose definitions fit to the classification as social engagement transdisciplinarity [R. Scholz, personal communication, 2020].

for disciplinary and interdisciplinary researchers who would like to develop a better general understanding of the topic, especially prior to becoming involved in TDR projects. We focus on definitions, characteristics, schools of thought, and an exemplary, conceptual three-phase model of TDR, along with three key challenges that TDR faces and approaches to addressing these challenges. The perspective presented here is strongly guided by our experience over the past years of introducing hundreds of new colleagues to the transdisciplinary, transformative research program[31,32] at the Institute for Advanced Sustainability Studies (IASS) in Potsdam, Germany.

DEFINITIONS AND CHARACTERISTICS

The terms ‘‘transdisciplinary’’ and ‘‘transdisciplinarity’’ have a 50-year history,[17–20] of which we provide a brief overview in Box 2. More comprehensive historical accounts are available for interested readers, e.g., in the *Handbook of Transdisciplinary Research*[21] and in a recent review by Bernstein.[22] The long-standing interest in transdisciplinarity from very different perspectives has resulted in a plethora of definitions, along with various approaches for putting TDR into practice, and numerous researchers[23,33,34] have noted that there is no widely accepted definition of transdisciplinarity.

To make it even more complicated, there is often confusion around the terms "multidisciplinary" and "interdisciplinary" research, which are sometimes used interchangeably or without a clear understanding of what they mean.[43] To help distinguish these terms from transdisciplinary research, we define them here as follows:[21,33,34]

- *Multidisciplinary research* is the cooperation of researchers from several different disciplines, but each working in their

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own context with little cross-fertilization among disciplines, primarily sharing information and results at the end of their research to support the overall combined findings.

- *Interdisciplinary research* in contrast involves a much closer interaction, including transferring methods and knowledge between the academic disciplines (sometimes in turn leading to the development of what are eventually considered new academic disciplines, with their own characteristic knowledge, approaches, and boundaries to other disciplines); like the long history of transdisciplinarity, extensive work has also gone into understanding forms of interdisciplinary integration of knowledge.[23,44]

To illustrate how transdisciplinarity is considered to be distinguished from other forms of research, we have compiled 16 widely varying definitions from the literature of the last half-century in Table S1. Perusing these quickly makes it clear that it is not sensible to choose one or even a few "representative" definitions, and that it can take considerable time to wade through them and form a clear understanding of what they encompass. To aid our readers in quickly gaining this understanding, we have carefully examined this range of definitions and identify seven key characteristics that are either explicitly or implicitly referred to in the various definitions, and that help to distinguish them into broader schools of thought about transdisciplinarity and what it encompasses:

1) a focus on theoretical unity of knowledge, in an effort to transcend disciplinary boundaries;
2) the inclusion of multidisciplinary and interdisciplinary academic research;
3) the involvement of (non-academic) societal actors as process participants;
4) a focus on specific, complex, societally relevant, real-world situations or problems;
5) working in a transformative manner, i.e., going beyond the focus on real-world problems to proactively support action or intervention;
6) an orientation toward the common good (including the betterment of society and a humanistic reverence for life and human dignity);
7) reflexivity, i.e., consciously contemplating the broader context and ensuring the compatibility of the project's components and tasks throughout the course of the project.

The presence of these characteristics in the definitions (explicitly or implicitly) is indicated by the numbers in the last column of Table S1. A graphical depiction is provided by the shading in Figure 1, which gives a straightforward overview of how these seven key characteristics are present in various combinations across the definitions.

Figure 1 reveals several interesting features about the definitions of transdisciplinarity. Most importantly, the definitions can readily be distinguished into two classes, or "schools of thought" around transdisciplinarity. One set of definitions (grouped in the top part of the figure) all explicitly include the unity of knowledge characteristic (#1), but none include involvement of societal actors (#3). The other set (bottom part of the figure) all include involvement of societal actors (implicitly or explicitly), but generally do not mention unity of knowledge (with the notable exception that Jahn et al.[23] implicitly include it as the "cognitive operation of establishing a novel, hitherto non-existent connection between the distinct epistemic, social-organizational and communicative entities").

Fitting to these primary characteristics, we call these two schools "unity of knowledge" and "social engagement" transdisciplinarity (though other labels could also be considered, such as "principle" and "pragmatic" transdisciplinarity). Others have similarly distinguished various schools of thought of transdisciplinarity. In particular, Bernstein[22] and McGregor[37] make the same basic distinction as we do here, but they label the two schools the "Nicolescuian" school and the "Zurich" school, based on their historical origins. Ironically, Nicolescu[33] himself had previously discerned three different schools: "theoretical," "phenomenological," and "experimental" transdisciplinarity. Others have proposed even more detailed classifications; for example Renn[54] recently distinguished five historical (primarily European) schools of thought.

Another key feature revealed by the depiction in Figure 1 is that the only characteristic that is generally shared between the "unity of knowledge" and social engagement schools of transdisciplinarity is that both build on multidisciplinary and interdisciplinary academic research (characteristic #2), with all but one of the definitions in Figure 1 and Table S1 explicitly or implicitly mentioning this characteristic. The fact that multidisciplinary and interdisciplinary academic research is embedded in nearly every definition of transdisciplinarity supports the point noted in the introduction: TDR is meant to *supplement* disciplinary, multidisciplinary, and interdisciplinary academic research, *not to replace it*. This point is often taken for granted and not always made explicit,[23] which has contributed to the misimpression that we have sometimes heard expressed by colleagues, who are concerned that the emphasis on TDR in various programs such as *Future Earth* is intended to eventually replace more traditional forms of research. A very clear, explicit assertion that this is not the case was made by Nicolescu:[33] "As one can see, there is no opposition between disciplinarity (including multidisciplinarity and interdisciplinarity) and transdisciplinarity, but there is instead a fertile complementarity. In fact, there is no transdisciplinarity without disciplinarity."

Furthermore, although none of the unity of knowledge definitions of transdisciplinarity includes the involvement of non-academic actors, this does not imply that non-academic knowledge is unimportant for this school of thought. Quite the contrary, the inclusion of non-academic knowledge is a central component in the quest for a greater unity of knowledge. However, this does not necessarily require the active involvement of the non-academic actors themselves. Instead, the involvement of non-academic actors is only seen as needed in some situations, to share information that cannot otherwise be attained through indirect sources, such as media archives, literature, and art.

Beyond these first three key characteristics, the further characteristics (#4–7) are noted to be much more common in the social engagement transdisciplinarity definitions than in the unity of knowledge definitions. In particular, all of the social engagement transdisciplinarity definitions include a focus on complex

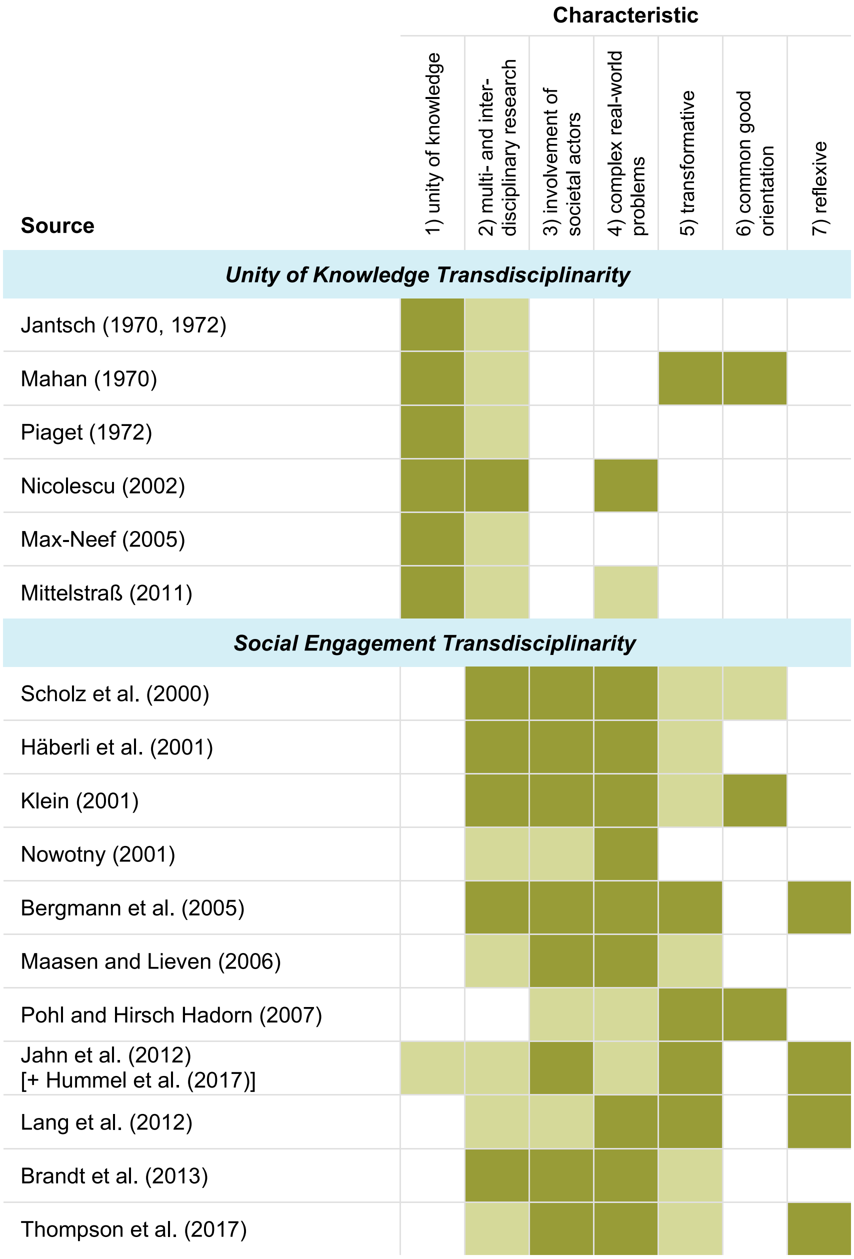

Figure 1. Key characteristics of transdisciplinarity included in a wide range of definitions proposed by various researchers
The seven characteristics are listed and described in the main text in the definitions and characteristics section. Here only the numbers and keywords are given in the header of each column. For the characteristics that are named explicitly in the respective definitions, the corresponding cells are dark green, while they are shaded light green for implicit characteristics that can be relatively clearly inferred as being necessary components of the definition (or which are included in the accompanying text in the original manuscripts). The definitions are grouped into "unity of knowledge" transdisciplinarity (top part of the figure) and "social engagement" transdisciplinarity (bottom part). This grouping is based solely on which of these two distinguishing characteristics are included in the respective definitions, not on whether the researchers themselves are characterized as proponents, practitioners, or developers of that particular school of transdisciplinarity (especially noting that some of the definitions stem from overview papers). See Table S1 for the full texts of the respective definitions. The sources are cited in the reference list, as well as in Table S1.[17–20,23,27,30,34,38,39,45–53]

real-world problems (#4), and all but one include a transformative character of TDR (#5). Only a few definitions include an orientation on the common good (#6) or reflexivity in the research process (#7); these characteristics become particularly important for analyses that focus on more subtle differences between the definitions, for example the distinction by Renn[54] into five schools of thought.

While the extensive primary literature on transdisciplinarity explores and discusses many more facets than we have described here, this brief overview should provide our readers with a useful introduction to the key aspects of the topic, including the different schools of thought about what transdisciplinarity entails, along with providing pointers to further reading for those interested in learning more. For our target readership, the social engagement school of thought will be by far the most relevant. Thus, throughout the rest of this Perspective, we will focus specifically on this school, which will be implicit whenever we simply refer to transdisciplinarity or TDR without specifying the particular school of thought.

CHALLENGES FACING TRANSDISCIPLINARY RESEARCH

Transdisciplinary research faces many challenges. This is reflected in the extensive thought and exploration over the past half-century that has been put into developing various concepts of transdisciplinarity and approaches to carrying out TDR (which in turn makes getting a good overview of the topic a challenge in itself, as discussed in the previous section). There have been a few efforts to catalog the numerous challenges that TDR faces; two of these analyses are summarized in Box 3 (and the accompanying full texts are provided in Table S2). These analyses typically focus on the challenges that are primarily of interest to those who are deeply involved in TDR, in terms of designing, leading, and evaluating TDR processes, as well as those who are analyzing and further developing the overall concept of transdisciplinarity. In the context of having a basic understanding of TDR, it is useful to generally be aware of the diversity of challenges described in Box 3. However, based on our experiences from designing and implementing TDR projects at the IASS, along with discussions and workshops analyzing these experiences, we will focus here on three challenges that we feel

Box 3. The myriad challenges faced by transdisciplinary research

In the primary literature on transdisciplinarity, there is a rich discussion about the wide range of challenges that TDR faces. To provide some insight into these, here we give an overview of the challenges that two studies have identified as being of particular relevance to the TDR community focusing on sustainability-related issues. The following are abbreviated summaries to provide a quick overview. Full versions of the descriptions with brief explanations and occasional examples are provided in Table S2.

Brandt et al.[27] conducted a systematic literature review (a quantitative and qualitative bibliometric analysis) of scientific journal papers focusing on sustainability science, and they identified five central challenges:

1. diverse definitions and understandings of transdisciplinarity, without a coherent general framing;
2. complex and unclear relationships in TDR projects between applied methods, transdisciplinary process phases and knowledge types;
3. a gap between "best practice" TDR as advocated in theoretical and concept studies and real-world TDR projects;
4. rarity of the highest levels of engagement with practitioners in TDR projects, especially "empowerment" (providing practitioners with the authority to decide within the process), although lower levels of engagement are common;
5. difficulty in evaluating impacts of TDR, in terms of both societal impacts and impacts on the scientific community.

Lang et al.[30] discuss twelve exemplary challenges based on a literature review of transdisciplinary sustainability-oriented research projects. Each challenge corresponds to one of their design principles for TDR projects, which in turn are components of their version of a three-phase conceptual model of TDR that they adapted from previous literature to match the discourse around sustainability-oriented research (see Table 1 and Figure 2).

Challenges associated especially with phase A:

1. a lack of awareness of the existence of a specific problem, or a lack of agreement over what exactly the problem is;
2. unbalanced "problem ownership," with a dominance of scientists driving the TDR process and limited involvement of non-academic actors in defining the project (including objectives);
3. a lack of legitimization of the team of researchers and actors, including underrepresentation of relevant actor groups;

Challenges associated especially with phase B:

4. conflicting viewpoints over methodological standards, especially between academic and non-academic participants;
5. challenges around various types of integration (knowledge types, social, organizational, communicative and technical) needed within TDR;
6. barriers to maintaining extended periods of engagement of participants in TDR projects, both internal to the project and externally driven;
7. the occasional tendency to keep the co-produced knowledge and results from TDR projects vague and ambiguous to gain approval by all process participants;
8. reversion to pre-packaged (technical) solutions, rather than exploring a range of solution options (due to the fear of failure);

Challenges associated especially with phase C:

9. a limited ability to generalize and scale up the results of specific case studies, as well as to transfer knowledge about the effectiveness of the applied TDR approach;
10. a lack of clarity about what role TDR results could or should play in relation to formally legitimized (non-transdisciplinary) procedures and political processes;
11. occasional distortion, misinterpretation, and misuse of results by project partners who are dissatisfied with the outcomes and implications;
12. difficulty with tracking the societal impacts (and sometimes the far-reaching scientific impacts) of TDR projects.

Most of the challenges focused on by Brandt et al., as well as some of those noted by Lang et al. are related to the definition and design of transdisciplinary process, which are discussed in the definitions and characteristics and phase model concepts of transdisciplinary research sections. The lists also include all three of the key challenges that we address in more detail in this Perspective paper: the issue of interaction between researchers and non-academic project partners is highlighted in many of the challenges identified by Lang et al., and in one challenge noted by Brandt et al.; challenges around normativity and bias are implicit in several of the identified challenges; and the challenge of tracking and evaluating societal impacts of TDR processes is the final challenge included in both lists.

Table 1. Phases involved in the TDR process, as delineated by several studies

Source	Phase 1	Phase 2	Phase 3
Bergmann et al. (2005)[45]	actors, project construction, and project formulation	project execution and methodology	results, products, and publications ("creating value")
Scholz et al. (2006)[55]	preparation (case selection, network establishment, project conception)	project work (analysis and synthesis)	elaboration and documentation (publications, case studies, evaluation)
Pohl and Hirsch Hadorn (2007, 2008)[46,56]	problem identification and structuring	problem analysis (including collaboration and organization work)	bringing results to fruition[46]/integration and application[56]
Jahn et al. (2008, 2012)[23,57]	formation of a common research object	production of new knowledge ("interdisciplinary integration")	transdisciplinary integration (assessment of integrated results and "second-order integration" into society and science)
Lang et al. (2012)[30]	collaborative problem framing and building a collaborative research team	co-creation of solution-oriented and transferable knowledge through collaborative research	(re-)integrating and applying the co-created knowledge (in society and science)

will be most relevant for our target readership to know about, especially to help avoid potential pitfalls when getting involved in TDR processes: (1) challenges related to the involvement of non-academic participants, (2) challenges around addressing normativity and bias, and (3) the challenge of evaluating impacts and effectiveness. These are discussed in the following three sub-sections, and we return to them later in the addressing key challenges of transdisciplinary research section.

Challenges around involving non-academic actors

The active engagement of non-academic actors together with academic researchers in TDR processes leads to numerous challenges, such as those noted in Box 3. In this section, we briefly discuss three specific aspects of this overarching challenge. Based on our experiences in discussions and workshops about TDR projects and processes, we consider these to be the most relevant for our target readership: (1) oversimplified concepts of TDR, (2) misuse and misrepresentation of knowledge, and (3) the discrediting of scientific knowledge.

As the notion of transdisciplinarity becomes more popular, the risk emerges that it will be frequently misunderstood, that oversimplified concepts of TDR will be applied, and that this may lead to unrealistic hopes for what can be accomplished, accompanied by an underestimation of the challenges involved in TDR processes.[23] Particularly with regard to the involvement of non-academic actors, the misimpression may arise that TDR is simply a matter of gathering the various actors figuratively "around the table" to openly discuss the issue, expecting that this mere act will give rise to the new, robust insights or pathways forward that are being sought.[31,54] Related to this concern, it has been noted[27] (see Box 3) that while at least basic levels of engagement with non-academic actors are indeed very common in TDR projects, higher levels (like "empowerment", i.e., having decision authority within the process) are much rarer.

A more insidious challenge is the intentional misuse and misrepresentation of knowledge, especially to serve particular interests, such as dominating the political discourse or gaining support from a membership or voter basis. There are several ways in which this challenge manifests, for example when knowledge is falsely depicted as being automatically legitimized by the mere act of involving academic researchers in a project together with non-academic actors. A prominent example of this is "greenwashing,"[58–60] i.e., deceptively promoting limited "environmentally friendly" initiatives, particularly when they are being investigated by environmental researchers, to distract from a company's own impact on the environment. Knowledge is also often highlighted or employed selectively, "cherry-picking" only the limited set of evidence that supports a particular point, rather than trying to provide a balanced scientific perspective.

Going beyond the misuse of specific knowledge, there are also efforts to more generally discredit the overall value and validity of scientific knowledge. Robust insights developed through established scientific methods (e.g., about temperature increases around the world or the spread of infectious diseases like COVID-19) are being downplayed as inaccurate, invalid, or even as conspiracies. At the same time, societal and political opinions are being posited as—and sometimes mistaken for—scientific insights. This has led to concepts such as "alternative facts" and "fake science," and a "post-truth" or "post-factual" relationship between science and society.[61] This can be exacerbated when the impression exists (justified or not) that scientists themselves are misusing their position of expertise and authority to push forward their own individual agendas and normative standpoints. Of course, scientists are also themselves societal stakeholders, and thus will have their own norms, standpoints, and agendas (and, in our perspective, are also entitled to these). The critical issue is how these flow into their work, and what measures are taken to channel this flow and limit bias, as discussed later. These and other issues around normativity and bias are discussed in the next subsection.

Challenges around normativity and bias

Norms provide a basis for engaging with knowledge and thus are fundamental to meaning-making. Nevertheless, terms like "objective," "neutral," and "unbiased" are often used to describe traditional science-based policy advice, especially when it is posed in the sense of "What would happen if… ?" Despite this aspiration, at least some degree of bias is commonly unavoidable. For example, priorities have to be set in scenario studies for choosing which scenarios to design and analyze, which has the consequence that biases will inevitably be introduced by taking some scenarios into account while others are not considered. This can in turn have significant effects, e.g., on climate policy deliberations.[62] It has been claimed that "the assumptions on which scientific regulatory analysis is based are not indifferent to policymaking purposes and may actually induce unwanted policy outcomes."[63] In general, the challenge of dealing with normativity and bias applies not only to TDR, but to any scientific research that is specifically aimed at supporting sociopolitical goals such as the UN Agenda 2030 and its Sustainable Development Goals.[64] Nevertheless, although not flawless, the traditional scientific method and established community procedures like peer review help considerably to limit the degree of bias in scientific studies and in the communication of their results (this is discussed further subsequently).

In contrast, TDR (specifically the social engagement school) is—by design—oriented on societal challenges and interactions, and on supporting the definition and achievement of specific normative sociopolitical goals. TDR processes often involve co-generated normative goals, which are then important as reference points for assessing their effectiveness, including weighing various consequences and trade-offs. This explicit attention to normative goals is unfamiliar territory for many researchers when they first become involved in TDR processes. Especially when this unfamiliarity is brought together with close interactions with non-academic actors, this can present several further challenges, as discussed in the previous section.

Furthermore, the central role of individual and community values and norms in the construction of TDR processes can be challenging, given that such design aspects will generally contribute to shaping the results of such processes.[65,66] A few examples of normative viewpoints that are sometimes imposed on such processes include the following: all involved actors should be taken into account equally; all viewpoints need to be treated fairly; and all factual knowledge necessary to make prudent decisions should be made accessible to the participants.[67] These may seem self-evident to anyone who prioritizes justice and the common good. However, vested interests frequently have normative standpoints that are quite contrary to these, for instance being driven by various forms of discrimination and asserting that the voices of certain racial, gender, cultural, religious, or other groups should be ignored. In general, these challenges around normativity and bias, along with the various challenges around forms of interactions with non-academic actors, are part of the reason for the extensive work that has gone into developing the wide range of approaches to TDR that were discussed earlier.

Challenges with evaluating TDR projects

Evaluating the societal impacts and the effectiveness of TDR projects has long been of interest, especially since the early 1990s, when the potential for TDR to contribute to effectively addressing wicked problems became widely recognized and elaborated on. Since then, there have been several efforts to develop methods and frameworks for evaluating TDR projects.[25,34,45,68–74]

Generally, TDR evaluation frameworks have two main components: assessing the effectiveness and outcomes of a project (including the quality and value of non-academic input into the process) and assessing the project's impact (e.g., its contribution to sustainability-oriented transformations). Both of these components contribute to learning about TDR (i.e., contributing to the "process knowledge" discussed subsequently, and toward improving the project and future projects based on this information). Both components also contribute to the accountability toward those who are investing in the process, in terms of both funding and the time invested by project participants. A related challenge regarding funding is making convincing arguments for obtaining adequate, long-term funding to carry out projects that often involve long timescales, especially to allow for participation of a wide range of non-academic actors, as well as to trace the outcomes through to impacts. This is exacerbated by the fact that funding bodies typically expect a research proposal to include fully formed research questions and planned project outputs. This makes it more difficult to engage non-academic actors in the early stages of conceiving TDR projects, since often by the time funding is available to support this engagement, many decisions about the aims and scope of the project will already have to be made. A further challenge with regard to evaluating TDR projects is the tension that exists when researchers can be "successful" in publishing results of research, even if that research does not lead to "success," i.e., concrete action, in the eyes of non-academic actors.[75] Prior to discussing approaches to evaluating TDR, in the next section we first describe how TDR projects can be designed and implemented and how this relates to the production and use of various forms of knowledge.

CARRYING OUT TRANSDISCIPLINARY RESEARCH

Due to the wide variety of definitions and varying emphasis on the characteristics of transdisciplinarity (see Figure 1), there is no clear, widely accepted "cookbook recipe" for setting up and running real-world TDR processes (continuing to focus specifically on the social engagement school of transdisciplinarity). However, considerable work has gone into developing conceptual models of the phases and components that are frequently involved in TDR processes. Here we first describe a widely used three-phase conceptual model of TDR, after which we introduce four forms of knowledge that can be distinguished within TDR projects, including the process knowledge that is needed to design and carry out TDR projects. This understanding of how TDR can generally be approached provides a framework for later discussing ways to address the challenges that were presented in the previous section, making use of illustrative projects and experiences with TDR at the IASS.

Phase model concepts of transdisciplinary research

Numerous studies[23,45,46,55,57,70,71,76–78] have developed conceptual models of idealized TDR processes. Many of these studies have found it useful to decompose TDR into three main phases, which are defined differently in the respective studies, but have similar main characteristics. A selection of these three-phase descriptions is provided in Table 1. These give a good initial impression of the main components of TDR projects,

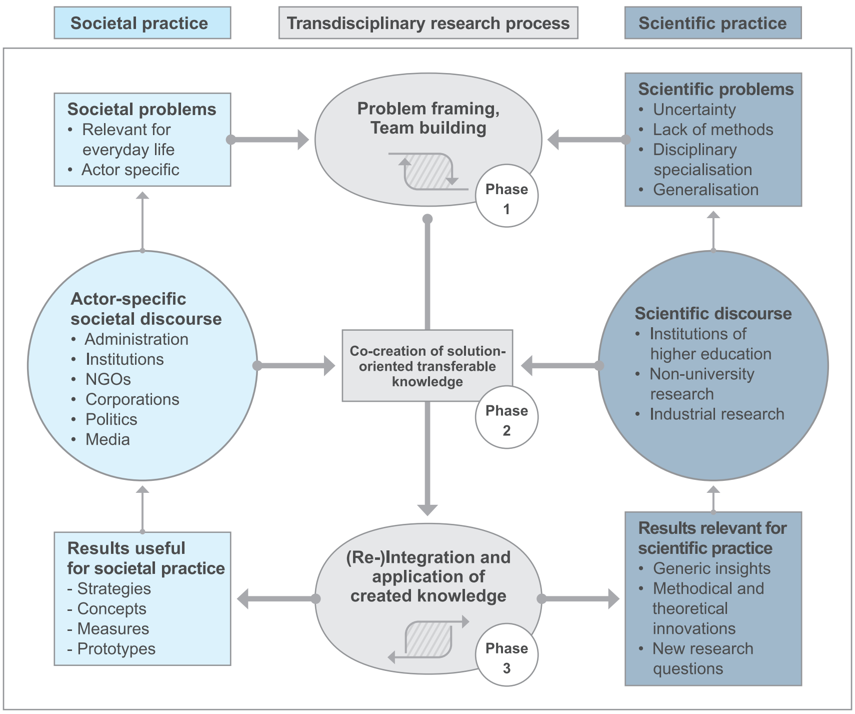

Figure 2. Depiction of a conceptual model of an idealized TDR process

The process was originally developed by Jahn et al.[23,57] and Bergmann et al.,[26] and further developed in various studies.[45,76,79] The depiction shown here is adapted from Lang et al.,[30] which we chose since it focuses on applying terminology that corresponds to the international discourse around sustainability research, and on carefully designing the interaction between academic researchers and non-academic actors. The central column represents the three phases that are central to this conceptual model of TDR processes (see Table 1), while the flanks depict the roles of society and science and the respective results that are primarily relevant for each. Adapted from Lang et al. (2012) with permission from Elsevier.[30]

how these fit together, and how these have been conceived somewhat differently by various researchers. Note that even though these phases are often numbered 1/2/3 (or A/B/C), they are not necessarily carried out sequentially in real-world TDR projects. Instead, often the whole sequence or individual phases need to be iterated, and the phases often run in parallel, indicating the importance of developing concepts for how to iteratively integrate the various components early on in TDR projects.[23,30]

These three phases are the basis for a widely used conceptual model of TDR, depicted in Figure 2, in which the core phases are flanked by "society" (on the left) and "science" (on the right). TDR is thereby seen as being initiated from societally relevant problems that lead to scientific research questions, with the three phases serving to integrate two distinct pathways: developing approaches (e.g., policies and regulations) to help resolve societal problems, and developing interdisciplinary approaches and scientific insights relevant to the problem under consideration. The model thus takes into account the distinct conventions and logics of science and society (and also the distinctions within these communities, e.g., between policymakers, activists, and religious leaders, and between natural and social scientists). These are brought together in the TDR process with the intention of leading to more robust and practicable outcomes through their synergetic, transdisciplinary integration. Despite this integrative intention of going beyond the traditional model of one-way policy advice, it is worth noting that the depiction in Figure 2 is susceptible to the criticism that it places science outside society, possibly being perceived as having a "superior" role as "experts" or the "superintendents of knowledge." A sensible future development for such depictions may thus be to depict science (or academics in general) as only one of the many distinct logics and procedures of various societal groups, poising academics as being on par with other distinct societal groups, not as separate from society.

Considerable work has gone into developing detailed descriptions of "design principles" or "transdisciplinary integration methods" for the work in each of the phases. These are often based on analyses of case studies and provide a much deeper insight into the workings of TDR projects, but they are too comprehensive to discuss in detail for the purposes of this Perspective. Interested readers are particularly referred to the analyses and depictions in the journal papers by Jahn et al.[23] and Lang et al.[30] and the book by Bergmann et al.[26] In the rest of this section, we will only provide a brief introduction to the main aspects of the three phases of the conceptual model depicted in Figure 2.

The first phase sets the framework for the TDR project. In this phase, a societal challenge is identified, initially explored to arrive at a basic understanding, and then reframed so that it is of concrete interest to the full range of societal and academic actors involved. This process is called "problem transformation,"[21,23,80] and such a reframed challenge is generally referred to as a "boundary object,"[21,23,26,30,45,81–83] a concept that was adopted from earlier work[84] in the field of science and technology studies. According to Bergman et al., "Boundary objects make transdisciplinary research possible and stabilize it" and "are usually described in everyday, non-scientific language"[26] in order to have a shared meaning that is easy for all partners to communicate. Boundary objects can be technical objects, ideas, plans, or concepts,[45] and can be abstract or concrete, with an example of an abstract concept being regional biodiversity, and a concrete technical object being a nature conservation area map.[23] Boundary objects provide a link between the societal and scientific flanks of conceptual models like in Figure 2. However, in order to be directly applicable to academic research, they generally need to be further transformed by using discipline-specific language and concepts to turn them into scientific, methodologically based "epistemic objects."[23,26] These in turn form the basis from which concrete, process-relevant research questions are derived. It is worth noting that while this transformation of societal problems to boundary objects and epistemic objects is a useful description for understanding what is often occurring in TDR processes, many conceptual models of TDR only include these steps implicitly rather than describing them explicitly.

In addition to the problem transformation to boundary objects and epistemic objects (whether explicit or implicit), the first phase includes a few other key steps. Particularly important is the formation of a collaborative research team for the TDR project, as well as developing mechanisms to "…maintain close ties between scientific and societal problem descriptions throughout the whole research process…[so that] (diverging) expectations among participants…as regards the desired outcomes of research [can] be managed successfully."[23] Finally, during this phase the main knowledge gaps need to be determined, focusing especially on various forms of knowledge that are discussed in the next section.

The second phase focuses on developing and applying integrative methods for jointly using and co-generating knowledge, building on the work in the first phase toward defining the problem and forming the collaborative participant network. In this phase, it is particularly important to define "who contributes what, supported by which means and to what end."[30,77] This will generally be the most familiar phase to our target readership: after the epistemic objects (or their implicit equivalents) are defined in the first phase, this phase then consists of "the actual doing of the research,"[30] often based largely on disciplinary research. Any semi-decoupled, specialized work (e.g., as part of a doctoral thesis project) then needs to be integrated through interdisciplinary methods, along with being connected to the discourse between the academic and practitioner participants in the TDR process. Self-critically assessing the integrative, interdisciplinary work is an important part of the reflection that is often included in TDR. Interdisciplinarity is seen here to be an integral part of transdisciplinarity, while transdisciplinarity goes beyond interdisciplinarity, especially through the engagement and empowerment of non-academic actors: "while transdisciplinarity sets the frame for a research dynamic that couples societal and scientific progress, interdisciplinarity is the science driven process of generating the new knowledge that fuels this progress."[23]

In the third phase, the co-generated knowledge from the second phase of the TDR project is documented and disseminated. The scientific reintegration occurs mainly through familiar forms, such as scientific publications and presentations, but it can also contribute to the development of new fields of research, the consideration of new recognition and incentive structures, and in extreme cases even shifts in scientific paradigms.[85] The integration into societally relevant structures occurs through processes like hearings, negotiations, political debates, and the development of regulations. Due to the involvement of societal actors in the first two phases, this integration and application of knowledge often takes on a different character and experiences a different degree of legitimacy than the traditional form of primarily one-way transfer of knowledge from science to politics or other societal groups. Furthermore, the contributions to societal structures are not necessarily all tangible outcomes; less tangible outcomes can also be important, e.g., motivation, empowerment, and enhanced social learning and decision-making capacities of the range of participants.[3,30,69,86] Finally, during this phase the effectiveness and outcomes of the TDR project are reflected on, possibly leading to reiterating the first and/or second phases.

Forms of knowledge in transdisciplinary research

Transdisciplinary research focuses on generating knowledge and also employs knowledge in order to design and carry out the TDR processes. This knowledge has been classified into various forms. Frequently it is divided into three primary forms: systems, orientation (or target), and transformation knowledge.[21,23,26,27,36,45,46] These three forms of knowledge are depicted in Figure 3 and the caption provides a brief description of each. In Figure 3, they are also accompanied by a fourth form, process knowledge, which is discussed in more detail in this section. Although this is not the only possible classification of knowledge forms, it is widely used, and at the IASS, we have made extensive use of this particular distinction and found it often very helpful for both academic and societal participants to identify their respective roles and contributions within TDR projects.

The three phases of the idealized conceptual model of TDR process depicted in Figure 1 are related to the forms of knowledge depicted in Figure 2. However, this is not a simple or linear relationship as one might initially suspect (e.g., with orientation knowledge being primarily generated during the first phase, when the problem and goals are being defined; systems knowledge primarily during the second phase, when the core research activities of the project are being conducted; and transformation knowledge primarily during the third phase, when the project results are being applied toward societal transformations and further development of scientific systems). Instead, a systematic literature review by Brandt et al.[27] reveals a complex relationship between the three phases and the three knowledge forms (see Figure 4), with both the first and second phases most strongly producing systems knowledge, though both phases also contribute strongly to the generation of orientation knowledge and transformation knowledge. The strongest overall producer of transformation knowledge is the second phase. This knowledge is then applied in the third phase, during which knowledge generation is generally weaker than in the first two phases and most strongly focused on further contributions to transformation knowledge in the context of its application during this phase.

Navigating these complex relationships in TDR projects requires a special form of knowledge, which involves knowing when and how to apply the range of context-specific tools and methodologies that are needed to practically design, carry out, and evaluate TDR projects. We call this "process knowledge" and have depicted it as a central component of Figure 3, since it differs from the other three forms of knowledge in the figure, which are more about specific societal and environmental phenomena and dynamics, and how these are interlinked. Process knowledge is being elaborated on in contemporary literature on transdisciplinarity, although commonly under other names, such as "catalytic process-oriented expertise,"[67] and "knowledge banks" of the "knowing-that" and "knowing-how."[87] We prefer the intuitive nature of the term process knowledge, although it has only rarely been used in the transdisciplinarity literature.[21,31,88]

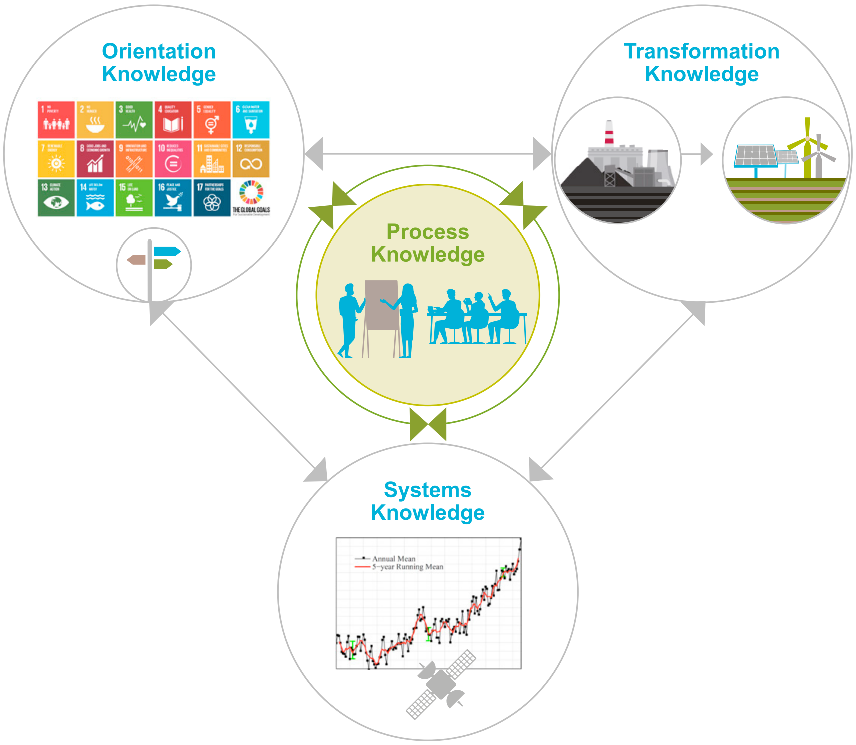

Figure 3. The relationship between systems, orientation, transformation, and process knowledge, which are generated and applied in transdisciplinary processes

Systems knowledge involves empirical and theoretical studies spanning the spectrum from the specific, disciplinary understanding of a single phenomenon to an integrative, interdisciplinary perspective on complex relationships between phenomena. *Orientation knowledge* is the formulation and justification of the goals and objectives of social change processes. This is also often called target knowledge; we prefer the term orientation because there is often not a singular target for highly complex societal challenges like wicked problems; viz. Box 1. *Transformation knowledge* involves the understanding and/or development of practical (technical, legal, social, and cultural) means to reach the desired goals or objectives. *Process knowledge* consists of the methodologies and procedures needed to design and carry out TDR projects (see the main text for further details).

Because of the variety of understandings of transdisciplinarity and the range of ways in which TDR projects can be carried out, process knowledge involves a range of components. In the context of this Perspective, we highlight three components of process knowledge that we feel are particularly valuable to consider:

- knowledge about effectively integrating the activities of academic and non-academic actors during the phases of TDR projects;
- knowledge about effectively integrating the systems, orientation, and transformation knowledge that are generated in TDR projects;
- knowledge about designing structures to support the continuous, reflective learning and adjustment processes that are frequently important for TDR projects.

Process knowledge is generated through an in-depth, meta-level analysis of TDR projects, especially considering effectiveness and trade-offs. This high-level process knowledge will mostly be generated, documented, and applied by designers and leaders of TDR projects. For most participants in TDR projects, in contrast, process knowledge will largely be accumulated via "on the job" experiential learning and via discussions with the project leaders and other project partners, who have in turn already accumulated significant process knowledge from previous TDR projects. As transdisciplinarity becomes more prevalent, a significant effort will need to be placed on strengthening the theoretical foundations and empirical testing of process knowledge and its many components.[31] In the next section, we discuss the development and application of process knowledge toward addressing the challenges that TDR faces, illustrated through analysis of a few example IASS projects.

ADDRESSING KEY CHALLENGES OF TRANSDISCIPLINARY RESEARCH

In this section, we revisit the three key challenges discussed before, describing various approaches to addressing them, along with considering how this relates to the development and application of associated process knowledge. To more tangibly illustrate this kind of work, we use three example projects from the IASS, described in Box 4. While we frequently refer to and base our arguments on the literature on transdisciplinarity, this section also contains several perspectives on TDR that are based on our experiences at the IASS, but are not yet established in the literature.

Addressing challenges of involving non-academic actors

One key aspect of the general challenge of engaging non-academic actors, as discussed earlier, is avoiding oversimplification and ultimately viewing TDR processes as simply ‘‘talking tables’’, rather than a form of deeply engaged research. To avoid this, structured processes are needed, e.g., based on conceptual models of TDR such as the three-phase model described in the previous section. To emphasize the active nature of the cooperation between the involved actors, especially between academic and non-academic actors, terms like "co-creation," "co-generation," "co-production," "co-design," etc. are commonly used. Such ‘‘co-X’’ processes involve non-academics as full partners in the production of knowledge.[100,101] This can be contrasted with more traditional academic research, in which non-academic actors are also frequently involved, though typically as intended users and beneficiaries of the outcomes. This is commonly in the sense of being a secondary audience, behind the primary academic audience, e.g., addressed through briefings based on the primary literature, especially

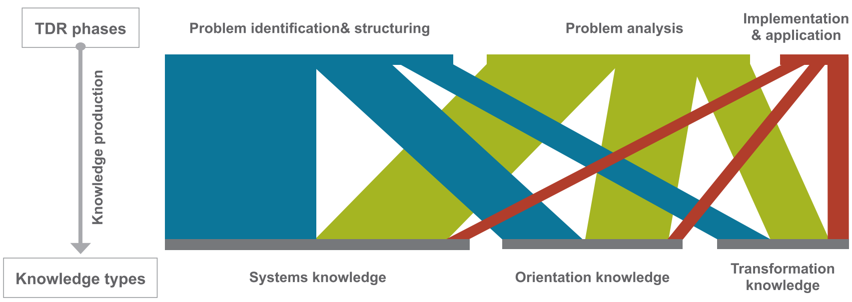

Figure 4. Depiction of the relationship between idealized TDR project phases and forms of knowledge produced during each phase

Figure based on a systematic literature review by Brandt et al.,[27] who concluded that "The two characteristics used to structure transdisciplinary projects (process phases and knowledge types) showed an overall weak linkage." The width of each bar in the figure is proportional to the overall degree of connection found between the three different process phases and knowledge types, based on the analyzed literature. The process phases considered in the study and shown in the figure are based on Pohl and Hirsch Hadorn (2008)[56] (see also Table 1). We have renamed the knowledge type "target knowledge" in the original figure to "orientation knowledge" in this figure, to be consistent with the terminology used throughout this Perspective. Adapted from Brandt et al. (2013) with permission from Elsevier.[27]

peer-reviewed publications. Co-X processes are thus crucial for more frequently establishing higher levels of engagement with non-academic actors (e.g., empowerment in terms of having decision authority within the process), which is still rare compared to more superficial engagement.[27] The associated process knowledge to design and carry out such co-X processes is based on literature about project design elements (such as committee structures) and interaction formats (such as world cafés and appreciative inquiry).

Illustrations of such structured approaches to engaging non-academic actors are seen in the IASS projects in Box 4. The DiDaT project, for example, relied on existing process knowledge in implementing several design choices to integrate academic and non-academic actors, to balance decision-making between the groups, and especially to engage non-academic actors in all stages of project planning, defining research topics, and scoping project outputs. Among the steps taken toward this were the following: defining clear and extensive responsibilities for a project steering committee with equal representation of academics and non-academics; developing working groups comprised of academics and practitioners, with topics defined through a series of academic-practitioner roundtables; and integrating the independent results of the working groups through a consultation process with all involved actors. Similar structured design choices to support the engagement between non-academic and academic project participants were also implemented in the other two example projects in Box 4.

Two further aspects of the challenge of involving non-academic actors in TDR are avoiding the misuse or misrepresentation of non-academic knowledge and avoiding the general discrediting of scientific knowledge. For the first of these, when designing TDR processes, it is particularly important to be aware of the motives of the project participants (non-academic as well as academic). Various frameworks are being developed to classify the motivations of project participants.[102–106] This knowledge can help determine if "hidden agendas" are involved, especially when they run contrary to overarching project intentions such as supporting specific sustainability-oriented transformations. Another contribution to avoiding the misuse of scientific knowledge, along with avoiding the general discrediting of the scientific approach and its resulting knowledge, is ensuring that the methodological rules of rigorous scientific analysis are followed diligently and documented carefully, and that they do not give way to political or social pressure in favor of interest-based interpretations of scientific results.[107] One step toward this is making the assumptions in scientific studies—such as the equations, parameters, and input values used in models—as explicit, understandable, and transparent as possible, which has sometimes been strongly criticized in the past, e.g., for socioeconomic scenario models.[108] This form of documentation and examination is already supported by one of the central components of traditional academic research: the peer review process for scientific literature. Although not foolproof, this system is widely acknowledged as being a major component of quality assurance in scientific journals, with open review processes[109] being a relatively recent development that further supports the trustworthiness of publications in these journals.

For TDR processes, establishing rigor and transparency additionally benefits from a strong emphasis on regular reflection on the process and outcomes together with the range of academic and non-academic actors. Such regular reflection has been noted as a key component of action-research-based approaches,[110] and it has been a central component of all three example projects described in Box 4. While these activities can help to reduce the misuse of knowledge and discrediting of science specifically within the communities involved in or directly affected by TDR processes, the larger issue noted earlier of a looming post-factual relationship between science and society[61] will not be resolved by TDR alone, but needs to be addressed by other means, including ongoing developments to improve science literacy and science communication worldwide.

Addressing challenges around normativity and bias

Norms and biases will play at least a limited role in nearly any form of research, as discussed earlier, but are particularly important for research associated with a specific normative stance (e.g., aimed at supporting sustainability-oriented transformations—although this also applies to research aimed at supporting very different activities, such as aggressive military interventions). Scientific methodologies and practices such as peer review generally aim to reduce the presence and impacts of norms and biases in academic research. In contrast, political discourses and other societal interactions fundamentally build on norms and biases and how these differ between various political and societal groups. Thus, the direct involvement of non-academic actors generally necessitates increased attention to the challenges that norms and biases present in TDR processes. In addition, TDR associated with sustainability-oriented societal transformations supports many researchers' intrinsic desire to

Box 4. Illustrative TDR projects at the IASS

In this box, we briefly describe three IASS projects that help illustrate various TDR approaches. These three projects are the subject of a more in-depth analysis that is currently in progress.

DIGITAL DATA AS SUBJECT OF TRANSDISCIPLINARY PROCESSES (DiDaT)

The rapid growth of digitalization in modern society results in challenges for data privacy and personal and national security, and through impacts of social media on political discourse and democracy, but it also presents the potential for substantially reducing environmental impacts of industries. The DiDaT project[89–92] addresses these issues in a transdisciplinary manner, including numerous measures to support strong interactions between the range of actors involved. Among these are a steering committee with parity between academic and non-academic participants, including co-leaders responsible for a balanced overall project planning and execution. Furthermore, the project work was divided into seven working groups that explored different major topics within data processing topics, organized around "vulnerability spaces," which emerged from a series of academic-practitioner roundtables in Germany and several other countries (rather than being pre-defined by the project scientists). Each working group included academics and practitioners and was tasked to independently develop a chapter for a "white book," which is being further developed in a consultation process with all the involved stakeholders. In discussions with the DiDaT project leaders and participants, numerous benefits from this TDR approach were noted, including bringing extensive new knowledge and understanding into the academic discussion, as well as highlighting knowledge gaps that could not readily be identified independently by academic or practitioner groups alone.

SOCIAL TRANSFORMATION AND POLICY ADVICE IN LUSATIA

The Lusatia (*Lausitz*) region in Eastern Germany, a former coal production hub, is being pushed toward a massive structural transition due to the nationwide phase-out of the coal industry. The project Social Transformation and Policy Advice in Lusatia[93–95] has been researching and supporting this socioeconomic transition with a particular focus on "investigating the societal challenges posed by a democratic and socially just transition in post-fossil societies."[96] The project involves IASS researchers working closely with local policymakers, governing bodies, and civil society initiatives. A series of discussions with politicians and civil society organizations was initiated to develop an understanding of the motives of the project partners and their expectations from the research team. Such discussions are a key part of the first phase of the conceptual model of TDR in Figure 2, especially clarifying managing roles and relationships. The project then worked to translate academic concepts (e.g., "multi-level governance") into terms that were understandable by project collaborators, while transformation knowledge was co-produced with local stakeholders through public engagement workshops. Interdisciplinary knowledge integration was also important due to the wide range of disciplinary perspectives in the team, which was sometimes found to be as challenging as the communication with non-academic project participants. To support the interdisciplinary and transdisciplinary knowledge integration, the project team was set up with two co-leaders with complementary expertise in interdisciplinary policy research and participatory process design and facilitation. The TDR effort has been perceived by the team to facilitate the understanding between researchers and non-academic project collaborators, as well as to support the analysis of the socioeconomic transition in the region.

CO-CREATIVE REFLECTION AND DIALOGUE SPACE (CCRDS)

Conferences like the UNFCCC COPs (United Nations Framework on Climate Change Convention/Conferences of Parties) provide extensive opportunities for formally sharing information in presentations and panel discussions, as well as for informal discussions during breaks and over meals. However, there is very little *formal* space dedicated specifically to deep dialogue and reflection. In response to this recognition, the CCRDS was developed to explore possibilities for alternative and potentially more effective communication cultures at the UNFCCC COPs and other similar venues. Following the first prototype implementation of the CCRDS at the 2018 COP24 in Katowice, the transdisciplinary project involved extensive consultation with scientific partners along with practitioners from the UNFCCC and civil society organizations, resulting in the decision to rent small, dedicated spaces (20–25 m^2) at the COP25 in Madrid (2019) and COP26 in Glasgow (2021). The spaces were used to facilitate over 40 sessions at each COP, using a variety of co-creative formats and based on co-creative communication principles.[97–99] Topics of the sessions varied widely, including the communication culture at the COPs; visions of a world with net zero carbon and near-zero climate-forcing air pollutant emissions; and the perspectives and actions of faith-based groups, indigenous peoples, women leaders, and youth climate activists. Written surveys were conducted after each session, along with structured interviews of selected participants, resulting in several publications,[97–99] with others in development. The insights from the COP25 implementation fed into the COP26 implementation (viz. phase 3 in Figure 2), which is in turn providing new insights, especially on dealing with extreme uncertainties in planning and the use of hybrid digital formats.

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do "good" and have research contribute to real-world impacts.[104–106] Applying academic expertise and process knowledge toward helping others take real-world action can certainly make it easier to motivate research groups, as well as non-academic process participants. However, the potential for use—or misuse—of this motivation further emphasizes the importance of paying attention to the norms and biases of researchers and their role in TDR projects.

Since this challenge is partly interwoven with the challenges of involving non-academic actors in TDR process, some steps toward addressing norms and biases in TDR were already outlined in the previous section. In general, in addressing this challenge, it is valuable to make the interests of various actors, along with their normative assumptions, desires, and requirements transparent and explicitly known to all project participants early on in the process, and to ensure that space for ongoing reflection and dialogue is embedded in the process. This framing of the problem and the normative space of the actors, which is part of the first phase of the conceptual three-phase model (Figure 2), has been a key component of all three example projects described in Box 4. The normativity and potential biases that are uncovered by this first part of the TDR process can then be addressed by various measures, such as ensuring that the range of relevant actors are explicitly included in the TDR process (e.g., through workshops and ensuring a broad representation in steering committees), and facilitating reflexive processes that continually bring out participant perspectives, attitudes, and goals (e.g., the DiDaT facilitated sessions that aimed to foster this openness[111]).

However, it should be recognized that addressing norms and biases in TDR processes does not imply simply trying to get rid of them. In particular, TDR provides a means to address different normative perspectives on the meaning of academic knowledge and what this implies for political measures and other transformative actions. It is important to acknowledge that consensus will not always be possible, and that contestation between views is an important aspect of sustainability-oriented transformations (see Williams[112] for an extensive discussion of this). Furthermore, the normative orientation of a TDR project provides a fundamental measure, albeit sometimes complex, against which the impacts and successes of the project need to be evaluated, as discussed in the next section.

Addressing challenges with evaluating TDR projects

Efforts toward evaluating TDR projects have a long history and face several challenges, as outlined before, where we distinguished two broad categories: assessing the effectiveness of a project in terms of its processes and outcomes (and improving the project based on this information) and assessing the project's broader impact (e.g., its contribution to sustainability transitions). The former is generally much easier to measure since project outputs and outcomes can be directly traced. The latter is typically much more difficult to capture, though often more important, especially to the non-academic participants in TDR projects. There have been several historical efforts to develop methods and frameworks for evaluating the processes, outcomes, and impacts of TDR projects.[25,34,45,68–74,113]

While there is no one-size-fits-all recipe for evaluating the effectiveness of TDR, it is possible to assess how—and in what ways—the challenges of conducting TDR have been addressed. As we have previously noted,[31] transdisciplinarity benefits from ongoing, systematic assessments of the implementation of process knowledge. For example, researchers can assess how—and to what extent—they have integrated the activities of academic and non-academic actors during the phases of TDR projects. This includes how issues of power, asymmetric access to information, and decision-making have been addressed. Similar assessments may be conducted to evaluate effectiveness in integrating different forms of knowledge (e.g., how academic and non-academic knowledge are valued and assessed) and how reflection and continuous learning have been implemented and supported.

Recent work on evaluating the contribution of transformative TDR processes to sustainability-oriented societal transformations has more broadly considered "sustainability transition experiments," or STEs. In STEs, TDR processes are typically employed to co-create project structures and co-produce knowledge. It has been suggested[73] that evaluation schemes for STEs (and thus for the embedded TDR processes) should have four main characteristics:

- generic: being applicable to different types of STEs;
- comprehensive: considering inputs, processes, outputs, and the ultimate outcomes;
- operational: including context-specific application guidelines;
- formative: feeding back to improved STE design.

The various TDR evaluation schemes that have been developed over time fill these criteria to differing degrees.

Particularly with respect to the aspect of comprehensiveness, Williams and Robinson[74] have noted that most of the literature on evaluating TDR projects and STEs has focused on the process and the short-term effects, but not on the longer-term impacts. Their study thus develops an evaluation framework which includes three components:

- process: fairness and inclusivity of the process, the quality and appropriateness of the tools and methodologies used, and the adaptive and reflexive capacity of the process;
- societal effects: short-term "splash" outputs and medium term "ripples" or outcomes of the process;
- sustainability transition impacts: longer-term impacts that reflect societal transformations, observed in socio-technical systems and governance, and in behaviors and structures at multiple levels from individual actors to socio-ecological systems.

The first two components are based on previous literature and on refinements through test applications to several case studies[112] (one of which was the process of preparing for the institutional evaluation of the IASS that was carried out in 2019–20, whereby the example projects in Box 4 and numerous other similar projects were part of the evaluation). The third component especially builds on the concept of assessing "transition markers," and also makes use of the case studies. These three components are each accompanied by extensive tables of specific criteria and indicators to help operationalize the process. Interested readers are referred to Williams and Robinson[74] for further information on the framework, and to Williams[112] for detailed examples of its application. In general, since TDR is very context specific, and thus different projects focus on capturing different impacts, evaluation frameworks such as those described previously need to be flexible enough for researchers to adapt them to their own context, while nevertheless being rigorous enough and retaining sufficient structure to allow a thorough analysis of the results and especially for comparing results across cases.

CONCLUSIONS AND OUTLOOK

In this Perspective, we have provided an overview of the range of definitions and characteristics that are applied to describe TDR. Analyzing these characteristics, we find (Figure 1) that the definitions can be broadly distinguished into two main schools of thought, which we call unity of knowledge and social engagement transdisciplinarity, whereby the latter is the most relevant for our target readership and has thus been the focus throughout this Perspective. We have also noted that there are several different (though generally related) perspectives on the phases involved in carrying out TDR projects (Table 1), which are the basis of a widely used three-phase conceptual model (Figure 2) that we have described as an example of how transdisciplinary research can be carried out, and how this relates to the various forms of knowledge (Figures 3 and 4) that are thereby generated and employed.

This overview of the definitions, characteristics, phases, and forms of knowledge provides the framework for the other main thread of discussion in this Perspective, namely three key challenges that TDR faces and approaches to addressing these challenges. We see these three challenges—close engagement between academic and non-academic actors, issues around normativity and bias, and evaluating TDR projects—also as important pillars for future developments in TDR methodologies. In addition to addressing each of these challenges individually, a valuable development will be further weaving these three challenges together. This was already noted briefly regarding the first two challenges, since academics and practitioners typically have notably different standpoints on bias and normativity. Connecting these to the evaluation of TDR is less immediately evident, but is of considerable importance since the evaluation criteria for traditional scientific outputs and impacts are relatively well established, while there is still much work to do on evaluating the quality and effectiveness of the involvement of non-academic actors in TDR projects and how the impacts relate to societal normative goals.

Further development of approaches to evaluate TDR projects will be important not only for accountability to those investing money and time into the projects, but also for learning within the projects and for generally improving the efficiency, effectiveness, and impacts of TDR.[74] While generally evaluations of academic projects bring together the different perspectives of the funders and those being funded, TDR projects will typically involve a much larger range of perspectives due to the more direct involvement of non-academic actors in the project. This leads to a multi-faceted tension between the need for evaluations to generate learning for those designing and managing TDR projects, while also providing accountability to funders and other responsible partners (e.g., governments). Navigating this tension between "evaluation for learning" versus "evaluation for accountability" is a topic of ongoing research at the IASS.[114]

The efforts on evaluation and the other challenges that TDR faces are instrumental in the development of process knowledge (Figure 2). As we have noted, the concept of process knowledge is only used and discussed explicitly in limited contexts in the TDR community. In our perspective, this is one of the most important development fronts for TDR in the coming years. On the one hand, this involves ongoing contributions to the wealth of process knowledge that already exists about how to carry out TDR. On the other hand, this implies explicitly acknowledging process knowledge as an independent and critical class of knowledge, together with systems, orientation, and transformation knowledge (viz. Figure 3). It is also important that process knowledge be made accessible in the contexts and terminology of the broader academic research community, rather than expecting all scientists in programs like *Future Earth* to themselves become experts in TDR, with their own extensive personal libraries of process knowledge. Putting process knowledge in the foreground and making it accessible in the sense of providing guidance for non-specialist research communities on how to choose which tools, methods, and project structures are appropriate in a specific context[115] is, in our perspective, an important role for transdisciplinary institutes in the larger, traditional disciplinary and interdisciplinary research landscapes.

Further efforts such as this paper (but also including workshops, seminars, classes, etc.) are needed to support a better understanding of what transdisciplinarity is, especially among the community of researchers investigating sustainability-related topics who are interested in knowing more about TDR, but who have limited capacity and/or willingness to read into the extensive primary literature to obtain a good overview. This improved community-wide understanding will become more important in the coming years as many large research funding sources (e.g., the EU Horizon, 2020 program, and its anticipated successors) are becoming more focused on impactful research, and sometimes specifically transdisciplinary research. In this context, the slowly unfolding "scientific revolution"[85] of TDR will continue to be developed as a framework in which traditional disciplinary and interdisciplinary research can in turn contribute to sustainable development and the common good in alternate and potentially more effectively ways, especially in the face of the wicked problems that are prevalent in the Anthropocene.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2021.12.010.

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AUTHOR CONTRIBUTIONS

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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