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CONCEPTUAL ANALYSIS
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When to Use Transdisciplinary Approaches for Environmental Research

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Transdisciplinary research (TDR) can help generate solutions to environmental challenges and enhance the uptake of research outputs, thus contributing to advance sustainability in social-ecological systems. Our aim is to support investment decisions in TDR; more specifically, to help funders, researchers, and research users to decide when and why it is most likely to be worth investing in TDR approaches. To achieve our aim, we: 1) define TDR and use a decision tree comparing it with alternative modes of research (i.e., basic, applied, disciplinary, multi-disciplinary, and interdisciplinary research) to help researchers and funders distinguish TDR from other research modes; 2) identify features of the research problem and context (complexity, diverse knowledge systems, contestation, power imbalance, and disagreement on the need for transformative change) where a TDR approach could be more appropriate than the alternative research modes; and 3) explore the idea that the intensity of the contextual features in (2), together with the problem at hand, will help determine where a research project stands in a continuum from low- to high-TDR. We present five studies exemplifying lower- to higher-TDR approaches that are distinguished by: 1) the number and variety of research participants engaged; 2) the strength of involvement of non-academic actors; and 3) the number and variety of disciplines and knowledge systems involved in the research.

Keywords: transdisciplinarity, participatory research, research co-design, research funding, cross-cultural research, research impact

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INTRODUCTION

Environmental sciences are a set of scientific disciplines that study the environment and, in specific cases, can help drive solutions to its protection (Sauvé et al., 2016), thus contributing to advance sustainability in social-ecological systems. However, most research published within the realm of environmental sciences is not focused on solutions that can be implemented by research users (e.g., policy makers, land and water managers, etc.) (Doubleday and Connell, 2019). In response to this problem, there has been a growing interest within the environmental sciences in transdisciplinary research (TDR) as a means to generate solutions to environmental challenges and enhance the uptake of research outputs (von Wehrden et al., 2019). The core elements of TDR are that it explicitly

focuses on societal outcomes as well as on science, and that it involves both academics (from diverse disciplines) and non-academics at all stages of the process.

Transdisciplinary research can be successful at providing implementable solutions to environmental problems because it brings science closer to society and thereby reduces the implementation gap (Rocha et al., 2020; Verwoerd et al., 2020). Key potential benefits of TDR include 1) the delivery of intermediate effects that take place within the project horizon, such as the development of new management practices, the provision of knowledge that builds decision-making capacity of participants, and the strengthening of networks; and 2) transformational changes towards sustainable development trajectories that might occur after the project concludes, and beyond project participants, potentially permeating whole social-ecological systems. The impacts listed above depend not only on the research process, but also on the interaction between decisions made, solutions implemented, socioeconomic benefits, and changes in norms or values (Walter et al., 2007; Klein, 2008; Wiek et al., 2014; Schuetz et al., 2017). However, these benefits may come at a cost as TDR generally requires additional time, effort, and resources when compared with other research modes (Wiek et al., 2014). Thus, it is critical to understand the circumstances under which the additional benefits are sufficient to outweigh the additional costs.

Such solution-focused partnerships between academic and non-academic actors are recognized as potentially contributing to the United Nation's Sustainable Development Goals (e.g., through supporting Goal 17 that is centered on building partnerships). For example, a review of local sustainability initiatives identified challenges to achieving sustainability goals such as: disagreements on what needs to be achieved; goals insensitive to local priorities; and the lack of preparation in the face of future uncertainties (Moallemi et al., 2020). The authors proposed a TDR agenda based on robust partnerships that include: joint framing local goals and actions; evaluating critical uncertainties; and co-creating adaptive pathways towards sustainability goals. TDR has indeed great potential to foster such partnerships, but serious consideration needs to be given to understanding the circumstances under which it would be the most appropriate approach.

Our aim is to support decisions associated with investment in TDR, at both a project and program (i.e., a suite of associated research projects) level. More specifically, we aim to help funders, researchers and research users to decide when and why it is most likely to be worth investing in TDR approaches. We used a qualitative synthesis approach (Denyer and Tranfield, 2006; Elsawah et al., 2020) based on a review of the literature and our experiences as environmental social scientists, environmental economists, applied ecologists, human geographers, and conservation planners having worked on both TDR and non-TDR projects.

To achieve our aim, we: 1) define TDR and compare it with alternative modes of research, presenting a decision tree to distinguish TDR; 2) identify features of the research problem and context where a TDR approach could be more appropriate than the alternative research modes; and 3) recognize levels of transdisciplinarity along a continuum that goes from "low" to "high" TDR.

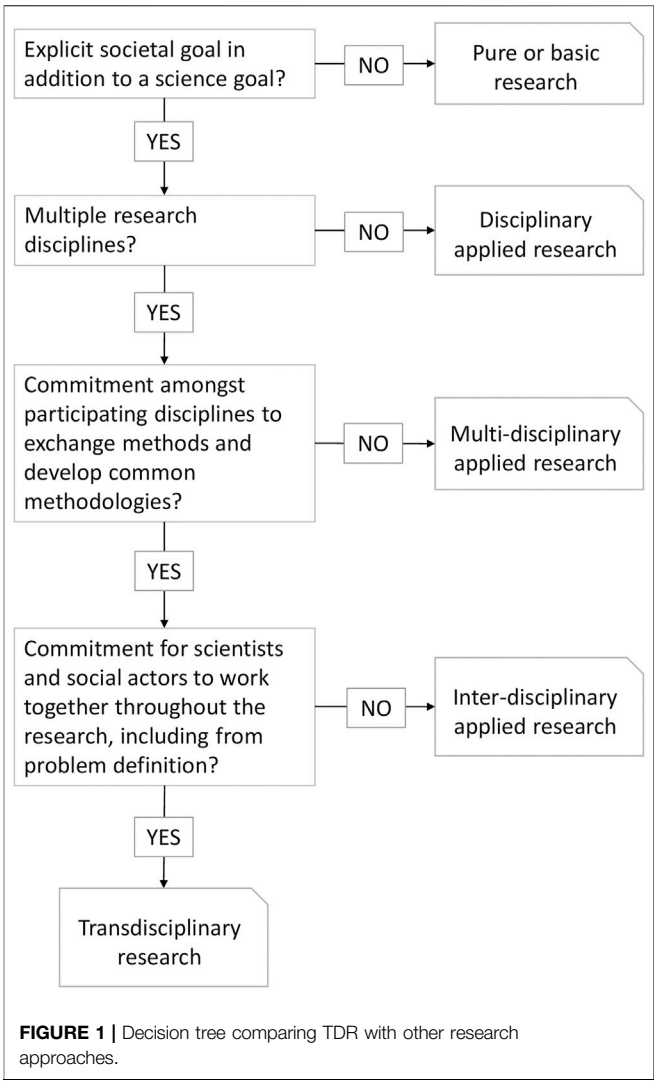

FIGURE 1 | Decision tree comparing TDR with other research approaches.

COMPARING TRANSDISCIPLINARY RESEARCH WITH OTHER RESEARCH APPROACHES

Those investing in research, including funders, may be interested in recognizing whether research projects are applying a TDR approach in order to ascertain a project's ability to deliver societal research impact. Clearly defining the features of TDR can help research funders to identify such TDR features in funding proposals, and to distinguish it from other research modes employed by research proponents.

The environmental and sustainability literatures contain various definitions of TDR, with some features appearing consistently in such definitions. We follow a widely accepted definition that emphasizes three features: 1) Explicit focus on solving a specific societal problem; 2) interdisciplinary research;

and 3) participatory approaches, with mutual learning from academic and non-academic actors (Lang et al., 2012).

Transdisciplinary research aligns and overlaps with other collaborative problem-solving approaches to science and research. Examples include "post-normal science" [the move from a traditional "predict and determine" model of science to a more contextually-oriented "assess and consult" one (Healy, 2011)]; "mode 2 knowledge production" [problem-solving which is organized around a particular application to produce solutions that are diffused through society (Carayannis and Campbell, 2019)]; and "participatory action research" [collaborative participation of trained researchers as well as local/global communities in producing knowledge directly relevant to stakeholders (Chevalier and Buckles, 2013)]. Within the realm of environmental sciences, TDR aligns with research approaches such as "translational ecology" (Schlesinger, 2010) or "action ecology" (White et al., 2015). The former focuses on enhancing communication between ecologists and stakeholders, conveying the relevant findings of basic ecological research on the one hand, and the knowledge needs of research users on the other (Schlesinger, 2010). The latter, more broadly, includes a reliance on "big data" to address societal problems, collaboration between researchers and users, and the intention to inform policy and management (White et al., 2015).

Distinguishing TDR

Transdisciplinarity, and allied approaches, can be contrasted with basic, applied, disciplinary, multi-disciplinary, and interdisciplinary research. We developed a decision tree to help researchers and funders distinguish TDR from other research modes (**Figure 1**).

Basic or pure science is concerned with "conceptual or methodological problems for a discipline to describe and explain processes by means of models and methods, which are taken to be universally valid under controlled conditions" (Hirsch Hadorn et al., 2006) [pp. 124]. While it is not directly concerned with societal goals such as informing environmental policy and practice, basic science can support the objectives of applied research (Hirsch Hadorn et al., 2006). Disciplinary and multidisciplinary applied research do focus on solving problems, differing mainly on the number and variety of disciplines included. Non-academics can also be strongly involved in these research modes, making them closely linked to a "participatory action research" approach, for example.

Multidisciplinary research tends to retain disciplinary autonomy over methodologies, with results being collated with limited integrating synthesis (Max-Neef, 2005; Wickson et al., 2006). Conversely, interdisciplinary research generally involves multiple disciplines sharing problem formulation and a methodological approach (Wickson et al., 2006). Interdisciplinarity is often considered as a feature of TDR (Wickson et al., 2006; Jahn et al., 2012; Lang et al., 2012; von Wehrden et al., 2019). Nevertheless, they differ in the prominent inclusion of non-academic actors in the latter (von Wehrden et al., 2019). The commitment between participants from research institutions and other stakeholders in TDR involves collaboration in most research stages, including problem definition and goal setting (Thompson Klein, 2004). TDR may also require: the group of participants to be representative of a particular community; the project process to involve a sufficient level of interaction between researchers and stakeholders, often resulting in the co-production of knowledge (Norström et al., 2020); and stakeholder inputs to be incorporated transparently (Wiek et al., 2014). These TDR features (explicit societal goal, interdisciplinary, and participatory) can encourage policy makers and managers to take up the results of research.

Setting the research scope and defining the research problem are particularly important stages, since they will influence, for example, research funders' ability to judge whether a project has been developed in collaboration with users, and whether a TDR approach would be beneficial in addressing a problem. For example, the research scope may be defined very narrowly (e.g., fish biology), implying that a certain problem does not require a TDR approach, which is often true. However, setting the scope in collaboration with research users and participants may reveal a broader research problem that could benefit from a TDR approach. Therefore, when judging whether a project's scope (and thus the corresponding research approach) was set appropriately, funders may use the "problem solving" feature of TDR as a criterion, critically enquiring what the core problem is, and whether the intended project outputs effectively contribute to a solution. This requires the assessor to know the research context to be able to judge such matter.

Projects using a non-TDR approach may be important components of a larger TDR program (e.g., Campbell et al., 2015). Thus, if funders are interested in supporting TDR, they may need to distinguish independent research projects from broader programs. For example, an "umbrella" environmental TDR research program on Integrated Water Management may include non-TDR projects to address basic knowledge gaps (e.g., on fish ecology). A research question such as "what does this fish eat?" can be addressed by pure disciplinary approaches. Nevertheless, it may be contributing to addressing broader questions such as "what are the consequences of water management in a river for people who rely on that fish?" In such a case, project assessments may consider whether there are clear links at program level that allow individual projects to contribute to broader research questions and ultimately address broader research problems.

We now turn to the features of the research problem and context where a TDR approach could be more appropriate than the alternative research modes.

WHEN IS A TDR APPROACH WORTH TAKING?

Transdisciplinary research is designed to deliver actionable solutions (or at least solutions that are more likely to be actionable) when research is done in situations characterized by complexity, diverse knowledge systems, contestation, power imbalance, and disagreement on the need for transformative change. These features are often inter-related as described below. TDR is also likely to be more costly and difficult to

undertake than non-TDR (Freeth and Drimie, 2016). The recognition of such features (complexity, contestation, etc.) could assist those investing in research to judge whether the additional investment in TDR is worthwhile. It may also assist funders in the assessment of whether the research scope of a project/problem has been appropriately defined. Below we discuss each of those challenging contextual features, and consider how TDR features can help addressing them.

Complexity

TDR is often adopted in response to complexity (Hirsch Hadorn et al., 2006; Simon and Schiemer, 2015; Fritz and Meinherz, 2020; Verwoerd et al., 2020). A complex issue likely involves multiple interacting variables, with multiple feedback loops, which could be either positive or negative. This results in difficulty discerning cause-and-effect relationships, and high uncertainty about the consequences of certain actions. Complex systems include those defined based on interactions between social, economic, ecological and political systems (Simon and Schiemer, 2015), or where there is high uncertainty about the "drivers of change" of the system (Peterson et al., 2003). When issues emerge in such complex systems that require changes in societal practices, they may involve disputed values, high stakes and urgent decisions (Hirsch Hadorn et al., 2006).

The benefits of TDR for addressing complex problems with socio-political dimensions arise in part from its emphasis on participation and inclusiveness: "research on complex sustainability problems requires the constructive input from various communities of knowledge to ensure that the essential knowledge from all relevant disciplines and actor groups related to the problem is incorporated" (Lang et al., 2012 pp. 26). Secondly, the involvement of a mix of disciplines, including social and natural sciences, is often needed to address complex socio-environmental issues. Some empirical problems, such as certain ecological models, can be highly complex but do not encompass societal problem solving, and so may not require an interdisciplinary approach. For example, biological research on the population dynamics of a single species could be addressed by disciplinary or multi-disciplinary research (Hirsch Hadorn et al., 2006).

In addition, most environmental management contexts are characterized by polycentric governance systems, with decision-making power distributed across local-state-national governments, and among both private and public enterprises across water, energy, food and other domains (Morrison et al., 2019; Pahl-Wostl et al., 2020). However, environmental decision support systems and tools often assume single types of decision makers, and hence are poorly suited for decentralized and polycentric decision-making contexts (Zulkafli et al., 2017). TDR can support the complex processes of negotiation, deliberation and social learning through which decisions arise in such contexts and build ongoing networks and adaptive capacity (Roux et al., 2017).

Diversity of Knowledge Systems

Environmental research often includes participants whose knowledge systems involve different worldviews, identities, practices and ethics. This may include, for example, biophysical scientists, social scientists, environmental practitioners, farmers, and the holders of Indigenous knowledge and other local knowledge (Tengö et al., 2017). Bridging or integrating such diverse knowledge types can be challenging (Reed and Abernethy, 2018). TDR, due to its participatory and inter-disciplinary features, can facilitate the co-production of knowledge between science and other knowledge systems. Drawing from a wider knowledge pool may achieve not only a more legitimate solution across multiple groups, but a more efficient and effective one. It can also give greater voice to those with non-dominant paradigm perspectives.

Researchers using TDR can employ diverse approaches to bridge diverse knowledge systems in the co-production of knowledge. Reed and Albernethy (2018) show how a professional facilitator can support research partnerships between scientists, policy advisors, and practitioners from diverse cultural backgrounds. Tengö et al. (2017) describe a Multiple Evidence Approach used within the Convention on Biological Diversity (CBD) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) to connect Indigenous and local knowledge systems with scientific knowledge systems. Their approach focuses on validation within, rather than across, those systems. Others similarly call for the inclusion of Indigenous and local knowledge as scientific paradigms in their own rights (e.g., Milgin et al., 2020), an idea that could be supported through the interdisciplinary feature of TDR. This would require de-colonising TDR (i.e., challenging the colonial practices that have influenced research in the past, and which are still present today) by including concepts such as Indigenous TDR, and Indigenous research methodology frameworks (Chilisa, 2017).

Contestation and Balance of Power

TDR can help researchers to navigate contested issues by bringing research participants together and providing multiple perspectives on the research problem (Schneider et al., 2019). Contestation is related to complexity, as it reflects a plurality of values and norms, and divergent perspectives on problem definition and acceptable solutions. It could also be present in research contexts with diverse knowledge systems such as colonial states. Developing research under such conditions can be challenging, especially when they include power imbalances between different social groups.

Power imbalances between different social groups associated with a research problem require the careful consideration of the ethical dimensions of research. Power imbalance does not necessarily relate to contestation, since lower power groups may be submissive or even unable to articulate their interests in a context of negotiation (Fritz and Meinherz, 2020). In situations of power imbalance, TDR may give greater voice to disadvantaged groups by enhancing the capabilities of research participants (what Fritz and Meinherz (2020) refer to as "power to"). It can also stimulate social learning to support research participants in using collective action to disrupt discourses and

structures holding power (through what Fritz and Meinherz (2020) refer as "power with"). However, if not carefully managed, TDR can further entrench disadvantage by, for example, proposing changes to resource uses that ignore vulnerable or marginalised social groups benefiting from such practices (Blythe et al., 2018).

Participation is a key TDR feature supporting research in contested and power-imbalanced contexts. Indeed, Jahn et al. (2012) suggest, in their typology of problems according to the strength of agreement on knowledge and values, that the higher the contestation, the more stages of research participants need to be involved in (i.e., research scoping, design, data collection, etc.). In such cases, additional time and resources may be required, potentially including approaches such as stakeholder analysis, working with lower capacity groups, hiring professional facilitators or mediators, supporting reflexive meetings, and open discussion forums (Lang et al., 2012).

Contestation and power imbalance may also increase the risk that even a TDR approach will fail to deliver research or societal outcomes (e.g., a solution to the problem at hand). However, using TDR could still be a better option than alternative approaches since the mutual learning, even from failure, can be beneficial for future attempts of solving the problem (Fam and O'Rourke, 2020). Moreover, non-participatory environmental management research approaches might succeed at delivering research outputs in a highly contested context, all the while reinforcing power imbalances (Blythe et al., 2018).

Need for Transformative Change

TDR is particularly suitable to achieving solutions that require transformative changes, meaning substantial or fundamental changes producing a novel state rather than moderate adjustments to the existing system (e.g., adaptation) (Blythe et al., 2018). However, desired sustainable futures can be strongly contested by groups with asymmetric power (Fritz and Binder, 2020). In such cases, achieving consensus may not be possible or even desirable, because consensus "can mask plural notions about what the problem is exactly, what constitutes relevant evidence, and what, therefore, are considered appropriate solutions" (Blythe et al., 2018, pp. 1214).

In a review of 31 TDR projects, Schneider et al. (2019) identified three general mechanisms that allow TDR to contribute to transformations towards sustainability. First, by promoting different types of knowledge for more informed and equitable decision-making. Access to information can help, for example, stakeholders to understand and prioritize certain problems such as irreversible changes to socio-ecological systems. Second, TDR can foster social learning for collective action; and third, it can enhance research participants' competences for reflective leadership. Thus, in projects aiming at transformations towards sustainability, an investment in TDR is more likely to be justifiable because it can link scientists and stakeholders into equitable partnerships that can mobilise the co-productive capacities (across cognitive, social, material and normative domains) required to generate the societal changes needed. Outcomes can potentially include overcoming conflict and an eventual shift in power (Hill et al., 2017).

Fritz and Binder (2020) analysed different types of power exerted by researchers, practitioners and funding bodies in five projects aiming to contribute to transformations towards sustainability. They showed how these actors can foster the second and third mechanisms described by Schneider and others above. Researchers often play a powerful role in initiating and controlling TDR by, for example, selecting participants and setting the rules of participation. Practitioners influenced the process by contesting the research rules, withdrawing from projects, and controlling researchers' access to the field. Funding bodies influenced participation practices in the projects by stipulating the topical foci, the types of project leadership desired, and resource allocation. Through the funding regulations, funding bodies could foster the realisation of TDR ideals, including shared ownership, responsibility and co-leadership. Conversely, funding bodies could play ambiguous or partly incoherent roles by, for instance, calling for participation without adapting funding mechanisms accordingly (Fritz and Binder, 2020).

LEVELS OF TDR

In this section, we explore the idea that the intensity of the contextual features described above (complexity, diverse knowledge systems, contestation, power imbalance, and disagreement on the need for transformative change), together with the problem at hand, will help determine where a research project stands in a continuum from low- to high-TDR. There is no assumption that a "higher-TDR" approach is automatically better than a lower one. Rather, the intensity of contextual features will influence the decision on the most adequate TDR level to address a certain research problem. There can also be contexts where such features are so intense that providing a solution is probably beyond the scope of even high TDR projects.

Lower- and higher-TDR approaches can be distinguished by several factors: 1) the number and variety of research participants engaged, e.g., in terms of their interests, or whether there are significant power differentials; 2) the strength of involvement of non-academic actors, indicated by the number and types of research stages that participants are involved in; and 3) the number and variety of disciplines and knowledge systems involved in the research.

Figure 2 provides examples of lower- and higher-TDR studies focusing on two of these features: the vertical axis includes the diversity of disciplines and knowledge systems involved in research, and the horizontal axes focuses on the diversity of non-academic actors included. While all TDR is solution-focused, lower-TDR projects may engage with a smaller subset of research users, or on problems that require a relatively lower diversity of disciplines, whereas a "high" TDR project might require even stronger engagement with a wide variety of users and disciplines. Stronger involvement of research users may increase the perceived legitimacy of outputs (Cash et al., 2003), but increased values in both axes will generally require more resources (money and time). Also, outcomes of TDR, especially of "high" TDR, may be highly uncertain and attribution may be difficult, especially in the longer term (Walter et al., 2007) given the higher complexity of context and thus research.

To demonstrate the concept of levels of TDR, we describe a suite of projects developed by the Northern Australia Environmental Resources Hub of the National Environmental

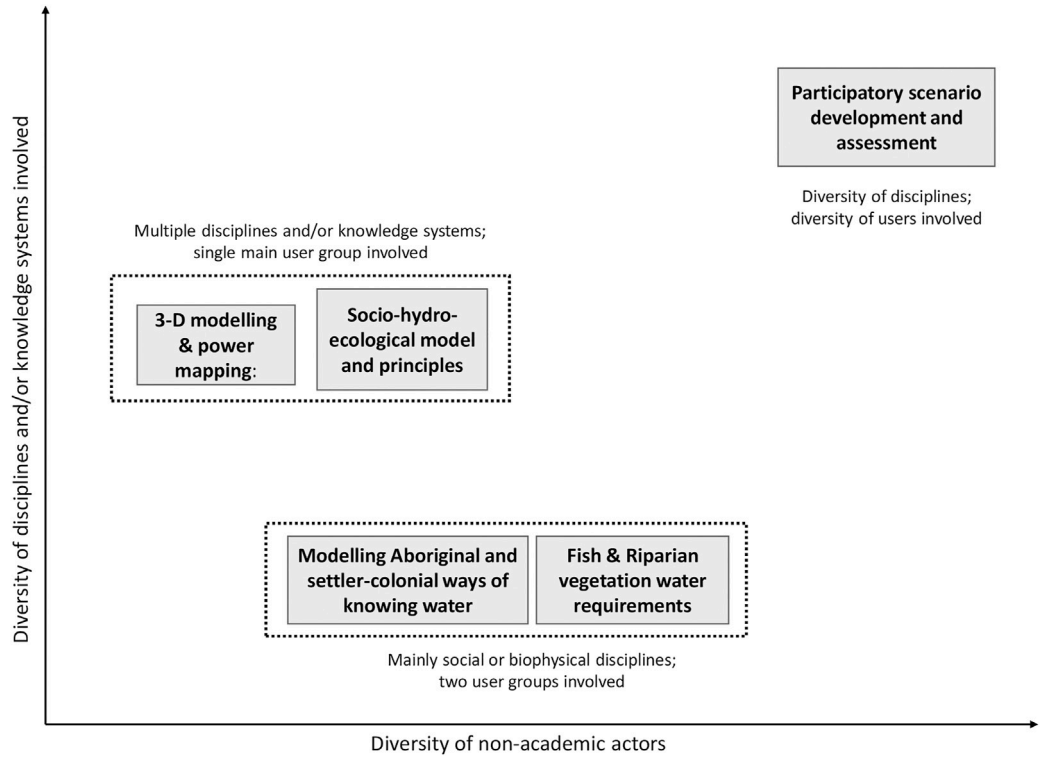

FIGURE 2 | Examples of TDR projects operating in the Fitzroy River catchment in the Kimberley region of Western Australia. Lower TDR projects are situated towards the lower-left area of the graph, while higher TDR projects are towards the upper-right area. The dotted box includes projects at the same level of TDR.

Science Program (https://www.nespnorthern.edu.au/nesp/). The suite of projects was developed to provide evidence for more informed decision-making by government and other interest groups within the Fitzroy River (Martuwarra) catchment in the Kimberley region of Western Australia (**Figure 3**). This area currently includes some of the contextual features identified above such as complexity, diversity of knowledge systems, contestation and power differentials.

The Fitzroy catchment is one of the least modified landscapes in Australia. The river connects ten major Aboriginal Australian (henceforth Traditional Owner) groups, and nine Indigenous languages are still widely spoken (McGregor 2004) and traditional uses (e.g., ceremony, burning, medicinal, fishing) support a local customary economy vital to the 6,000 Indigenous people living in the catchment (Jackson et al., 2012; Jackson et al., 2014; Jackson and Brisbane, 2015; ABS, 2016; Petheram et al., 2018; DPLH, 2020). The globally significant cultural and natural values of the catchment have been partly recognized through the West Kimberley National Heritage Place listing.

Traditional Owners, as other First Nations, have been affected by colonisation, currently having significantly lower socio-economic and health standards associated with structural disadvantage than other Australians (Commonwealth of Australia 2018). Within this area, Traditional Owners hold exclusive native title rights (i.e., exclusive possession of an area) and non-exclusive native title rights (e.g., access and use the land for fishing, ceremony or camping) over 32% and 63% of the basin respectively (National Native Title Tribunal Data: data-nntt.opendata.arcgis.com). The predominant land-use in the catchment is broad-scale cattle grazing, which covers 81% of the catchment, followed by irrigated agriculture (0.05%) and other intensive uses (0.2%), such as roads, housing, and mining. The area is also a major tourist destination. The state government is currently leading significant planning initiatives in the region (including a water allocation framework and a river catchment plan), with interest groups holding diverse and at times contrasting views on development. The studies below were designed to contribute to addressing the scarcity of data on the natural and social systems in the region.

Research project development occurred through 2 years of consultation with all interest groups, particularly the State Government and the Traditional Owners. We describe here a subset of five TDR studies with respect to their level of TDR (**Figure 2**). The relevant adaptations to the contextual features, especially regarding the inclusion of non-academic actors and researchers from diverse disciplines, are highlighted in italics in each example below.

Fish and Riparian Vegetation Water Requirements

This project used scientific knowledge from the ecological and hydrological disciplines to determine the water requirements for the significant aquatic fauna and riparian plants (e.g., Beesley et al., 2020; Burrows et al., 2020; Beesley et al., 2021; Canham et al., 2021).

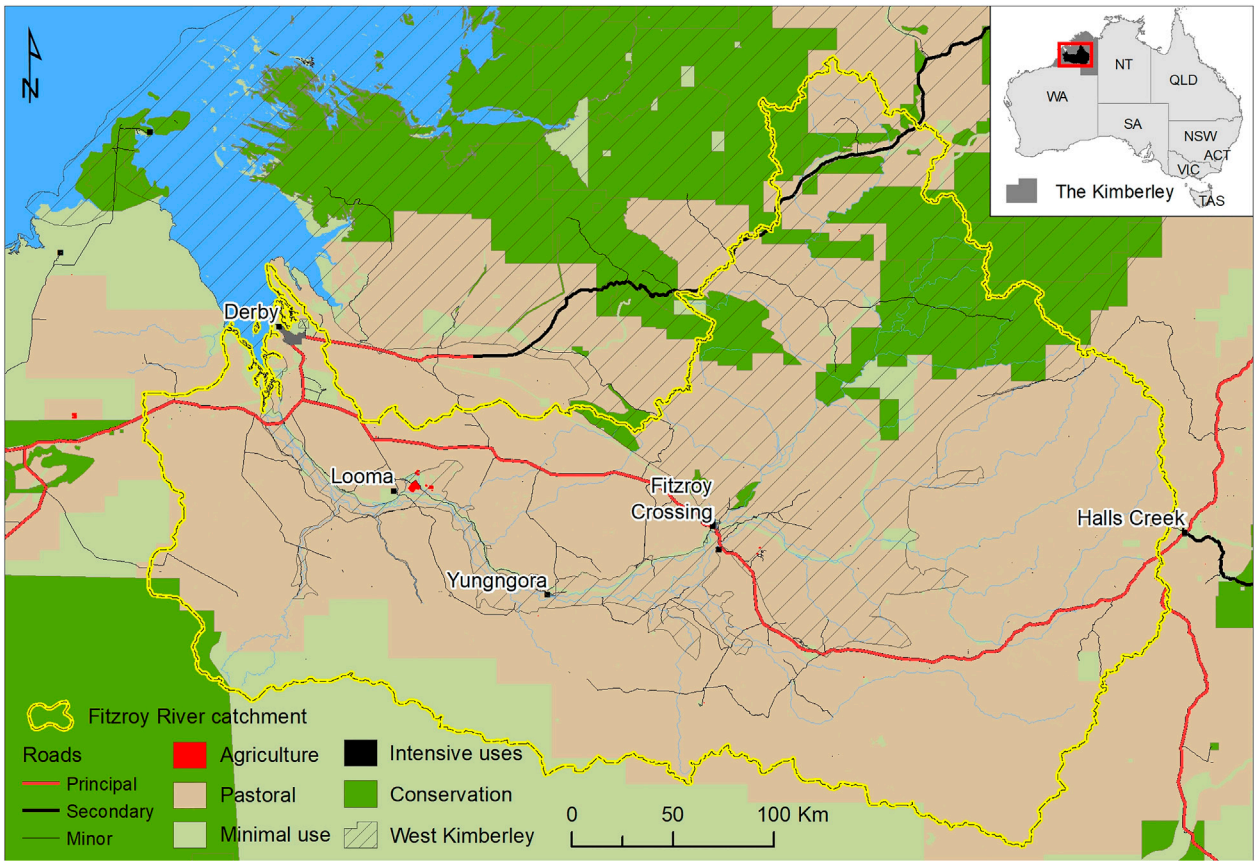

FIGURE 3 | Case study area. Location of the Martuwarra (Fitzroy River) catchment in the Kimberley region of north Western Australia (WA); the map shows major land uses, conservation areas and boundaries of the West Kimberley Heritage Place. Data sources: Catchment Scale Land Use Mapping for Western Australia 2018; Collaborative Australian Protected Areas Database 2018; Geoscience Australia (2006) GEODATA TOPO 250K Series 3.

Two main groups of non-academic actors were involved in the project: government scientists and planners, and Traditional Owners and Indigenous rangers. The project was designed with government planners to address key ecological knowledge gaps to inform a water allocation plan. The research was then undertaken by a collaborative team of university and government ecologists, hydrologists, statisticians, government policy-advisors, Traditional Owners and Indigenous rangers. Traditional Owners and Indigenous rangers advised on field sites and species of interest and jointly collected field data, and government staff also collaborated on the interpretation and publication of scientific findings. *To improve its potential to address the current contestation around water allocation planning in the region, the outcomes of this ecological research were delivered in formats appropriate for both the government and Traditional Owners to ensure the different groups could use this information in discussions about water allocation in the catchment and the potential consequences for the environment.*

Modelling Aboriginal and Settler-Colonial Ways of Knowing Water

This study built on the need, identified by the study "Socio-hydrological model, principles and key considerations", *to support better consideration of Traditional Owners' ways of knowing and managing water. The study did so by collaboratively articulating Aboriginal water governance principles and identifying gaps in current settler colonial water policy for the consideration of these principles.* A collaborative team of researchers (social scientists) and Aboriginal custodians of the Martuwarra/Fitzroy River waters worked over 3 years via iterative action research to produce a conceptual model of custodial relationships with Living waters. The same researchers also consulted with government water policy staff to produce a conceptual model of the water resource paradigm that is the basis of water policy in Australia (Laborde and Jackson, 2022). There were two main user groups involved in this study: government staff and Aboriginal custodians of the Martuwarra/Fitzroy River.

Socio-Hydrological Model, Principles and Key Considerations

This study used published literature to 1) develop a conceptual model that represented the potential impacts of water resource development on the hydrological, social and ecological relationships of water regimes in the Fitzroy River, and 2) use

the model to derive a set of principles and considerations to protect aquatic ecosystems and their dependent human cultures and livelihoods (Douglas et al., 2019). *The study drew on disciplinary evidence from hydrological, ecological and social sciences to account for the complex interactions between cultural, ecological, socio-economic and governance systems involved.* It was developed collaboratively by university researchers, government scientists and water policy staff, the latter being the primary non-academic actors involved in this desktop study as they required knowledge on the available evidence and knowledge gaps for planning consultation and decision-making processes for water allocation planning. *Native Title has been determined over the near-entirety of the Martuwarra/Fitzroy River catchment. Thus, the study identified that building legitimacy in e-flows and water planning requires recognizing the diversity of knowledge systems existing in the region, thus including both the Indigenous and non-Indigenous governance and management systems operating at multiple scales.*

3D Modelling and Power Mapping

This project aimed to support Traditional Owners to bring together both scientific and Indigenous knowledge to improve adaptive environmental management and decision-making in their traditional territories (Country) (Hill et al., 2021). Participatory construction of a 3D model of a river catchment, augmented with projected digital data, and diverse maps of power relations among social groups in the catchment, supported showing and sharing of different types of knowledge relevant to the governance and planning goals of the Traditional Owners. *The project involved diverse knowledge systems, providing an opportunity for multiple Traditional Owner groups in the catchment to come together with one another, and with social and natural scientists, to strengthen their relationships and build trust. By sharing their knowledge and learning scientific and political knowledge together, Traditional Owners reported feeling empowered to use these knowledges to inform management and development decisions.*

Participatory Scenario Development and Assessment

This project aimed to demonstrate how to operationalize participatory, multi-objective catchment planning. *It included conservation planners, economists, ecologists and social scientists collaborating closely with a team of research users from Traditional Owner groups, government, the agricultural, mining and tourism industries, and environmental organizations (Kiatkoski Kim et al., 2021a; Álvarez-Romero et al., 2021).* This group collaboratively constructed and assessed the outcomes of alternative development and management scenarios. *Differences in perspectives, interests (i.e., contestation) and power were navigated by following a participatory scenario planning approach and investing significant time and resources on stakeholder engagement, a detailed understanding of the context, and by hiring a professional facilitation team knowledgeable of the region to assist in those tasks.*

The studies were situated in the same socio-environmental system and operated concurrently. The project teams collaborated around the explicit aim to undertake a TDR approach to research, and such collaboration, including its detailed outcomes, are described elsewhere (Kiatkoski Kim et al., 2021b). All projects involved strong engagement with research users. However, their different aims and societal goals resulted in a varied number of disciplines, research users and knowledge systems being involved in each study. Thus, the location of different studies in the continuum between lower- and higher-TDR (**Figure 2**) generally depends on the scope of the study and on the strategies adopted to deal with the contextual features that are most relevant to its objectives. The outcomes of such studies also depended on their scope and the strength of their links to certain stakeholders. Studies 1–3 focused on water management, held close links with government (a key decision-maker), and thus have directly contributed to the Fitzroy catchment water allocation framework and to stakeholders' feedback to government on this plan. Studies 4 and 5 had much wider scopes and focused on discussions broader than the water allocation plan. They contributed with outcomes such as fostering discussions about desirable and undesirable futures, and strengthening relationships and Indigenous institutions (Kiatkoski Kim et al., 2021b). The latter set of outputs might be less tangible than the former (and thus more difficult to measure objectively), but they can be equally as important for planning and decision-making processes. Last, it is also important to note that, in the studies portrayed, costs tended to increase (in proportion to study size) towards higher TDR approaches due to investments in addressing the features described in **Section 3**.

CONCLUSION

Overall, TDR can increase the chance of environmental studies achieving outcomes that are valued by participants for research problems or contexts characterized by complexity, diverse knowledge systems, contestation, power imbalance, and disagreement on the need for transformative change. It brings researchers together with research users from the outset, and recent work on the evaluation of TDR projects indicates that a transdisciplinary approach to research can lead to uptake and longer-term solutions in global sustainability (e.g., Brugger et al., 2018; Hansson and Polk, 2018; Schäfer et al., 2020; Verwoerd et al., 2020), potentially contributing to progress towards the achievement of the United Nation's Sustainable Development Goals (Moallemi et al., 2020). However, the additional resources required by TDR can hinder its application in circumstances where research funding availability is low, TDR is not well understood, existing inequalities make initiating TDR difficult, capacity and expertise are limited, or disciplinary silos are difficult to overcome.

Currently, no simple criterion exists for deciding whether the additional difficulty and expense of TDR are worth bearing. Rather, the four factors discussed above (complexity, diverse knowledge systems, contestation, power imbalance, and disagreement on the need for transformative change) are all

potentially relevant to the decision and need to be weighed up carefully. Future research could combine the aforementioned factors in an index or rubric to allow a rapid assessment of the need for TDR. Such metric might be useful to explore the trade-offs between the factors, perhaps linking different factors with the defining features of transdisciplinarity.

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