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Testing Analytical Frameworks in Transdisciplinary Research for Sustainable Development

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Abstract: This article discusses the concept and the practice of transdisciplinary research, including how it is conceived and implemented through the cooperation of different actors involved. With transdisciplinarity gaining recognition as an approach to addressing sustainable development challenges, the successful integration of various disciplines and actors in the process of knowledge generation becomes essential. Through the Cooperation and Development Center (CODEV), the Ecole Polytechnique Fédérale de Lausanne (EPFL) has promoted transdisciplinary research by proposing a space where North–South partnerships integrating academic and non-academic actors enable the expansion of appropriate technologies and innovations adapted to local societal contexts. This study examines five collaborative research projects conducted at the EPFL. By using an analytical framework consisting of design principles for ideal transdisciplinary research, we conducted semi-structured interviews with academic and non-academic members of the research projects to assess the degree of transdisciplinarity. This framework proved to be a useful tool for exploring transdisciplinary dynamics and assessing the effectiveness of joint knowledge generation. We found that the transdisciplinary cooperation involving different actors is not a linear process, as it depends on the social context in which the project is carried out and on the internal and the external organizational structure established for its implementation. We provide recommendations on how transdisciplinarity could be expanded through institutional support and its results could be effectively transferred into science and practice and discuss the implications for further studies in the conclusions.

Keywords: transdisciplinarity; transdisciplinary research; analytical frameworks; design principles; knowledge integration; sustainability science; scientific cooperation

1. Introduction

In recent times, as global agendas have called for closer interaction between science and society to jointly advance knowledge and offer accurate solutions to promote sustainable development, interest in transdisciplinarity (TD) as a concept and research practice has steadily increased [1–3]. This growing awareness has emerged after years of discussion about the need for a more integrative academic response that breaks with the exclusively disciplinary approach and transcends the barriers of specialists' expertise to address the challenges that we are facing and bring about transformative change [4]. As the concept and research approach of TD evolves, scholars have tried to clarify what distinguishes it from inter- and multidisciplinarity in a debate that animatedly reemerges as a result of multiple conceptualizations of these interrelated concepts [5–7].

Regardless of the increased significance of TD, in practice, the realities of the science of sustainability suggest that effective participatory approaches integrating both academic and non-academic stakeholders in knowledge co-production benefitting science and society alike currently exist more as an ideal than as a reality [4,8,9]. Also, recent studies show that transdisciplinary research still faces a number of challenges that hinder the expansion of its practice and restricts its potential in addressing crucial matters of sustainable development [10–13].

This article provides new empirical observations on the practice of transdisciplinary research, including how it is conceived and implemented and how the key actors involved are applying its results. The paper has two objectives. Firstly, it reviews the evolution of the definition of TD in sustainability science, differentiating it from the concepts of multi- and interdisciplinarity. Secondly, it contributes to the ongoing discussion on the added value of TD to research practice. The paper examines five projects conducted at Ecole Polytechnique Fédérale de Lausanne (EPFL) based on evidence collected through semi-structured interviews with academic and non-academic team members using an adapted analytical framework with a set of design principles for ideal transdisciplinary research [11,14]. The study shows how the practice of TD depends on the context in which research is carried out, on the organizational structure established for its implementation, and on the specific way in which the expertise of both academic and non-academic actors is integrated. By observing how the projects are designed and executed and identifying the challenges and opportunities faced during their implementation, we test here the utility of analytical frameworks for assessing the practice of TD. We also provide recommendations on how TD could be expanded as well as implications for potential further research.

2. The Concept and Practice of Transdisciplinarity

2.1. Transdisciplinarity in Sustainability Science

The origin and the evolution of TD as a concept spans the last 50 years. While some scholars [15,16] attribute the origins of the concept of TD to Bohr [17], others place its initial discussion in the early 1970s, namely, in the talks of Jean Piaget, Erich Jantsch, and Andre Lichnerowicz during the workshop, "Interdisciplinarity: teaching and research problems in universities" organized in France [18–22]. TD appeared as a response to a crisis identified in the traditional creation of knowledge in disciplines in teaching and practice [18,23]. Piaget [24] describes TD as a superior research stage that recognizes interactions and reciprocities between specialized forms of research within a system without firm disciplinary boundaries. For Jantsch [25] and Emmelin [26], TD entails a common set of axioms and methods for a range of disciplines. In the Global South, TD is associated with Paulo Freire's "Pedagogy of the Oppressed" [27], which questions economically- and technologically-driven development models born from disciplinary knowledge and connects the evolution of TD in Latin America to Leonardo Boff's Theology of Liberation [28].

In the late 1980s to 1990s within environmental research in Northern Europe, a parallel conceptualization of TD started to form. By the 1990s, the concept of TD had grown within health and social sciences [20], where "real-world" problems constitute the focus of research. Increased awareness on society–natural ecosystem linkages and complex global challenges related to climate change, loss of biodiversity, desertification, and so forth led to the 1992 Earth Summit and the birth of sustainability science, with an increasing need to transcend disciplines to solve these problems [29]. The First World Congress of Transdisciplinarity held in Portugal in 1994 adopted the Charter of Transdisciplinarity [22,30]. Soon after followed other concepts associated with TD and sustainability, including Gibbons et al.'s [31] new mode of knowledge production (*mode 2* or *post normal science*), which confronted the traditional academic *mode 1* by proposing an attenuation of the epistemological limits between the domains of science and society to address a problem and obtain a far-reaching communication of results involving various stakeholders. In Latin America, a desire to integrate nature conservation objectives and socio-economic aims emphasized the need to pay special attention to governance, development of scientific capacity-technology, and the rescue of traditional knowledge [32].

With the turn of the millennium, the ambitions of global development agendas calling for interdisciplinary perspectives and closer collaboration between relevant stakeholders in order to attain far-reaching and necessary impacts reinforced the interest in transdisciplinary science [33,34]. The 2000 "Zurich International Transdisciplinary Conference" consolidated Switzerland's national initiative prioritizing an action-oriented discourse towards "joint problem solving" with societal stakeholders focusing on sustainable development [20]. Already in the 2000s in Latin America, the collaboration of scientists, practitioners, and communities in information exchange and the joint development of methods and tools led to the application of the ecosystem approach to the management of conservation corridors [35]. A special issue of the journal "Futures" in 2004 consolidated TD as an approach to sustainability science [36] with proposals calling for the integration of different academic disciplines and actors, in the process opening space up for new knowledge, including "socially robust knowledge" [37], and achieving a common objective [30,38,39]. The association of transdisciplinary research with sustainability science gained force with the assertion of their similarities and parallel concepts, including action-oriented research, problem-based focus, participatory or transformative science, and "wicked" problems [12,40].

The emergence of the 2030 Agenda for Sustainable Development and the complex and highly interconnected issues embodied in the 17 Sustainable Development Goals (SDGs) highlighted the need for transdisciplinary research even further. Debates questioning the capacity of "traditional" disciplinary research to tackle the grand challenges humanity is now facing have only intensified [41].

2.2. Disciplines, Interdisciplinarity, and Transdisciplinarity

With the evolution of TD as a concept and a research approach, academic efforts have frequently attempted to clarify the difference between inter-, multi-, and transdisciplinarity. A deep-rooted disciplinary core is the initial piece of the puzzle of transdisciplinary research for sustainable development, and the first prerequisite is the researcher's proven competence in his or her discipline. This competence stems as much from the researcher's knowledge—theoretical and conceptual—as from the methodology used in problem assessment from the researcher's scientific viewpoint and expertise in translating results into products complying with a personal or an external requirement. This disciplinary focus is essential, yet it is insufficient to encompass all the elements of a complex issue. A basic principle thus underpins the transition from discipline to interdisciplinarity, that of the complementarity of different disciplines when questions are tackled comprehensively in order to analyze the interdependences between the diverse dimensions of a problem and to resolve them in a holistic perspective.

Klein [19] (p. 2) understands interdisciplinarity as "the process of answering a question, solving a problem, or addressing a topic that is too broad or complex to be dealt with adequately by a single discipline or profession". Even if this concept is sometimes indiscriminately confused with other terms such as "pluridisciplinarity" or "multidisciplinarity", its strength lies in its ability to establish a dialogue between disciplines [42], resulting in the synthesis of their approaches and methods [43]. The originality of interdisciplinarity thus resides in how new approaches grasp the societal stakes of the issues under examination. Viewing issues in their complexity and redefining scientific boundaries is therefore not a random choice but a necessity. The study carried out by Lam et al. [44] on the interaction between interdisciplinary research and issues of sustainable development tells us that 50% of publications combine both natural and basic sciences and social and human sciences. As Høyer and Nass [45] remind us, interdisciplinarity is fundamentally linked to the debate on ecology as well as that on sustainable development, similarly targeting a balance between society's environmental, economic, and social dimensions [7].

The relevance of interdisciplinary research does not prevent it from having to overcome obstacles in practice. Lélé and Norgaard [46] list four types of barriers. First, there are the values, often implicit, that differentiate each discipline, particularly when starting with the debate between social sciences and hard sciences on the "objectivity" of the scientific approach. The second barrier is linked to the disciplinary assumptions on which theories and explanatory models are based, which are often difficult to consolidate. The third obstacle refers to epistemological differences and the methods of investigation that are derived therefrom, as well as the types of proof that each discipline tends to favor. The last barrier concerns relations between scientific disciplines and society, whereby certain disciplines are favored in the research practice at the expense of others (technological research is a prime example). Rist et al. [47] (p. 323) refer to an interdisciplinarity that seeks "to coordinate the objectives and methodologies in order to achieve a less fragmented view on environmental issues, e.g., as is currently happening in research on climate change". This headway nevertheless remains confined to research, resulting in a lack of societal participation in issue-setting; its application to concrete development goals are almost the same as they are in the case of discipline-based knowledge production. The transition from interdisciplinarity to TD involves a willingness to structure research differently, aiming to apply its results by increasing the scope and the number of interactions for knowledge production and social transformation. TD can then be understood as complementary to interdisciplinarity but going beyond it, as it transcends the boundaries of the organized accumulation of knowledge in university-based disciplines by including non-academic actors in knowledge production [22,38]. By responding to the societal claims to go beyond the confines of academic scientific actors, TD has become a widespread approach when addressing sustainable development. While science is fundamental to providing empirical evidence, the malfunctioning dialogue between science, society, and policy making has manifested the need of participatory approaches integrating a broad range of stakeholders in the process of knowledge generation [13,48–50].

2.3. Definition and Analytical Frameworks

In the last decade, the academic discussion on the definition of TD in sustainability science crystalized along four components that transdisciplinary research projects should include: focus on real-world problems; integration of various disciplines and actors; cooperation and mutual learning of all actors involved; and production of scientific and other societal knowledge relevant for sustainable development [9,13,51–53]. Accordingly, TD can be defined as "a research approach that refers to the co-production of knowledge between stakeholders and researchers to address real-world problems" [13] (p. 367). A transdisciplinary research project should ideally include the following phases: collaborative problem identification and framing; interdisciplinary integration, co-creation, and problem analysis; and incorporation and application of produced knowledge and results [9,11,52,54]. It should also aim for a high level of involvement of the different stakeholders on each phase [3,8]. Scholars have also addressed the notion of participation in transdisciplinary research, conceiving it as a *relational space* shaped by institutional and structural factors and influencing the power relations and the adscription of roles amongst those who participate [13,48,55]. Wuelser and Pohl [4] suggest that, in the context of sustainable development, involving important non-academic knowledge holders in project framing is crucial to maximize the potential societal benefits of scientific endeavors.

The latest literature proposes an extensive range of frameworks to analyze and facilitate implementation of transdisciplinary research and the practice of new forms of scientific reflection and effective problem solving [13,56–58]. These proposals include frameworks with practice-oriented design principles for assessing successful or ideal transdisciplinary projects [11,14,54,59]; a framework of transdisciplinary outcome spaces proposing a back-casting guideline for the research design focusing on three desired outcomes (situation, knowledge, and learning) and concerned with the interface between research and practice [58]; a framework evaluating knowledge co-production in focal areas (inclusion, collaboration, integration, usability, and reflexibility) and research stages (formulate, generate, and evaluate) of transdisciplinary projects [2]; a framework for the comparative analysis of transdisciplinary research [60] and of transdisciplinary synthesis projects [51] according to knowledge type, type of actor, and level actor involvement at different stages. By focusing on the ties amongst stakeholders, the components of transdisciplinary research, and the interplays between them, such frameworks contribute to advancing the understanding of TD, to identifying the challenges in terms of knowledge integration and actors' involvement, and to expanding its use.

2.4. Challenges in Transdisciplinary Research

The documented experiences of the practical implementation of transdisciplinary research illustrate the challenges faced by the different actors involved, and show, as stated by Polk [12] and Scholz and Steiner [61], that its undertaking proves more difficult than anticipated. Challenges include: disagreement on a common language, lack of recognition and integration of disciplinary and practical knowledge and methods, uneven participation and power asymmetries, contrasting timelines, unbalanced ownership of problems to be addressed, different expectations, and conflicting interests [3,4,11,51,55]. Fritz and Binder [48] focus on the notion of participation in transdisciplinary research, pointing out that the level of involvement of non-academic stakeholders affects power relations and ultimately the outcomes of transdisciplinary projects. Transdisciplinary research specifically involving North–South collaboration shows that some of these challenges tend to intensify in the research practice due to deepening conflictual interests of institutions or actors involved and the existing power structures, as stated by Schmidt and Pröpper [13].

The integration of methods is a further challenge, given that the diversity in knowledge co-production methods is necessary to identify, analyze, and propose solutions to complex real-world problems; this calls for clear and reproducible frameworks consistent in language and terminology [8,11,52,62]. Additional challenges include finding pertinent outreach and communication methods to generate impact on the wider academic community and society; measuring and defining progress and success; and ensuring the harnessing of results in the institutional contexts in which societal change occurs for effective use [2,9,54]. Increasing the scalability and the transferability of transdisciplinary research results and dealing with the insufficient recognition and legitimacy of its outcomes are additional difficulties [11,13]. Various proposals related to design principles [11,14], diverse integration methods [54,56], and evaluation criteria [11,14] have been developed to confront some of these challenges.

3. A Study of Transdisciplinarity in Research Projects

3.1. Transdisciplinarity and Scientific Cooperation for Development at EPFL

For over four decades, researchers from the Ecole Polytechnique Fédérale de Lausanne (EPFL) have actively engaged in knowledge production and collaborative research with researchers from Global South countries with the aim to jointly develop appropriate technologies and innovations adapted to the local societal contexts. The Cooperation and Development Center (CODEV) at EPFL, with its recognized expertise in scientific cooperation for sustainable development, contributed to early discussions on TD in Switzerland, both on the conceptualization of TD and the transition from disciplinary research to interdisciplinarity [63,64]. Focusing on North–South partnerships as a relevant approach to increasing possible societal impact, CODEV has encouraged a participatory approach to research on socio-economic and technological development in the poorest countries by involving various stakeholders in scientific field experimentation to collectively address the problems raised.

Various examples illustrate how CODEV has promoted transdisciplinary research over the years and has remained committed to North–South collaboration as a research approach when addressing sustainable development. CODEV has done so by proposing a space where academic and non-academic actors within a given cultural context intervene, and where the methods are constructed in correspondence with the values and the practices of the concerned society. The studies we conducted at EPFL in the 1990s in the field of habitat research were already part of that first crossing of disciplinary borders, which was then followed by associating with non-academic actors. Further research in this field over several decades aimed at identifying the methods that need to be implemented to achieve slum upgrading [64,65]. The subsequent diagnosis called for knowledge of architecture, urbanism and engineering, as well as the inclusion of the main dimensions of sustainable development (namely, the contributions of economy, sociology, and environmental sciences) [66]. In addition, in view of implementing future projects, financial, institutional, and political dimensions and the involvement of non-academic stakeholders for jointly determining the societal framework within which such projects would be implemented completed the picture. The transdisciplinary approach entailed mutual definition of the framework conditions for the organization and the implementation of the project based on management and financial knowledge of partners involved. This is how, when granted a mandate by the Bolivian government to define the rules for a new national popular housing plan, for instance, we then constituted an inter- and transdisciplinary research group comprising architects, geographers, and sociologists, to which we added representatives from the Ministry of Habitat, a cooperative bank interested in becoming involved, and a non-profit organization (NGO) working in the popular housing districts that provided the interface with the local community. We thereby sought to integrate the stakeholders ultimately in charge of implementing the results into the whole action-oriented research process [67].

In addition to these projects, the United Nations Educational, Scientific and Cultural Organization (UNESCO) Chair in Technologies for Development, hosted by CODEV since 2007, has been a powerful tool in advancing such actions and facilitating science–society interfaces. The Chair works as an international cooperation platform enabling linkages between disciplines and stakeholders and aims to provide appropriate technological solutions that will contribute to sustainable development in countries of the Global South in four priority areas: sustainable habitat and cities, information and communication technologies for the environment, technologies for disaster risk reduction, and sustainable energy production. In the last decade, a biannual UNESCO Chair Tech4Dev Conference organized at EPFL has promoted synergies between academic and non-academic actors from diverse countries (see examples in [68–70]) and advanced the discussion of opportunities and challenges of TD in sustainability science.

The Seed Money Program is a further instrument with which CODEV promotes TD at EPFL. It financially supports EPFL researchers and academic and non-academic actors in countries of the Global South in carrying out small projects in their initial stage. Created in 2005 and with a total of 110 projects supported until 2019 through an annual competitive call, the Seed Money grant has become popular for EPFL researchers interested in linking their scientific endeavours to real-world challenges. The program recommends the Swiss KFPE Guide for Transboundary Research Partnerships as a guideline for constructing research partnerships (http://www.kfpe.ch/11-Principles/), bearing in mind North–South scientific cooperation as a mutual learning practice promoting equality among partners.

3.2. Research Design and Methodology

For this study, we adapted an existing analytical framework with TD design principles in order to analyze five research projects conducted by EPFL researchers and their partners. The main aim is to contribute to the understanding of and the discussion surrounding the practice of TD and to test the usefulness of a specific framework in analyzing transdisciplinary research projects. We examined how these projects were designed and executed and observed the difficulties that the different actors involved faced. Our research is guided by the following questions: To what extent do the reviewed projects adhere to the proposed transdisciplinary research framework? What are the main challenges faced within transdisciplinary research? How useful is an analytical framework based on design principles in examining and assessing transdisciplinary research projects?

We are using the following operational definition of TD based on Schmidt and Pröpper [13]: “Transdisciplinarity is a research approach that refers to the co-production of knowledge between stakeholders and researchers to address real-world problems” (p. 367). We selected five out of 22 possible projects as case studies based on their apparent adherence, at least implicitly, to the four main components of TD (focus on real-world problems; integration of various disciplines and actors; cooperation and mutual learning of all actors involved; and production of scientific and other societal knowledge relevant for sustainable development) and on the availability of principal investigator or project manager to contribute with information. Also, the selection ensured diversity of projects in terms of geographic location, disciplines and topics, and funding agencies. The five selected projects are described in Table 1.

Table 1. Overview of selected projects (See Appendix A: Summaries of the five projects).

Project/Case: Components of TD and General Characteristics	**Case 1: Info4Dourou 2.0**	**Case 2: Effective Methodology for the Assessment of Integrated Energy Strategies**	**Case 3: Urbis: Georeferenced Mobile Platform for the Interdisciplinary Study of Socio-Urban Problems in Mexico**	**Case 4: Hybrid Cities: Informal Resistances to the Violence of Urbanization in China, India, and Venezuela**	**Case 5: Protection of Critical Infrastructure against Electromagnetic Attacks**
Components of TD:					
Objectives	Improving water management for smallholders in semi-arid regions, as well as food security empowering vulnerable communities in Burkina Faso.	Developing reliable strategies that could be used to improve energy supply and its associated environmental impacts in Cuba.	Identifying social behaviors and needs related to urban security and mobility in the city of Guanajuato, in Mexico.	Studying the processes embodied in habitat production in current cities built by architectural, urban, territorial, and social hybridization in China, India, and Venezuela.	Increasing the safety of critical infrastructure in Europe against electromagnetic attacks.
Main participating disciplines and areas	Communication systems, agriculture (incl. irrigation), environmental sciences	Energy, air physics and chemistry, meteorology	Computer sciences and engineering, social sciences, education	Architecture, anthropology, sociology	Electromagnetic compatibility
Main non-academic actors	Civil society (beneficiaries), private sector, local government	Government	Civil society, schools, local government	Local inhabitants, technical services of urbanism of the city of Caracas, mayor of Caracas	Industry
Cooperation and mutual learning of all actors	Proxy: time and energy of team members dedicated to participate in the project	Proxy: time and energy of team members dedicated to participate in the project	Proxy: time and energy of team members dedicated to participate in the project	Proxy: time and energy of team members dedicated to participate in the project	Proxy: time and energy of team members dedicated to participate in the project
Production of scientific and societal knowledge	Water use efficiency of irrigation systems; better water management for smallholders in semi-arid regions and food security	Methodology to design a strategy for energy and air quality; reliable strategies that could be used to improve energy supply and associated environmental impacts	Machine learning and artificial intelligence applications; allow citizens to organize themselves and participate in urban planning	Participatory process of habitat production; construction of inclusive cities addressing social expulsion	Innovative methods for numerical simulations and experimental analysis; increase awareness and knowledge of risks from electromagnetic attacks
General characteristics:					
EPFL lab or center	CODEV–VPE	LASIG–ENAC	LIDIAP–STI	LASUR–ENAC	EMC–STI
Geographic location	Burkina Faso and Palestine	Cuba	Mexico	China, India and Venezuela	Europe
Main funding agency	SDC	SNSF R4D	CONACYT Mexico	SNSF	EU 7th Framework Program
Approximate duration	February 2012–May 2018 (72 months)	May 2016–June 2019 (36 months)	2014–2016 (24 months)	May 2016–April 2019 (36 months)	2012–2015 (36 months)

TD, transdisciplinarity; EPFL, Ecole Polytechnique Fédérale de Lausanne; CODEV-VPE, Cooperation and Development Center - Vice-presidency for Education; LASIG-ENAC, Laboratory of Geographic Information Systems – School of Architecture, Civil and Environmental Engineering; LIDIAP-STI, Idiap Research Institute Laboratory – School of Engineering; LASUR-ENAC, Urban Sociology Laboratory - School of Architecture, Civil and Environmental Engineering; EMC-STI, Electromagnetic Compatibility Laboratory – School of Engineering; SDC, Swiss Agency for Development and Cooperation; SNSF, Swiss National Science Foundation; R4D, Swiss Program for Research on Global Issues for Development; CONACYT, Mexican National Research and Technology Council; EU, European Union.

During the design of our study, we selected and used what we believe is a more encompassing definition of the different types of team members that convene during design and implementation of transdisciplinary projects: “academic” and “non-academic” to refer to team members coming from academic institutions and those coming from other institutions, respectively. We believe that defining academic members as the only “scientists” and “researchers”, as is generally found in the transdisciplinary literature, encourages power asymmetries and disregards non-academic contribution to knowledge creation in TD projects. If co-development of knowledge is a premise of TD projects, a more legitimizing definition of the types of team members and their roles should be used.

We collected data using a semi-structured interview (comprising multiple choice and open-ended questions) applied to academic and non-academic team members. The questions of the interview were based on an analytical framework with a set of design principles for ideal transdisciplinary research proposed by Lang et al. [11] based on various strands of the literature on TD in sustainability science and then adapted by Luthe [14]. Lang et al. [11] conceived the framework proposed as an ideal standard “to practically guide transdisciplinary research processes and facilitate effective and efficient research processes for all actors involved” (p. 35). Luthe [14] proposed six additional complementary design principles that surfaced when testing the applicability of the framework in the analysis of five projects.

With this study, we aim to test empirically Lang et al. [11] and Luthe’s [14] principles for the analysis of the experiences and the challenges of transdisciplinary research projects by observing the adherence of the project to those principles. Our proposed framework includes Luthe’s complementary principles to Lang et al.’s [11] original scheme and explains them to simplify their operational usefulness (Table 2).

Most of our interview questions are based on Lang et al. [11], to which we added a number of open-ended questions. The interview’s closed questions confirmed the adherence, or lack thereof, to the transdisciplinary research principles during the three main project phases (project framing and team building, co-creation of knowledge, and application of results) and the application of the general principles cutting across them (facilitating formative evaluation, mitigating conflict, and enhancing participation capabilities). Open-ended questions invited interviewees to explain their individual understanding of TD and to openly discuss the origin of the project, the collaboration, including team formation and their response to closed questions. The interviews gathered detailed information on the practice of TD, stakeholders’ experiences, North–South partnerships, and the perceived challenges thereby encountered. The team piloted the instrument once in August 2018. A total of ten interviews were conducted between August and November 2018. Interviewees included at least one EPFL academic member and one non-academic member per project. By including the perspectives of both academic and non-academic members, the analysis contributes to broadening our understanding of the practice of TD research. Each interview lasted 1.5 hours on average. We conducted the interviews in English and accepted responses in English, Spanish, or French. We entered the answers directly into an Excel database or in the interview formularies, which, once completed, were then registered into the database. We cleaned and edited the data and summarized the results according to the adherence to TD design principles and complementary principles. For the closed questions and during the analysis, we used an overall scale of three (“yes”, “partially”, and “no”) to measure adherence to each TD principle and complementary principle. Since our main interest was to understand the general level of adherence of these projects to the TD framework in order to synthesize the analysis—and because many complementary principles feed into an overall principle—we pondered the number of “yes,” “partially,” and “no” to arrive at an overall result or level for each main principle. For example, if all complementary principles of one principle were adhered to, then the overall principle was summarized with a “yes” or complete adherence to such principle. Likewise, if all complementary principles were not adhered to, the overall principle was summarized into a “no” or lack of adherence to such principle. Otherwise, we used “partially” to denote a mixed adherence to complementary principles and principles (see tables in the following pages).

Table 2. Framework with design principles for ideal transdisciplinary research.

TD Design Principles.	Description
Phase A: Collaborative problem framing and building a collaborative research team	
I. Building a collaborative research team	The team includes scientists of diverse disciplines and non-academic stakeholders. Explicit team-building processes and a common language among team members are developed. A balanced organizational structure including the establishment of a co-leadership is clearly defined.
* *Available of quick seed or initiation funding*	The project was put together with quickly available seed or initiation funding.
II. Joint understanding and definition of the real-world problem	The entire project team defines the real-world problem to be addressed while balancing their specific interests.
* *The project initiated from society*	The project is initiated by and originates from society; it addresses a societal problem.
III. Joint definition of the research framework (objectives, questions, success criteria)	The definition of general and specific objectives and questions explicitly accounts for the different interests of team members. The project team agrees on common success criteria to evaluate if objectives are met.
IV. Joint definition of the methodological framework	The methodological framework considers the views of all team members.
* *Practice of adaptive management and flexibility in time, context, and methods*	Project team and external factors or actors allow for the project to have flexibility in time, content, and methods.
Phase B: Co-creation of solution-oriented and transferable knowledge through collaborative research	
V. Transparent assignment and support of appropriate roles	Tasks and roles of the project team are defined in a transparent manner. Project leadership facilitates a transdisciplinary approach during the research process.
VI. Apply and adjust integrative research methods and transdisciplinary settings	Project team employs or develops methods suitable to generating solutions for the problem addressed.
* *Acceptance of processes and results*	Project team accepts transdisciplinary processes beyond project results.
Phase C: (Re-)integrating and applying the co-created knowledge	
VII. Realize two-dimensional integration	Project results are implemented to resolve or mitigate the real-world problem addressed. Results are integrated into existing scientific body of knowledge.
VIII. Generate targeted products for both parties	Project team provides practitioners and scientists with products, publications, and services in an appropriate form and language.
* *Public outreach: science communication for a larger public*	Project team generates science communication focusing on public and viral media outreach for a broader audience.
IX. Evaluate scientific and societal impact and sustainability	Project team achieves the project goals and accomplishes additional (unexpected) positive effects.
* *Transition to a follow-up project partnership*	Perspectives of transition to a follow-up project and partnership are developed.
General Principles	
X. Facilitate continuous formative evaluation	Evaluation (including formative) is an integrative part of the project.
XI. Mitigate conflict constellations	The project team prepares for/anticipates conflict and adopts procedures for its management.
XII. Enhance capabilities for and interest in participation	Adequate attention is being paid to the capabilities required for effective and sustained participation in the project over time.

Note: Taken from Lang et al. [11] and Luthe [14]. I–XII are the principles proposed by Lang et al. [11]. * refers to the complementary principles added by Luthe [14].

4. Results and Discussion

We discuss here the results of the five case studies by summarizing the interviewees' perspectives on the practice of transdisciplinary research. We assess the level of adherence to the proposed definition and framework of TD during the three project phases and the application of the general principles cutting across them. We observe the main challenges influencing project design and development, and we also look at some unexpected positive impacts that arose during the practice of TD, which are depicted as opportunities.

The five projects have different origins, organizational structures, and topics. In addition, their team members did not conceptualize them under the same explicit TD lens. While our main aim is not to compare them, it is worth noting some general observations and commonalities in addition to their specificities. All five projects had an overall partial adherence to the proposed TD framework. This was due to none of the teams explicitly following a TD framework during the design of their projects. The teams had an extemporaneous approximation to TD that surfaced given the type of project they designed or were required to propose in order to obtain research funding. We observe that, in some cases, non-academic members had more limited knowledge on the adherence (or not) of a principle than academic members. While we do not aim to compare them, it is interesting to note that the discrepancies of the responses between academic and non-academic members interviewed may have been a consequence of their different visions of how the project was implemented or the power structure that prevailed in their collaborative arrangements.

4.1. Understanding of TD Definition and Main Elements

During the interviews, we asked three questions related to the interviewees' understanding of TD: Is your research project transdisciplinary? How do you define transdisciplinarity? In your opinion, which of the following elements should a transdisciplinary research project include? Here, they were able to select from a list of transdisciplinary elements we proposed and add others. Although nine interviewees out of ten responded positively to the first question, several interviewees verbalized that it was during the interview that they became aware of a more formal definition of TD and the knowledge of transdisciplinary elements and frameworks.

In one case, the academic and the non-academic members' conceptions and understandings of TD partially reflected our proposed operational definition of TD and corroborated the main elements that transdisciplinary research should entail. Their narratives endorse the action-oriented approach of TD and the joint work between academics and non-academics required throughout the project process. In another case, only the academic member observed the integration of expertise from non-academic actors. In contrast, the definition provided by the non-academic member is more in line with interdisciplinarity: "(TD is when) different branches of science, energy engineering, pure physics, geographic information systems are linked together to have a final product." Both academic and non-academic members of another case believed their project was explicitly transdisciplinary, yet they specified that such characterization would depend on how TD is defined. However, for the academic member, an essential element of TD is the "interdisciplinary co-production of knowledge", and the other elements are "not necessary".

Several authors [8,11,14] have recognized the need to further socialize practical experiences on how to implement transdisciplinary research projects and become aware of TD's key elements, frameworks, and practical guidance. Such familiarization should place research project proponents in a better position to better identify best practices, risks, and pitfalls to avoid when implementing TD. Socializing the existing body of knowledge in TD continues to be imperative. Equally important is the responsibility of academic and non-academic members to actively search for TD specific guidance when embarking upon the design and the implementation of TD research projects.

4.2. Phase A: Collaborative Problem Framing and Building a Collaborative Research Team

The level of adherence to Phase A design principles by the five projects or cases gives a mixed picture (Table 3). Most projects (three) were initiated explicitly from society. This can be explained by the nature of the grants' calls to which these particular projects responded. For example, Case 2, Case 3, and Case 5 responded to calls designed to finance projects that find solutions to specific societal challenges.

At least three of the five projects (i.e., Cases 2, 4, and 5) lacked a clear co-leadership of academic and non-academic members. For the two first cases, this could be explained by the type of funding mechanism and the institution that includes stringent rules when it comes to who is and who is not a researcher, but this could also have been related to power relations within the partnerships, as we discuss later. For Case 5, the size and the complexity of the project may have limited such definition. Although there was a primary coordinator and leader for the project, diverse leaders and coordinators for specific "packages" (linked to disciplines) were defined.

Conversely, only one project had initiation funding available. Luthe [14] argues that the lack of funding mechanisms to support team formation, co-design of project frameworks, and team building at the inception of complex projects may pose an additional risk during implementation and transition to follow-up projects, as lack of success of the main project in phases B and C limit such transition. However, the discussion is inconclusive, and we need further empirical studies to clarify the interplay between the availability of initiation funding and project implementation and follow up.

Although most interviewees mentioned the use of criteria for inclusion of team members, they either did not develop or did not apply them explicitly. In most cases, teams were formed by previous knowledge of the work and the research of its members or existing medium to long-term partnerships.

All projects adhered to adaptive management. By looking at the reasons and the explanations put forward by academic and non-academic members for the need for adaptive management, we can confirm that research that is more participatory requires more time and flexibility than disciplinary or traditional approaches [14,54,71]. This finding also speaks to the need for funding schemes to allow for more flexibility [14]. Furthermore, in countries of the Global South with complex politico-social and economic contexts, adaptive management becomes essential for projects such as Case 1, which required consideration of context-based influences. We can argue that not adhering to specific principles may impact—positively or negatively—the adherence to other ones. For example, joint framing of the research project may facilitate the joint definition of the methodological framework, and the lack of the former arguably hinders the latter. Luthe [14] further discusses this with an emphasis on how his six complementary principles combine or relate to Lang's et al. [11] TD framework. Still, the specific interplay of the different factors in a research framework affecting a particular project is an issue that requires further investigation.

Table 3. Main results on the adherence of the different projects to Phase A principles.

	Case 1		Case 2		Case 3		Case 4		Case 5	
TD Principle	**AcM**	**N-AcM**	**AcM**	**N-AcM**	**AcM**	**N-AcM**	**AcM**	**N-AcM**	**ACM**	**N-AcM**
I. Building a collaborative research team	Partially (mostly no)	Partially (mostly yes)	Partially (mostly yes)	Partially (mostly yes)	Partially (mostly yes)	Partially (mostly yes)	Partially (mostly yes)	Partially	Partially	Partially (mostly yes)
*** Availability of quick seed or initiation funding**	No	No	Yes	Yes	No	No	No	Does not know	No	Does not know
II. Joint understanding and definition of the real-world problem	No	No	Partially (mostly yes)	Partially (mostly yes)	Partially (mostly yes)	Partially (mostly yes)	No	Partially (mostly yes)	Yes	Yes
*** The project initiated from society**	No	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
III. Joint definition of the research framework (objectives and questions)	Does not know	Partially	Yes	Yes	Partially	Does not know	Partially	Partially	Partially	Partially
IV. Joint definition of the methodological framework	Partially	Yes	Yes	Yes	Yes	Does not Know	Yes	Partially	Yes	Yes
*** Practice of adaptive management and flexibility in the context and methods**	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Partially	Yes	Yes

I–IV are the principles proposed by Lang et al. [11]. * refers to the complementary principles added by Luthe [14]. AcM = academic member; N-AcM = non-academic member.

4.3. Phase B: Co-Creation of Solution-Oriented and Transferable Knowledge through Collaborative Research

Lang et al. [11] argue that there is no specific rule on who (academic or non-academic members) should lead specific tasks and activities of projects; yet, they emphasize the need for clarifying and transparently assigning appropriate roles. Three cases (2, 3, and 5) adhered entirely to the principle of transparent assignment and support of appropriate functions (Table 4). In Case 4, only academic members carried out the assignment of roles. In part, this could be explained by the type of funding source [the Swiss National Science Foundation (SNSF)] that requires researchers within Swiss academic institutions to be the project leaders.

Table 4. Main results on the adherence of the different projects to Phase B principles.

	Case 1		Case 2		Case 3		Case 4		Case 5	
TD Principle	**AcM**	**N-AcM**	**AcM**	**N-AcM**	**AcM**	**N-AcM**	**AcM**	**N-AcM**	**AcM**	**N-AcM**
V. Transparent assignment and support of appropriate roles	Partially	Partially	Yes	Yes	Yes	Yes	Yes	Partially	Yes	Yes
VI. Apply and adjust integrative research methods and transdisciplinary settings	Partially	Yes	Yes	Partially	Partially	Partially	Yes	Yes	Partially	Partially
*** Acceptance of processes and results**	No	Yes	Yes	Yes	No	No	Yes	Yes	No	Yes

V–VI are the principles proposed by Lang et al. [11]. * refers to the complementary principles added by Luthe [14]. AcM = academic member; N-AcM = non-academic member.

For Luthe [14], the "acceptance of process" vs. "project results" principle complements Phases B and C of the framework. Mainly, it adds to the following principles and subprinciples: "Apply and adjust integrative research methods and transdisciplinary settings in phase B", "Realize two-dimensional integration", "Targeted products", and "Evaluate scientific and societal impact in Phase C". Because researchers may not attain project results within the project duration due to resource limitations or cultural barriers, he emphasizes that such failures should be more accepted in transdisciplinary research without risking the overall success of the project. The process then becomes equal or more important than the results. In three of our Cases (1, 2, and 4), interviewees considered the acceptance of both process and results. The academic member of Case 1 said, "The process itself is a result of the research, and we intend to use this kind of approach in other countries". In contrast, both interviewees in Case 3 valued the acceptance of results only.

4.4. Phase C: (Re-) Integrating and Applying the Co-Created Knowledge

Even though projects did not attain a transition to follow-up projects immediately after, they all were able to achieve project goals and the generation of additional positive effects (Table 5). It is, however, difficult to say if the projects would evolve into another project, as at least two were still under implementation at the time of the interviews. As stated by Luthe [14], if such a transition to a follow-up project occurs, the phases A and B of the new project are more likely to be successful. It comes as no surprise that quickly available initiation funding is also required for a transition to a follow-up project, as it provides more time and flexibility for the pre-project phase with a higher chance for a successful main project phase [14]. As we saw in our study, only one project had access to such funding. However, the discussion is inconclusive here, and further empirical studies are needed to clarify the interplay between the availability of initiation funding and project implementation and follow up.

Table 5. Main results on the adherence of the different projects to Phase C principles.

	Case 1		Case 2		Case 3		Case 4		Case 5	
TD Principle	**AcM**	**N-AcM**	**AcM**	**N-AcM**	**AcM**	**N-AcM**	**AcM**	**N-AcM**	**AcM**	**N-AcM**
VII. Realize two-dimensional integration	Partially	Partially	Partially	Partially	Partially	Partially	Partially	No (not yet)	Yes	Partially
VIII. Generate targeted products for both parties	Yes	Yes	Partially	Partially	Yes	Yes	Partially	Yes	Yes	Yes
*** Public outreach: science communication for a larger public**	Yes	Yes	No	No	Yes	Yes	No	Does not know	Yes	Yes
IX. Evaluate scientific and societal impact and sustainability	Partially	Partially	Partially	Partially	Partially	Partially	Partially	Partially	Partially	Partially
*** Transition to a follow-up project partnership**	No	No	No	No	No (not yet)	No (not yet)	No (not yet)	No (not yet)	No	No

VII–IX are the principles proposed by Lang et al. [11]. * refers to the complementary principles added by Luthe [14]. AcM = academic member; N-AcM = non-academic member.

Two of the projects lacked communication of findings to a larger public, which could be explained by political and contextual factors of the concerned countries or the level of implementation of the project (e.g., Case 4 was in its initial implementation phase). Case 5 included a mechanism for dissemination of progress and results mainstreamed during the implementation process. Luthe [14] states that communicating findings to a larger public complements Lang et al.'s [11] framework (i.e., "Targeted products" and "Evaluate scientific and societal impact"). He argues that, even though peer-reviewed scientific papers are required to ensure scientific rigor and academic excellence, even the limited emphasis that academic papers place on communicating results to practitioners and the public at large is essential. He stresses that popular science communication needs to be considered more a part of the formal dissemination of transdisciplinary research projects, and one indicator of success here could be the number of people reached (paper downloads or site visitors) rather than the impact factor of a journal.

4.5. General Design Principles (Cutting across the Three Phases)

As observed in Table 6, perceptions of most interviewees identify a lack of adherence to two general transversal principles: "X. Facilitate continuous formative evaluation" and "XI. Mitigate conflict constellations". We observe that knowledge of results frameworks and Theory of Changes is minimal or non-existent within transdisciplinary research projects. The facilitation of continuous formative evaluation is lacking. In some cases, the interviewees considered evaluation as part of the research only because the funding agency requested this. One academic member put it this way: "We did not spend a lot of time on evaluations, except when we wrote the reports for the donors." Bergmann et al. [54] argue that formative evaluations are more than just a retrospective appraisal of the performance of projects and institutions; they can also be designed as a learning tool.

Table 6. Main results on the adherence of the different projects to General Design Principles.

	Case 1		Case 2		Case 3		Case 4		Case 5	
TD principle	**AcM**	**N-AcM**	**AcM**	**N-AcM**	**AcM**	**N-AcM**	**AcM**	**N-AcM**	**AcM**	**N-AcM**
X. Facilitate continuous formative evaluation	No	Yes	No	No	No	Does not know	No	No	No	No
XI. Mitigate conflict constellations	Partially	Partially	Partially	No	No	Does not know	No	Does not know	No	Does not know
XII. Enhance capabilities for and interest in participation	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

X–XII are the principles proposed by Lang et al. [11]. AcM = academic member; N-AcM = non-academic member.

It might be surprising that projects did not explicitly address the mitigation of conflict constellations. However, independent of their affiliation or the project, interviewees mentioned the almost non-existence of conflicts within teams. If conflicts existed, they were solved as they came. In some cases, these were circumvented through the establishment of contracts with specific procedures in the event of disagreement. Luthe [14] also observes a lack of substantial conflict within teams from his study projects. He attributes this positive aspect to experiences during project implementation and flexibility of the entire team. Conversely, the lack of knowledge about various aspects by non-academic members may suggest a lack of sufficient effective communication within the team, which is an important aspect linked to the challenges.

4.6. Challenges and Opportunities

4.6.1. Initiation of Project from Society

Society actors initiated three out of five of the projects, which is unusual for transdisciplinary projects. It is more frequent for scientists to approach partners outside academia to get them involved in joint transdisciplinary projects tackling societal problems than non-academic actors approaching scientists [11,72]. This is relevant insofar as the lack of a joint definition of the research problem may lead to some difficulties over the course of the project, including natural asymmetries, unless counterbalanced by the establishment of a clear organizational structure that balances ownership by academic and non-academic members, including joint leadership from the outset, as argued by previous research [3].

4.6.2. Organizational Structure

Some of the challenges faced during implementation are indeed related to the organizational structure of the project teams. One member of Case 1 said: "An explicit organizational structure understood by all was lacking. It was defined by the previous project leader but was not clear enough, and it was not disseminated or spelled out to the team at the outset, except in the document for the donor". The particular characteristics of the project determined the form of the organizational structure, and, in some cases, the established structure did not allow flexibility, even when the academic members and other involved members were interested in encouraging TD. This explains why there was no co-leadership in some of the projects. The academic member on Case 2 said: "Because the project is managed in different phases, there are some phases where there is more research and more academic people involved, and then there are phases where non-academic partners, particularly the Cuban partners, do more, and the academic members do not need to be there". While there is evidence suggesting that discontinuous participation of team members in transdisciplinary projects hinders implementation [11], it is also recognized that not all phases in the project have to be carried out jointly and in a transdisciplinary way but may need either purely disciplinary research or only the actors from practice in between [73].

In Case 3, team members cited the lack of a clear organizational structure with defined responsibilities and competencies as a significant hindrance during implementation. The non-academic member said that he was unaware of the project-specific objectives and team composition. Similarly, studies by Lang et al. [11] and Walter et al. [74] show significant correlations between project involvement and increased decision-making capacity. We assume that a higher decision-making capacity automatically generates a higher level of ownership in the project and therefore strong involvement. In the opinion of the academic member, non-academic members participate in the project but do not belong to the team. Similarly, the non-academic member sees himself as a collaborator at certain times and as a co-leader at others, which points to an unclear definition of the roles of all the actors involved. This finding corroborates what Lang et al. [11] state by pointing to insufficient legitimacy of all actors involved as a common limitation in transdisciplinary research.

We observed one structural issue within Case 1. The project leader facilitated exchanges between scientists and farmers, taking the needs of both into consideration during the implementation and finding the middle ground. She said: "The scientists wanted to grow onions but the beneficiaries needed another crop, so we had to compromise. I told the scientists to adapt. It was a facilitation role without forcing anyone. I had to tell farmers why some things were important for the research". Also, the academic member highlighted that, because of the lack of an explicit team organization structure, "everything needed to be more explicit". For example, the main tool for dealing with and overcoming conflict was the establishment of specific contracts with clear procedures in the event of disagreement.

4.6.3. Roles and Power Asymmetries

Even though the established organizational structure was perceived as balanced between academic and non-academic members at all levels in Case 2, and the different interests were integrated and considered, some power issues in the relations between the team members suggested that this was not the case in reality. For example, all academic members were from Switzerland, while the non-academic members were from Cuba. Since the scientific component of the project was stronger and the funding agency was Swiss, the academic partners clearly exercised a greater power of decision in the project. The non-academic member in Cuba said: "Countries like Switzerland have the resources to develop things and transfer technology and knowledge; and this is very helpful". This shows how the disparities in terms of financial resources between the countries of the members involved in a project may influence the creation of a dynamic of power relations and ultimately the sustainability and the long-term effect of the action. As the academic member stated: "The long-term sustainability of the project will be ensured through the people and the support of local partners".

In Case 5, both academic and non-academic members expressed a similar view regarding who carried out science and research. For the academic member, as the project was a scientific one, all team members were scientists, and some just happened to work in the private sector. In this case, therefore, both the academic and the non-academic members had recognized and clear roles in conducting scientific research. The project included a steering committee where people working on the topic were invited to the project meetings. The aim of these meetings was to inform a broader audience (e.g., military, civilians, etc.), share results, and, for the wider audience, to provide input for the research project. Previous studies considered the setting of a steering committee a useful tool for reinforcing institutional support to the project, both from scientific and practical viewpoints, as well as for augmenting its integration in the specific regional context and within science [61,73]. This opens up opportunities for further research as to how transdisciplinary processes and methods could help in broadening knowledge dissemination and adaptive management with academic and non-academic members.

The lack of a balance between academic and non-academic members in decision-making and leadership was a limitation observed in Case 1. As the academic member said: "It was always clear who was reporting to whom. We were not equal leaders. I was the main decision maker. For me, it was not a co-leadership role. The local coordinator needed to discuss any big decisions with me". This vision differs from that of the non-academic member who said that every team member had a clear role in the organizational structure and he felt this represented co-leadership between the academic and the non-academic members. The lack of agreement on what constitutes co-leadership between academic and non-academic members resulting in unbalanced power relations during project implementation was one of the main challenges that corroborated Fritz and Binder's study [48]. By observing their own appraisal of their ownership in the decision-making process, academic and non-academic members bring light to the explicit or the implicit power relations embedded in their collaboration. We assume that the designation of roles amongst those involved in the project shapes the relational space in a particular manner. Similarly, the inherent power relations stemming from the origin of the project (in terms of who perceives who had the original idea, who provides the funding, who counts on more experience or resources, etc.) may impede a joint co-leadership arrangement to be on a level playing field [13,73]. Nonetheless, the discussion surrounding the impact of power relations on the organizational structure and the designation of roles in transdisciplinary research remains inconclusive as to whether the designation of roles and decision-making capacity linked thereto is a cause or an effect of power relations. Further research shedding light on such issues of power, particularly within

North–South transdisciplinary research partnerships and power relationships within each overall team group (academic and non-academic members) would be beneficial.

4.6.4. Contextual and Structural Factors

There were particular restrictions related to contextual and structural factors [12,51] during implementation. For Case 1, weather conditions in Burkina Faso were a significant limitation, and, as the academic member mentioned: "When the field was not ready to start the experiment, they had to wait a few seasons before starting. Sometimes it was not possible to weigh the vegetables in the field because of disease". Other specific context-related limitations delayed the experiments. The academic member stated: "Our system had negative effects because of the potential danger from other species. The seeds were not good, there were water shortages, animals were eating plants, etc. These problems were worse than we originally expected". Furthermore, political instability in Burkina Faso reduced the geographical scope of the possible intervention by project team members. One contextual factor mentioned by Case 2 was the bureaucracy of the Cuban administration, which delayed the delivery of air-pollution-measuring equipment. Poor American–Cuban relations also limited the free mobility of American researchers who wanted to participate in one of the project events in Cuba. Getting Cuban permission to use American parts in the technology was less problematic but equally important. Red tape and administrative work at EPFL related to project management was also cited as a contextual burden. To overcome these problems, the team members allowed their project to be flexible in time, content, and methods by adopting an adaptive management approach. The academic member on one of the projects said: "This flexibility is mandatory when working in developing countries. We needed a year or more to buy and send the equipment from Switzerland to Cuba. We had to permanently adapt the schedule to meet objectives". Adaptive management was not just a tool to adjust the time frame to the necessary changes but also to adapt the methodology during implementation, and, as the non-academic of the project put it: "We were not applying a strict established methodology but rather a methodology that was developed with practice as needs arose". This confirms that transdisciplinary research projects have a strong need for flexibility and adaptive management. The joint work of science and practice requires the acceptance to readjusting research questions and methods due to unexpected changes in the political environment or the needs of the practitioners [4,61]. Interviewees from Case 1 said: "More time should be provided during implementation if needed, and the project-planning timeline should be more realistic". Since TD involves working with different type of actors in particular contexts, the knowledge-integration process sets its own pace according to the actors involved and the realities of the local context. This adaptation is important in terms of achieving the expected outcomes. Wuelser and Pohl [4] say that, in transdisciplinary research, adaptive management that allows for flexibility is key to maximizing the potential societal benefits of scientific endeavors.

4.6.5. Common Language

Developing a common language, which is crucial to translating and bringing together the different disciplinary forms of knowledge and approaches of the main stakeholders, arose as a structural burden for Case 1. As stated by Binder et al. [73], communication requires time, and linguistic adaptations need to occur in order to fulfill both the needs of science and of practice. Interestingly, the challenge here was to bring the different disciplines together rather than achieve a common understanding between stakeholders. As the academic member mentioned: "Finding a common language among disciplines was far more challenging than the issue of bringing academics and non-academics from Switzerland and Burkina together". She found that ensuring a good level of communication between team members and improving it systematically during implementation played a decisive role. This confirms that, in any transdisciplinary project, sufficient attention has to be given to language choice and communication [28,62]. Also, and as previous research suggests, communication issues have the tendency to intensify during time pressure and should thus be planned for [10,11].

4.6.6. Transdisciplinarity Definition and Approaches as a Challenge

Other issues that arose from the experiences of the projects provide a general view of the difficulties in implementing TD. In Case 4, the academic member said that one important challenge was trying to define a project a priori as transdisciplinary. Within the framework of the project, there was no conscious effort to work in a transdisciplinary way. Even though the team included experts from different disciplines (e.g., architects, anthropologist, sociologists, etc.), no attempt was made to integrate the different disciplinary methods into the research and work on real-world problems. There was no common position on TD, and the team did not even mention TD; they only talked about interdisciplinarity. For the non-academic member, it was important to emphasize the need for instruments or tools to enhance the connection, the communication, and the participation of academic and non-academic members as well as tools that could help to develop a network of transdisciplinary knowledge and practice.

The academic member of Case 3 also identified as a challenge the notion that TD is an implicit and hidden process that many follow but nobody talks about. Therefore, from a pragmatic point of view, donors and institutions should more explicitly request TD and consider it when deciding budgets, evaluating teams, and, at an institutional level, by creating TD programs. If TD remains an implicit topic, all stakeholders will continue to regard it as inconsequential. Additionally, transdisciplinary processes are still unspecified and time-consuming. Given that the existence of funds to implement TD is minimum, team members "will continue to focus on implementation as usual" unless donors explicitly ask for TD. North–South partnerships in transdisciplinary research may provide another layer of difficulties if donors restrict funding for the participation of Northern or Southern institutions. According to the academic member of Case 3, the conditions of the academic system incentivize scientists in the South to imitate and follow research agendas from countries in the North. As Schmidt and Pröpper [13] mention, the donor's influence over the transdisciplinary research process from its conception onward greatly determines the discourse on structural challenges throughout and the possible reproduction of North–South asymmetries and dependencies. Restricted funding schemes for TD may be caused by different factors, and this may lead to various limitations. One of these factors could be the restricted knowledge that funding programs and institutions may have on TD. A further factor is that faced by program managers when trying to design and implement structures and processes that enable the production of TD within research-funding programs [75,76]. To overcome this, Schneider et al. [76] developed a model with 10 relevant key stages to enable successful TD research within funding programs.

Moreover, there is a dichotomy between what the donor requires and what a transdisciplinary research project should be. In Case 5, the academic member referred to specific packages and deliverables that the EU framework program demanded, which might not have necessarily corresponded to the flexibility required by TD: "It is hard to follow TD within the EU framework". Furthermore, researchers viewed a lack of feedback upon project completion as a limitation on bridge building with other stakeholders interested in these subject areas. According to team members, there was uncertainty as to whether the donor obtained what it needed and about how the other EU team members approached the real-world problem. Furthermore, the potential but unanticipated costs geared towards a random financial control by the EU impacted one of the small enterprises, which absorbed all these costs rather than sharing them with other team members and institutions. Such a requirement was included in the agreement with the donor. However, small enterprises may find it more difficult than larger ones to implement these checks, thereby making the small enterprise's work even more difficult.

4.6.7. Project Evaluation

A general lack of transdisciplinary research project evaluation culture or know-how can explain the lack of continuous formative evaluation. Although Scriven [77] defined formative evaluations over 40 years ago in development projects, their implementation only began a few years later [78]. Historically, in science, peer reviews have mainly conducted quality assessments that are mostly based on an assessment of standards that account for the scientific discipline's culture and rules. Discipline-specific standards are limited in carrying out transdisciplinary project evaluations, because such standards do not consider integrative aspects of the research activities or their results. Also, the context of transdisciplinary research makes it challenging to establish TD-centered traditions, specific criteria, methods, and quality standards [54].

4.6.8. Identified Opportunities

Some opportunities surfaced during project implementation in the form of positive results that were not anticipated at the outset. In Case 1, three of these are worth highlighting. Firstly, the creation of a constructive partnership with the School of Agricultural, Forest, and Food Sciences (HAFL) in Switzerland, which was not involved at the start, ended up being advantageous for the project, as this opened new, fruitful research avenues. Secondly, the project got institutional actors in both Switzerland and in Burkina Faso interested in technologies developed by EPFL that could help local society. Thirdly, the technology attracted the attention of industrial actors due to its high commercialization potential and its social impact. The non-academic member said: "We should be able to develop automatic irrigation stations adapted to local producers and commercialize these through local enterprises to increase production and the income of the local population".

In Case 2, the research generated some unexpected opportunities. Firstly, the project enabled the creation of new partnerships, specifically between American and Cuban researchers, who plan to launch joint projects and education programs in the future. The expansion of networks and the intense increase in existing collaborations is an important outcome of transdisciplinary research, as mentioned by previous studies [59]. Secondly, the initial seed funding came about as a catalyst for team building, identifying the problem, and finding partners' complementarities, while also being used to test the partnership. There was conflict among team members during the preparatory phase, and this meant that they were better prepared for any potential conflicts during the project itself. The academic member said: "It was important to clarify the roles and tasks of every partner before starting; once this was discussed, everything was clear". Thirdly, the opportunity to offer significant evidence for policy making to address a real-world challenge is something that reassures the researcher and the importance of the science–policy interface. It is thus essential to take the views of all the members involved throughout the project into consideration. As the non-academic member put it: "Especially in a project like this one, as we are trying to provide evidence for decision making, decision makers must be integrated into the team". As both the Cuban and the European partners were using the methodology and making recommendations, they integrated the results into scientific practice. However, in terms of generating policies, the potential impact of the project depends on how policy actors handle the results, and this is no longer the task of the researcher. Ideally, the proposed methodology will help to produce solutions related to energy consumption, which is very relevant for society. This points to the knowledge integration process embedded in transdisciplinary research, which includes the process of making the results useful for both scientists and societal actors. While mainly the former seeks new knowledge, empirical evidence, and advancements in methods and theoretical discussion, the latter view the results as contributing to solving societal problems [10,11].

In Case 3, the mutual trust between team members who had worked together in the past was an advantage and triggered opportunities at institutional and structural levels during project implementation, as this encouraged systematic flows of communication and information and transparency from both sides. However, circumstances that were external to the context in which the project was being implemented could have hindered these advantages, as shown in Case 4. Here, the team's advantage in terms of working in countries and with partners or universities that it had successfully collaborated with previously was obstructed by the specific political situation of some of the countries where this project was being implemented (namely, Venezuela and China). In the case of Venezuela, given the political situation in the country, the non-academic member had to participate in the project as an independent consultant rather than as a researcher within a university, and this created important implementation challenges for the project. In the case of China, collaboration was difficult because of state control about who is authorized to collaborate and who is not. As argued by Scholz and Steiner [61], this points to the need of sufficient institutional backing given to academic and non-academic members in transdisciplinary projects, meaning they are well integrated into their respective organizational structures and supported in their objectives through them. One positive contextual factor mentioned relates to the country where the project originates—Switzerland—which is considered to be politically neutral and a reliable partner, an image that allows research cooperation with most countries. Finally, the fact that the academic member views social actors (citizens and dwellers) as non-academic "experts" helps to foster an authentic recognition and integration of the different knowledge, just as the ideal practice of TD requires.

In Case 5, the positive results the project obtained while working with universities and other stakeholders in a transdisciplinary manner were seen as opportunities, and, as the non-academic member stated: "The experience of working in a transdisciplinary project was very positive, as TD helps to bring knowledge and define new products".

5. Conclusions and Recommendations

With regard to the extent to which the reviewed projects adhered to the proposed transdisciplinary research framework, we conclude that the five projects adhered, at least partially, to most of the principles of the framework compiled and used during our study. However, the information of a project that adheres to eight rather than eleven of the twelve principles may simplify the discussion to an undesired level, and it may even take some merit away from projects on the basis of a number. As Lang et al. [11] argue, these frameworks should not be understood "as a recipe applicable to any given context" (p. 40). Neither Lang et al. [11] nor Luthe [14] provide a minimum number of principles that a project should adhere to in order to be considered successful in transdisciplinary terms or transdisciplinarity at all. Accordingly, it is not the intention of this paper to rank the projects according to their level of TD but rather to observe their adherence or not to specific transdisciplinary principles in order to identify and assess common challenges and overall knowledge and practice of TD over the course of the projects.

Although our study did not set out with the objective to assess the validity of Luthe's [14] complementary principles vis-à-vis Lang et al.'s [11] TD framework and principles, we found that adding Luthe's complementary principles to Lang et al.'s TD framework helped provide further information to understanding the challenges and the experiences of TD projects, thereby increasing the lessons obtained that could be disseminated to help TD proponents. While the framework certainly has its limitations, from the examination of these five projects, we could not identify further principles that could be added. However, this study helped us identify various key issues for the discussion and the practice of transdisciplinary research that were not included in the framework, such as the importance of identifying possible negative effects of transdisciplinary projects or the definition of the different types of team members, as previously mentioned.

We can offer various observations in response to the question of how useful an analytical framework based on design principles to examine transdisciplinary research projects can be. In the implementation of transdisciplinary research projects addressing challenges related to sustainable development, analytical frameworks with design principles can be practical tools for assessing the effectiveness of integrating a broad range of stakeholders in the process of knowledge generation [62]. However, gathering information through analytical frameworks is not sufficient in terms of studying transdisciplinary dynamics, as Lang et al. [11] show. The use of this particular analytical framework with design principles to examine these five projects highlights three points. Firstly, no matter how fully or partially the transdisciplinary principles have been met according to the current literature, all projects can claim to be transdisciplinary projects in terms of outcomes and processes. Secondly, through interviews with two project team members, all projects show that the two members rarely define TD in the same way. It is likely that interviewing all the team members would result in even larger discrepancies within each project without compromising the project's overall level of TD. Thirdly, the definition of TD varies, and the interpretation of the definition largely influences project design and implementation. Of the five examples studied above, a large part deals with subjectivity and what is considered to be a priority principle within TD.

The team members of the projects observed believed that their projects were explicitly transdisciplinary, but they did not necessarily agree openly at the outset regarding the transdisciplinary methods and tools to be applied during implementation. We can therefore say that TD was conducted in a mostly implicit manner in these projects. When asked about their definitions of TD, and notwithstanding their differences, the narratives resonated in one way or another with our operational definition and the main elements entailed in this type of research. The importance of integrating several disciplinary domains and methods and the utility of the research in solving a specific problem were aspects that stand out in their understanding. However, the integration of academic and non-academic knowledge in a space in which various actors contribute and benefit from was somewhat less present.

In agreement with other authors [2,10,11,14,79,80], we believe that mainstreaming evaluation practices in TD research projects is needed. As a specific recommendation and standard evaluation practice within development evaluation, we find it imperative to include the assessment of anticipated and unanticipated negative effects and not just anticipated and unanticipated positive effects of TD projects. Understanding potential negative effects during TD project design will help teams address risks and propose more realistic mitigating activities.

We struggled during our study to select and use a more encompassing definition of the different types of team members convening during design and implementation of transdisciplinary projects. We noticed that even the transdisciplinary literature refers to "researchers" and "scientists" on one side and "stakeholders", "practitioners", "non-scientific actors", or "extra-academic members" [11,13,14,48] on the other. We believe that defining academic members as the only "scientists" and "researchers" encourages power asymmetries and disregards non-academic contribution to knowledge creation in TD projects. If co-development of knowledge is a premise of TD projects, a more legitimizing definition of the types of team members and their roles should be used. For us, as for some of the team members we interviewed, non-academic members produce knowledge and therefore are also scientists and researchers. On the other hand, academics may as well be seen as practitioners when finding solutions to "real-world" challenge-focused projects.

The observed projects provide a good example of the importance of integrating different methods and expertise to address crucial issues for sustainable development. They also show how the approach and the practice of TD depend on the context in which research is carried out and on the organizational structure established for its implementation. As with collaborative research, the participation level and the designation of roles amongst those involved in the project shape the relational space in a particular manner [13,48,55]. Both academic and non-academic members in general viewed the experiences gained during the implementation of their projects in a positive light and interestingly did not refer explicitly to the potential problems linked to the lack of joint co-leadership arrangements on a level playing field.

For projects developed through a North–South partnership, the dynamics of transdisciplinary research increase complexity and challenge researchers and experts involved. We observed that the factual implementation of transdisciplinary research projects involving various stakeholders is often more difficult than expected and is affected by expected and unexpected contextual, structural, and personal restraint factors [12,51]. These factors may cause deviations from the original work plan and ultimately influence the research impact, thus confirming that, in transdisciplinary research, the joint generation of knowledge entails an iterative reflexive cycle rather than a linear process [11]. In terms of recognition, some researchers feel there is more at stake than funding and publications, as they strive for a constructive collaboration process that might lead to social transformation. However, they often struggle with the rules set by funding agencies that demand a focus on scientific results (only). It would be desirable to have new research governance structures that recognize the importance of transdisciplinary research to tackle real world problems and bring academics, society, and policies closer together through the provision of appropriate funding programs. Funding institutions should make it even clearer that there should be a scientific as well as a social impact in the tangible returns they expect from the projects they support. This will also help overcome the challenge addressing real world problems that is often experienced in the field of sustainability science—the lack of an evident link between the results related to the societal issues and the concrete application of solutions or policies in the short term in the concerned societal context, which we also observed across the five cases of our study (some of which are still not finished).

Our results confirm that, in sustainability science, design principles represent a generic transdisciplinary research process, as argued by Lang et al. [11]. Within such a research process, each stage and principle might take a specific form that reflects the singularities of the transformational character of research for sustainable development, the concrete contexts where research is being implemented, and the particular way in which expertise of both academic and non-academic actors is integrated in each phase.

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Appendix A. Abstracts of the 5 Projects

Case 1: Info4Dourou2.0

The Cooperation and Development Center (CODEV) at EPFL launched Info4Dourou2.0 in 2012 and implemented it until late 2018. It originated from a previous research project dedicated to understanding a watershed basin in south-east Burkina Faso, which had shown the significant potential of networked soil moisture sensors developed to monitor environmental data at low cost, even in (semi-)arid regions [81]. Notwithstanding the interesting research results, the project struggled to have a tangible socio-economic and environmental impact in the field. In order to address this, CODEV implemented Info4Dourou2.0 to test improved irrigation scheduling for smallholders in Burkina Faso [80,81]. It measured soil-matric potential continuously and sent the data to a database via radio waves and General Packet Radio Service (GPRS). When the soil became too dry for the plants (i.e., upon reaching a certain soil moisture threshold), farmers were sent cellphone alarms advising them to irrigate to prevent water stress. The technology is autonomous, robust, and adapted to extreme climatic conditions; local production of the components in Burkina Faso was planned to lower costs and ensure maintenance and accessibility. CODEV tested the technology in Burkina Faso from 2012 to 2018 and in Palestine in 2016. Results showed that improving irrigation scheduling resulted in a 20–80% reduction in water use with simultaneous crop-yield increases of up to 15%, and that farmers expressed interest in adopting this technology [82,83]. Water management in agriculture is a challenge that involves stakeholders from a wide variety of backgrounds. The project brought together partners from public and private sectors, academics, research institutes, and NGOs from the North and the South. Smallholder farmers were actively involved in the project through their roles during the field trials and through the workshops where researchers collected their feedback and suggestions. The main project leader (academic member) was based in Switzerland and acted as facilitator between scientists and farmers. The project manager based in Burkina Faso (non-academic member) reported to the project leader. Swiss private and public donors funded the project.

Case 2: "Effective Methodology for Assessing Integrated Energy Strategies"

The project "Effective Methodology for Assessing Integrated Energy Strategies" brings integrated decision support tools that can be used in developing countries to improve air quality and energy supply systems. The initial idea came from a young Cuban lecturer who received a grant to conduct research at EPFL on specific problems within the energy and transport sector in Cuba. Motivated by a need to find solutions to minimize the negative impacts of energy use, EPFL researchers and Cuban partners jointly implemented the research, taking the country's available energy resources into account. The goal was to develop a new, integrated assessment methodology for energy strategies, combining process system design methods and emission and air quality models. Cuba is an excellent test case for designing and applying energy transition strategies for developing countries. On the one hand, the climate offers good opportunities for the integration of renewable energy sources. On the other, the US embargo has dramatically affected the island's energy supply. Authorities are encouraged to improve the country's energy self-sufficiency. The proposed methodology identifies the most encouraging energy supply strategies. It considers economic and environmental costs, and the impact, especially on air quality, in-situ available resources, and energy demands, by combining process system design methods with air quality modeling [84]. The measures to enhance the urban transportation system and improve Havana residents' accessibility to their social and natural resources will ultimately improve their quality of life [project report delivered to the Seed Money Program management at CODEV EPFL (December 2013)]. The project received seed funding from the CODEV Seed Money Program in 2013 and 2014, helping to establish the collaboration between CUJAE (the University of Technology of Cuba at Havana), UNAL (the National University of Columbia in Bogota), EPFL, and several ministries and governmental agencies in Havana and Cuba. SNSF and SDC in Switzerland, through the r4d program, are the main institutions funding the project (http://www.r4d.ch/modules/thematically-open-research/integrated-energy-strategies (accessed on 1 August 2019).

Case 3: Georeferenced Mobile Platform for the Interdisciplinary Study of Socio-Urban Problems in Mexico (UrBis)

The project "Georeferenced mobile platform for the interdisciplinary study of socio-urban problems in Mexico" (UrBis) was created as a technological platform to help people in Mexico, particularly youth, document, characterize, and reflect on socio-urban difficulties. The platform supports an integrative approach that blends mobile crowdsourcing, social technologies, and community practices to develop potential solutions through the effort of citizens [85]. The project was built on an initial research project, SenseCityVity, funded by the Seed Money Program of CODEV. SenseCityVity was developed to implement a multigenerational framework to study urban awareness of different population groups living in three cities in central Mexico. The key idea was to integrate the collective action of individuals ranging from youth to senior citizens with existing participatory sensing, social media, and crowdsourcing technologies; to document and scientifically quantify the perception of these urban environments; to reflect upon sustainable urban development challenges defined by the communities themselves; and to foster social cohesion across populations. The proposed multigenerational framework used to study urban awareness provided a rich tableau of the urban environment of important cities of central Mexico. The insights about the socio-urban problems detected in these cities were key to designing concrete solutions to address such problems. The project also enabled additional funding from the Mexican government to develop state-of-the-art technology to apply this methodology at a larger scale. The research also revealed the need to design new strategies to apply crowdsourcing-based methodologies that are sustainable in ways that can be continuously used to achieve long-lasting impact (taken from final report of SenseCityVity project submitted to CODEV Seed Money Program, dated 15 January 2015).

UrBis was funded by CONACYT Mexico, was led by IPICYT (the San Luis Potosi Institute of Scientific Research and Technology), Mexico and it was jointly implemented by CIDE (the Center for

Research and Teaching in Economics) and Centro Geo in Mexico, and LIDIAP-EPFL in Switzerland. The Swiss partner did not receive any funds.

Case 4: Hybrid Cities. Informal Forms of Resistance to the Violence of Urbanization in China, India, and Venezuela

The formal planning of territory at the expense of informal settlements within contemporary urbanism often involves forms of violence, as informal settlements often violently resist their scheduled deletion. In some cases, this confrontation overcomes the duality between formal and informal. The confrontation of two icons of the modern city, the informal slum and the formal skyscraper, produces hybrid structures, objects, and details that move towards a new urbanism. This process creates an innovative and critical approach to the modern models of formal urbanization that seems to persecute the inhabitants of informal settlements, giving rise to resistance movements. The Hybrid cities project is a collective effort born from previous collaboration among researchers from EPFL and researchers in Venezuela, China, and India, with the interest of studying the often-unseen processes in habitat production in three large urban areas simultaneously—Chennai in India, Guangzhou in China, and Caracas in Venezuela—as separate expressions of a global and complex process. This project considers the phenomenon of population expulsion from cities that started in the 1970s and subsequently the evolution in the mid-1990s and the early 21st century towards political organizing to reclaim the right to the cities built in an effort to overcome these expulsion forces. The study examines how these practices contribute to the understanding of the city from a regional justice perspective and also from the innovation that the population produces in the construction of cities. The project was funded by CODEV Seed Money initially and then by SNSF, and it had a duration of three years. It brought together researchers and other actors from EPFL and Instituto de Estudios Avanzados and Fundación Caracas and counted with the participation of the South China University of Technology in Guangzhou, Anna University in Chennai and the University of Hong Kong.

Case 5: Protection of Critical Infrastructure against Electromagnetic Attacks

Security and quality of life in industrialized countries depend on continuous and coordinated performance of a set of infrastructures [energy systems, information and communications technology (ICT) systems, transportation etc.], or "critical infrastructures" (CI). The project "Protection of critical infrastructure against electromagnetic attacks" aims at analyzing possible effects of electromagnetic (e.m.) attacks, and, in particular, the e.m. of intentional interference (IEMI) on such CI's, thereby assessing their impact on our defense and economic security. It identifies innovative awareness and protection strategies and provides a picture for policy makers on the possible consequences of an electromagnetic attack. The project responded to the concern of many European countries and was financed by the EU 7th Framework Program. It was designed and implemented by a consortium of universities [(University of Applied Sciences of Western Switzerland in Yverdon; University of York, UK; Helmut Schmidt Universität, Germany; Leibniz University, Hannover; Bergsche Universität Wuppertal; University of Twente in Netherlands; Instituto Superior Mario Boella, Italy, Politecnico di Torino)] and the private sector [(Montena Technology SA and Rheinmetall Waffe Munition GmbH and Ingenieria dei Sistemi (IDS)]. Navigate Consortium of Italy managed the project. The project originated from previous relevant work conducted jointly by the partners and funded by the Seed Money Program of CODEV-EPFL.

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