Transdisciplinary Research to Solve Complex Public Health Problems:

Identifying Unique Outcomes in Two National Institutes of Health-funded Transdisciplinary Initiatives

Sarah Hohl

A dissertation

submitted in partial fulfillment of the

requirements for the degree of

Doctor of Philosophy

University of Washington

2019

Reading Committee:

Beti Thompson, Chair

Paul A. Fishman

Marian L. Neuhouser

Joseph M. Unger

Program authorized to offer degree:

Health Services

University of Washington

Abstract

Transdisciplinary Research to Solve Complex Public Health Problems:

Identifying Unique Outcomes in Two National Institutes of Health-funded Transdisciplinary Initiatives

Sarah D. Hohl

Chair of the Supervisory Committee

Beti Thompson

Member, Cancer Prevention Program, Public Health Science Division

Associate Director for Minority health and Health Disparities Emeritus

Fred Hutchinson Cancer Research Center

Professor Emeritus, School of Public Health, Department of Health Services

University of Washington

Background: In research and academic institutions, health problems are commonly examined within the confines of a single discipline. Yet, a combination of various biological, genetic, social, and environmental factors influences public health problems, including obesity, cancer, cardiovascular disease and health disparities. In this setting, it is necessary to involve transdisciplinary teams—those with a wide range of disciplinary expertise who must often work across operational, disciplinary, and institutional boundaries—to holistically understand the complexities of public health problems and their solutions. Transdisciplinary collaborations can comprehensively address complex public health challenges by examining all facets of the health domain from basic biology to public health impact. Transdisciplinary research methods are relatively new to public health, and although conceptual frameworks have been developed for transdisciplinary research that addresses environmental problems, none have been adapted or developed for transdisciplinary public health research. The overall goal of the proposed research is to investigate the field of transdisciplinary research for public

health challenges using as our model two NIH-funded initiatives, the Transdisciplinary Research on Energetics and Cancer (TREC) and Centers for Population Health and Health Disparities (CPHHD) initiatives.

Methods: This dissertation utilizes a multi- and mixed-method approach to assess contexts and outcomes of transdisciplinary research in two center grant initiatives funded by the NIH between 2010-2016. First, I employed a sequential mixed-method approach that involved a web-based survey, semi-structured interviews, and focus groups to establish collaborative transdisciplinary outcomes and assess perceptions of the public health impact of the outcomes among participating investigators in the TREC initiative. Second, I used longitudinal quantitative survey data collected from TREC investigators four times over a 5-year period to assess changes over time in attitudes towards and behaviors that promote transdisciplinary collaboration. I used linear mixed models with fixed and random effects to assess how changes differed by career stage and primary discipline. Third, I used a multi-method parallel convergent study design and applied constant comparative analysis to document data and semi-structured interviews to compare context and outcomes between TREC and CPHHD.

Results: In 2014, twenty-three invited TREC members completed a web-based survey and 26 participated in a semi-structured interview. Investigators described nine outcomes they perceived to result from their transdisciplinary collaborations in TREC: 1) new transdisciplinary team and consortia formation; 2) integrated theoretical framework development; 3) multi-level intervention model development and testing; 4) development and adaptation of relevant statistical models; 5) translation of findings across levels of influence; 6) public policy influence; 7) transdisciplinary manuscript publication; 8) transdisciplinary grant awards; and 9) training the next generation of transdisciplinary researchers. Although the outcomes identified were similar to those expected from non-transdisciplinary approaches, they are distinguished by their involvement of team members representing diverse disciplines, reliance on integrated theoretical frameworks, and a social-problem-oriented focus. In

2011-2015, between 57 (2015) and 78 (2011) TREC investigators completed a survey regarding behavior and attitudes towards collaborative transdisciplinary research. Transdisciplinary orientation, interpersonal collaboration, participation in collaborative activities scale scores increased at a constant rate across disciplines and career stages over time. Compared to senior career investigators, early career investigators had significantly lower scores on transdisciplinary orientation, interpersonal collaboration, and participation in collaborative activities. In 2015-2016, 51 TREC and CPHHD investigators participated in a semi-structured interview. Multiple and similar transdisciplinary outcomes emerged from the efforts of TREC and CPHHD investigators, but the nature of those outcomes and the contexts that supported them differed between initiatives. Interview and document analyses revealed two thematic areas six sub-themes. The thematic area *culture shifts* includes three sub-themes: *scientific community awareness, institutional commitment*, and *collaborative partnerships and sustainability*. The thematic area *integrative and innovative products* also includes three sub-themes: *integrated theoretical frameworks, multilevel models*, and *transdisciplinary training.*

Conclusion: The comprehensive set of transdisciplinary outcomes established in this dissertation, combined with the understanding of attitudes, behaviors, and contexts that influence transdisciplinary collaboration offer the public health research and practice community three tools to advance transdisciplinary research. First, the work proposes a conceptual framework for planning and evaluation of transdisciplinary research to address public health problems. Second, it demonstrates the diverse data sources and analytic techniques that can be used to evaluate such initiatives. Finally, it provides evidence regarding how and where to invest in and prioritize resources in a transdisciplinary initiative for the greatest potential of achieving desired outcomes.

Table of Contents

Acknowledgements and Dedication

This work was supported by NIH grants U01 CA116850. Sarah Hohl was also supported by NIH grant T32 CA092408, Biobehavioral Cancer Prevention and Control Training Grant, and the Patrick-Beresford Fellowship in Social Epidemiology.

I would like to thank my dissertation chair, Dr. Beti Thompson, who took a chance on me eight years ago when she hired to me manage the TREC Evaluation Core, and who has opened infinite opportunities for me since. I am also grateful for my committee members, Drs. Marian Neuhouser, Paul Fishman, Joseph Unger, and Shirley Beresford for their support, motivation, expertise, patience, and wisdom. I brought each of you on to my committee to question my work, ask me difficult questions, and challenge me to grow as a scholar. Thank you for doing just that.

This work would not have been possible without all the TREC, CPHHD, and NIH members who participated, or the program administration staff who expertly herded cats for me. Thank you.

I am grateful for my family and friends who have known just the right time and way to listen, to hug, to be silent, and to urge me forward during the long slog. We made it!

Chapter 1. Introduction

1.1 Background

Classical theorists, philosophers, physicists, engineers, and critical scholars have used transdisciplinary research to investigate complex societal issues (1-4). More recently, in response to the recognition that valuable knowledge generated from monodisciplinary research has not resulted in expected population health benefits, health scientists have adopted transdisciplinary approaches to address multifactorial health challenges like cancer and chronic disease (5-8). Transdisciplinary research, which integrates concepts from multiple disciplines—represents a promising approach to pressing, complex health problems such as cardiovascular disease and cancer, two leading causes of death in the U.S. (9). Rosenfield is attributed to bringing the approach to health research in the early 1990s, suggesting that health research requires an approach that not only draws on expertise from multiple disciplines, but also integrates methodological approaches drawn from these disciplines. The transdisciplinary approach aims to move beyond the limits of individual disciplines by purposefully mixing concepts from two or more disciplinary fields. Its purpose is to both create new knowledge *and* solve societal problems (4, 10-12).

No single accepted definition of transdisciplinary research exists, nor does a shared lexicon exist to describe it. **Table 1.1** illustrates the diversity of definitions and descriptors offered by global scholars from a range of scientific backgrounds including health sciences, agriculture, environment, technology, and sociology. Despite these differences, there is consensus about certain features of transdisciplinary research. Scholars agree that transdisciplinary research differs from other cross-disciplinary approaches in its more explicit integration of theories, frameworks, and methodologies, innovations in study questions and designs, and prioritization of research translation and implementation. Most descriptions of transdisciplinary research also state that this approach focuses on problems that are complex, multi-factorial, and relevant to society; lack a single, prescribed methodology; and require both integration

and collaboration. Stokols and colleagues' definition of transdisciplinary research guided both the development of my conceptual model and the framework for this dissertation. They define the transdisciplinary research approach as:

> *…an integrative process whereby scholars and practitioners representing different disciplines work jointly to develop and use novel conceptual and methodological approaches that synthesize and extend discipline-specific theories, methods, and translational strategies to yield innovative solutions to a particular scientific and societal problem* (13).

In the US and abroad, public agencies have funded transdisciplinary research programs to address the individual, interpersonal, environmental, and socio-political causes of chronic disease and health disparities. For example, the Transdisciplinary Tobacco Research Centers (TTURC) funded by the National Cancer Institute (NCI) and the National Institute on Drug Abuse was a transdisciplinary research initiative designed to understand, investigate the effects of, and reduce tobacco use (14, 15). The Transdisciplinary Research on Energetics and Cancer (TREC) and Obesity-Related Behavioral Intervention Trials (ORBIT) initiatives, funded by multiple National Institutes of Health Programs and Centers, were charged with integrating disciplinary approaches to understand and address factors related to obesity (5, 16). The Centers for Population Health and Health Disparities (CPHHD) was a transdisciplinary initiative funded by the NCI, National Institute of Environmental Health Science (NIEHS) and the National Heart, Lung, and Blood Institute (NHLBI). CPHHD grantees collaborated with communities to understand and address disparities in social determinants of cancer and cardiovascular disease (8, 17). Transdisciplinary teams outside of the U.S. have also worked to address social problems by aiming to reduce poverty, improve housing standards, slow climate change, and address a variety of environmental issues (18-26).

Published studies that have evaluated and described these initiatives describe some team processes of conducting transdisciplinary research and characteristics of transdisciplinary collaboration, such as its nature of being integrative, comprehensive, collaborative, and time intensive (27, 28). This

work also highlights challenges of transdisciplinary research conduct that include conceptual and scientific differences among investigators and academic systems that do not incentivize or support transdisciplinary research (29, 30) . The fields of economics, public policy, and environmental science have grappled with both processes and outcomes of transdisciplinarity (31-34). However, to our knowledge, no investigation has been conducted to propose outcomes of transdisciplinary research that addresses public health problems, nor has any study examined how transdisciplinary attitudes and behaviors change over time among investigators who participate in transdisciplinary research initiatives.

In a 2003 study, Stokols and colleagues developed a conceptual model of transdisciplinary science based on the TTURC initiative, in which they called for more comprehensive depictions of transdisciplinary research to promote new knowledge and improve population health (35). Since that effort, multiple subsequent transdisciplinary initiatives have been funded. Consequently, the evidence base of transdisciplinary research conduct and its evaluation efforts have grown. The goal of this dissertation is to build on early investigations to advance the knowledge base and expand the field of transdisciplinary research complex public health problems. To do so, we utilize multiple data sources and analytic approaches to develop, illustrate, and test constructs of a conceptual model of the determinants and outcomes of transdisciplinary research approaches.

1.3 Conceptual model of transdisciplinary research

Figure 1.1 illustrates the conceptual model of transdisciplinary research that guided this dissertation. It is influenced by Hall et al.'s Conceptual Model for Evaluation of Collaborative Initiatives (36), Stokols' model of Transdisciplinary Scientific Collaboration (35), Carew and Wickson's Transdisciplinary Wheel (37), a review of theoretical literature on transdisciplinary research, and publications resulting from grant-funded US transdisciplinary public health initiatives. The model posits that the problem focus, i.e., the topic area that a research endeavor aims to address, can assist in determining whether transdisciplinary research is the appropriate approach. Our model also proposes

that transdisciplinary research efforts are collaborative and that the desired long-term goal is societal impact. Based on these features the model posits that the ***problem focus*** and ***institutional resources and organizational structure*** influence ***collaboration characteristics***, which, in turn influence ***outcomes*** of transdisciplinary research (18, 19, 28, 35, 36, 38-44). Because considerable previous efforts have focused on describing the determinants of transdisciplinary research, this dissertation provides a more extensive discussion of how those determinants have influenced achievement of transdisciplinary research outcomes in US-based transdisciplinary initiatives. We also describe the relationship across the outcomes and their contribution to societal impact.

1.3.1 Problem focus

Transdisciplinary scholars emphasize that the ***problem focus*** of any transdisciplinary research effort must reflect a societal interest (4, 13, 20) and aim to both create new knowledge and develop concrete solutions (4, 13, 20, 45). At the initiative level, the problem focus represents the general topic area that a research endeavor aims to address. At the project level, the problem focus may be the specific research question under investigation. Accordingly, investments in the transdisciplinary initiatives explored in this dissertation (i.e., TREC, CPHHD)) focused on improving health outcomes and disparities related to cancer and obesity, and cardiovascular disease. In this model, the problem focus shapes achievement of transdisciplinary outcomes and subsequent societal impact through development of teams and consortia and collaboration characteristics.

1.3.2 Transdisciplinary research determinants

In our model of transdisciplinary research approaches, determinants are factors that promote or inhibit achievement of transdisciplinary outcomes. Specifically, **institutional resources and organizational structures** such as coordinating mechanisms, grant structure, administrative capacity, advisory boards, geographic proximity, and leadership are key determinant. The existence or lack of these structures—and the nature of their operation—shape **collaboration characteristics**—including

team composition, collaborative capacity and processes, and participation in transdisciplinary activities which act as mechanisms for achieving transdisciplinary outcomes (35, 38-41). For example, a team's geographical proximity and coordinating mechanisms may also influence a team's capacity to collaborate (36, 46) and increase social networks (43, 47). Furthermore, coordination mechanisms, such as the funded coordination center in the TREC initiative, that bring teams together—either virtually through technology or in-person–increase opportunities for communication, collaboration, and innovation (36, 48-50). Leadership at the initiative, research center, and project team level also influences collaboration characteristics. Specifically, leaders' emotional and intellectual intelligence, content area knowledge, and their ability to foster trust among team members is associated with team effectiveness (51, 52). Effective leadership in transdisciplinary initiatives is characterized by a commitment to transdisciplinary collaboration and cooperation, provision of infrastructure for such interactions to occur (28, 52) and creation of environments in which team members are encouraged to exchange ideas (42).

1.3.3 Transdisciplinary research outcomes

The conceptual model illustrates nine ***transdisciplinary research outcomes*** influenced by institutional and organization resources through collaboration characteristics: 1) transdisciplinary teams and consortia, 2) integrated theoretical frameworks, 3) multi-level intervention models, 4) adapted statistical and analytic models, 5) translation across levels of influence, 6) public policies, 7) transdisciplinary publications, 8) transdisciplinary grants, and 9) transdisciplinary training programs. These outcomes represent a range of intellectual, institutional, and societal products that result from a transdisciplinary research approach. The model proposes that considering the multiple influences on social problems requires the formation of **teams and consortia** with a range of disciplinary expertise. Such ancillary consortia can grow the awareness and value of a transdisciplinary approach, mobilize diverse stakeholders to translate research into practice and policy, and foster long-term collaborations

that foster innovation, creativity, and sustainability. Transdisciplinary teams' composition evolves to respond to the respective research needs and project foci, and these teams work together to develop **integrated theoretical frameworks**, that is, frameworks that bridge concepts from multiple disciplines (10, 20, 53, 54). The novel frameworks established for transdisciplinary projects can guide the development of new **multi-level intervention models** designed to target proximal, intermediate, and distal causes of public health problems. Moreover, integrated theoretical frameworks and multi-level intervention models necessitate **adapted statistical and analytic models** that can make sense of the complex data generated from transdisciplinary projects. Monodisciplinary projects typically consider variables acting at a single level of influence (e.g., the influence of dietary changes on obesity). Statistical models relevant for transdisciplinary projects, by contrast, must consider variables acting at multiple levels of influence. Transdisciplinary teams possess both scientific and practical expertise and can thus speed **translation of findings across stages of research**, from basic science to intervention and policy development to improve population health. Transdisciplinary teams are equipped to holistically tackle the complexities of public health problems and to inform **public policies and** programs that contribute to their solutions. These teams are poised to inform evidence-based policies, as they can bring the diverse expertise necessary to navigate the policy process (55). Findings from transdisciplinary research can also inform policies to improve population health (56). **Publishing research findings** in peer-reviewed journals and securing new **grants** are outcomes that are not unique to transdisciplinary research. However, the involvement of teams of individuals with differing disciplinary backgrounds *and* the development and use of integrated theoretical frameworks differentiate these outcomes from those of non-transdisciplinary efforts. For example, prior transdisciplinary evaluation activities considered the levels of analysis and number of co-authors representing different disciplines as indicators of how well a grant or manuscript was integrated across disciplines (57). Previous work has demonstrated higher overall publication rates from center-initiated and transdisciplinary projects compared to investigator-

initiated, often single-discipline projects (58). Transdisciplinary initiatives with a coordination center and leaders with previous experience guiding transdisciplinary centers also demonstrate higher publication rates than those without (43). **Transdisciplinary training programs** are fundamental to educating the next generation of transdisciplinary researchers. Such programs generally target early career investigators but can train investigators and collaborators at all career stages to use transdisciplinary approaches to confront population health problems. These programs have been distinguished from other training programs by the number of disciplinary fields from which mentors are drawn, the training in analyzing multiple levels of influence, and degree of solving problems relevant to society (57, 59).

1.2 Specific aims

In the three studies of this dissertation, I use the conceptual model presented above to assess and evaluate context and outcomes of transdisciplinary research in two NIH-funded transdisciplinary center grant initiatives.

1.2.1 Specific Aim 1: Establish transdisciplinary outcomes based on the TREC experience.

Study 1 aimed to establish transdisciplinary outcomes based on the TREC experience. In this multi-stage mixed methods study I utilized a web-based survey (n=23) and semi-structured interviews (n=26) to establish a comprehensive set of outcomes of transdisciplinary research and to assess their relevance to solving public health problems. I hypothesize that TREC investigators will articulate outcomes of transdisciplinary research beyond those traditionally recognized in research settings such as publications, presentations, and grants.

1.2.2 Specific Aim 2: Test the association between career stage and primary discipline and change in transdisciplinary attitudes and behaviors over time.

Study 2 uses longitudinal survey data to 1) assess changes over time in transdisciplinary behaviors and research orientation among investigators who participated in TREC; 2) assess how change varies by career stage and primary

discipline. We fit a Linear Mixed Model with fixed and random effects to test the hypothesis that changes in attitudes and behaviors varied by career stage and discipline.

1.2.3 Specific Aim 3: Compare contexts and transdisciplinary outcomes of TREC and CPPHD

. The aim of this multi-method parallel convergent study is to compare transdisciplinary outcomes across two NIH-funded transdisciplinary initiatives, TREC and CPHHD. The study uses data from TREC and CPHHD Requests for Applications (RFAs), scientific meeting agendas, and project abstracts, as well as in-depth interviews with initiative investigators. I applied constant comparative analysis to document data and semi-structured interviews to assess how context and outcomes were similar or different between TREC and CPHHD.

The results of this research will offer a unique contribution to public health research and researchers seeking to integrate disciplinary perspectives to solve complex public health problems. A more comprehensive grasp of transdisciplinary research will in turn enhance approaches to solving complex public health problems. By developing and empirically substantiating a conceptual framework for transdisciplinary public health research, this work will provide a tool to envision, design, implement and evaluate the quality and success of transdisciplinary research. Finally, it will help facilitate assessment of the value of transdisciplinary approaches to resolving complex public health problems and promoting gains in public health.

Figure 1.1. Conceptual model of transdisciplinary determinants and outcomes

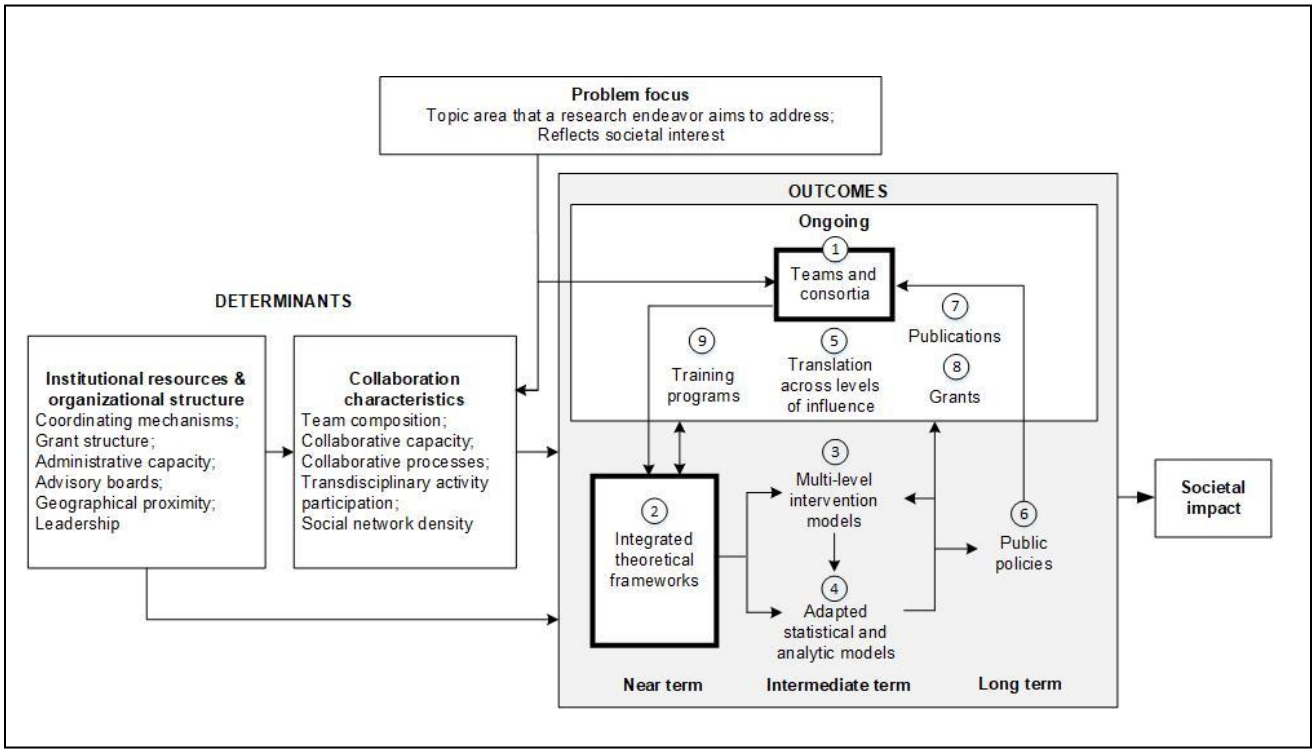


Table 1.1. Transdisciplinary research defined: Examples from the literature

(Jantsch, 1972)	"the coordination of all disciplines and interdisciplines in the education/innovation system on the basis of a generalized axiomatics (introduced from the purposes level) and an emerging epistemological pattern"
(Rosenfield, 1992)	"a project in which researchers from different fields [...] work closely together on a common problem over an extended period [...] create a shared conceptual model of the problem that integrates and transcends separate disciplinary perspectives"
(Flinterman et al., 2001)	"systematically, explicitly, and deliberately integrating knowledge from different scientific and nonscientific sources"
(Balsiger, 2004)	“problem oriented, theory guided, methodologically driven…goal is to satisfy public interests”
Wickson et al., 2006	"multiple research approaches critiquing and deconstructing one another to develop an evolved methodology"
Pohl and Hadorn, 2008)	"scientific disciplines and sectors of the real-world are getting interrelated and are transformed”
(Russell et al., 2008)	"as a practice that transgresses and transcends disciplinary boundaries […] with potential to respond to new demands and imperatives."
(Stokols et al., 2013)	“an integrative process whereby scholars and practitioners representing different disciplines work jointly to develop and use novel conceptual and methodological approaches that synthesize and extend discipline-specific theories, methods, and translational strategies to yield innovative solutions to a particular scientific and societal problem.”

Chapter 2. "Innovation happens at the intersections of disciplines." Transdisciplinary research outcomes based on the Transdisciplinary Research on Energetics and Cancer (TREC) II Initiative experience

2.1 Abstract

Public health problems are influenced by multiple and interacting biologic, social, behavioral, and environmental factors. The dominant strategy to addressing these problems relies on monodisciplinary methods. Dynamic research approaches in which transdisciplinary teams of scientists collaborate beyond traditional disciplinary, institutional, and geographic boundaries have emerged as promising strategies to address pressing public health priorities. Transdisciplinary research is conceptualized as yielding unique outcomes given its novel and collaborative nature where research teams develop and use new methods outside their immediate area of expertise. However, little prior work has attempted to identify and characterize the outcomes of transdisciplinary research undertaken to address societal issues as upstream factors associated with health. We used a multistage mixed methods framework to identify and explore outcomes of transdisciplinary research using the Transdisciplinary Research in Energetics and Cancer (TREC) II initiative as a case example. A survey of TREC II investigators and trainees identified nine initial transdisciplinary outcomes that were further refined using interviews and focus groups. The final transdisciplinary research outcomes, whose relevance to addressing complex societal problems affecting health we describe using the TREC II experience, included: 1) new transdisciplinary team and consortia formation; 2) integrated theoretical framework development; 3) multi-level intervention model development and testing; 4) development and adaptation of relevant statistical models; 5) translation of findings across levels of influence; 6) public policy influence; 7) transdisciplinary manuscript publication; 8) transdisciplinary grant awards; and 9) training the next generation of transdisciplinary researchers. Although the outcomes identified were similar to those expected from non-transdisciplinary approaches, they are distinguished by their involvement of team members representing diverse disciplines, reliance on integrated theoretical frameworks, and a social-

problem-oriented focus. These transdisciplinary outcomes could guide inquiry about the value added to research to public health research using a transdisciplinary approach.

2.2 Introduction

Solutions to public health problems require consideration of the biologic, behavioral, social, and environmental factors that interact to shape health and disease (10, 58, 60). Transdisciplinary research approaches that break down disciplinary, institutional, and geographic barriers have emerged as promising strategies for addressing such problems (8, 10, 58, 60-63). The Transdisciplinary Research on Energetics and Cancer (TREC)—a National Cancer Institute (NCI)-funded initiative from 2005-2016—exemplifies this approach. TREC integrated social, behavioral, clinical and basic sciences to examine relationships among obesity, nutrition, physical activity, and cancer and proposed novel interventions to reduce the obesity burden (5, 64).

The transdisciplinary research process is conceptualized as yielding expanded outcomes relative to traditional research models that are grounded in single disciplines (10, 34, 35, 37, 65, 66). Outcomes of the transdisciplinary research process serve to enrich the ultimate scientific outcomes of research investigations. For example, Stokols and colleagues identified five outcomes of transdisciplinary research based on their evaluation of the Transdisciplinary Tobacco Use Research Centers (TTURC) initiative: *professional validation, collaboration, scientific integration, communication*, and *health impacts* (35). *Scientific integration*, specifically, represents the creation of new theoretical and methodological frameworks that bridge two or more disciplinary perspectives (35). Carew and Wickson developed an adaptable outcomes framework for transdisciplinary projects that address social and environmental problems. Their work emphasized *mutual learning,* in which transdisciplinary collaborators' perspectives are challenged and transformed through transdisciplinary collaboration (37). Mitchell and colleagues proposed a framework for transdisciplinary projects that seek to create change to address societal challenges, including those relevant to public health problems; they identified three

transdisciplinary outcome domains: *aiming to improve a given situation*, *creating new knowledge*, and *fostering mutual and transformational learning* (34). Others have described characteristics of transdisciplinary collaboration, suggesting that it is *integrative*, *comprehensive*, *collaborative*, and *time intensive* (11). Prior empirical work has also demonstrated the increased quantity and degree of integration of peer-reviewed publications (58), growth in researchers' social networks (67), and enhanced transdisciplinary competencies and scholarly productivity among trainees resulting from transdisciplinary collaborations (68). Establishing clearly defined outcomes of transdisciplinary research could facilitate measurement of those outcomes, and ultimately, evaluation of the success of this approach.

Few studies, however, have attempted to develop a comprehensive set of transdisciplinary research outcomes and no prior work has focused on outcomes of transdisciplinary research undertaken to specifically address public health problems. To address this gap, we use a multistage mixed methods framework to identify and characterize outcomes of transdisciplinary research and describe its relevance in addressing complex public health problems using the TREC II initiative. We define transdisciplinary outcomes as *the conceptual, intellectual, institutional, and societal products that result from application of a transdisciplinary research approach*. These outcomes are distinguished from those of single and cross-disciplinary research approaches by the disciplinary integration they reflect and their specific goals to address complex societal problems.

2.3 Methods

TREC background. In 2005, NCI established the Transdisciplinary Research on Energetics and Cancer (TREC) initiative, a transdisciplinary, cooperative center grant mechanism in energy balance and cancer. The initiative was designed to promote transdisciplinary science by providing funding for a coordination center, allowing for within- and cross-center pilot grants and coordinated initiative-wide working groups. Known as TREC I (2006-2010), NCI, four research centers, a centralized coordination

center, and NCI program staff comprised the initiative. From 2011-2016, NCI funded four new research centers and the same coordination center; this was named TREC II, which has been described elsewhere (5, 29, 69). TREC II is the focus of this report. Briefly, in addition to 3-5 integrated research projects (each with project leader(s)), each TREC II center was required to support administrative, training, biostatistics, research support cores and pilot project cores. The TREC II Coordination Center included an evaluation core whose goal was to facilitate integration and evaluation of the transdisciplinary research conducted across the initiative. The evaluation core sought to build on NCI evaluation efforts in the TREC I initiative (30, 36, 68, 70) by engaging TREC II members in the initiative's evaluation. Engagement occurred through ongoing qualitative interviews, targeted presentations and activities during TREC II scientific meetings, and the convening of a cross-center Collaboration and Outcomes Working Group. A central goal of both the evaluation core and the working group was to determine, characterize, and ultimately to measure transdisciplinary research outcomes.

2.3.1 Research Phase I: TREC II member engagement.

Table 2.1 illustrates the purposes, methods, and products of the study's three phases. In phase one, evaluation core members synthesized literature on transdisciplinary research, existing transcripts of interviews with TREC II investigators conducted in the first year of the initiative, and program documentation (e.g., meeting notes, RFAs, grant proposals). Evaluation results were presented to the Steering Committee, which included TREC II Center Directors, the TREC II Coordination Center Director, and NCI scientific leaders— for discussion and approval. TREC outcomes included: 1) formation of new cross-and within-center collaborations; 2) building awareness of the transdisciplinary approach; 3) multi-level models; 4) new statistical models; 5) translation; 6) public policy influence; 7) transdisciplinary manuscript publication; 8) transdisciplinary grant awards; 9) training the next generation of transdisciplinary researchers.

2.3.2 Research Phase II: Web-based survey.

We used an explanatory sequential mixed methods approach in which we first administered a brief web-based survey to TREC II members to determine whether a larger sample of TREC II members agreed with the transdisciplinary outcomes identified in Phase I. The survey included 14 yes/no questions to identify investigators' perceived involvement in activities related to the nine transdisciplinary outcomes identified in Phase I. The survey did not include questions about influencing policy or forming new collaborations because the Steering Committee identified these areas as *a priori* essential outcomes of transdisciplinary research warranting qualitative follow-up. TREC II Center Directors were asked to identify a random stratified sample of investigators who represented Project Leaders, Core Leaders, and Trainees (e.g., doctoral students and post-doctoral fellows) to complete the survey. All Center Directors, Co-Directors and Project Managers were also invited to complete the survey. Trainees who participated in a focus group were not invited to complete the survey, as the focus group sought to explore trainees' range of experiences in a transdisciplinary program and not to obtain in-depth information about specific outcomes outside of training. Survey data were uploaded into Excel to calculate summary statistics.

2.3.4 Research Phase III: Interviews and focus groups.

We expanded on the results of the web-based survey using semi-structured interviews with TREC II investigators and focus groups with TREC trainees (e.g., postdoctoral fellows, graduate students). Specifically, we developed a semi- structured interview guide containing a bank of 30 questions. Questions aimed to elicit 1) TREC II members' perceptions of how they had achieved each transdisciplinary outcome; 2) whether that outcome was relevant to addressing complex public health problems; and 3) what, if any, additional outcomes might result from transdisciplinary research approaches. We used individual interviewee's responses to the web-based survey to select specific questions from the question bank for each interview. For example, if a participant had responded positively to having contributed to an outcome in the survey, she or he received directed questions to probe for deeper description of that outcome. We designed the focus

group guide to determine TREC II trainees' goals and expectations for participation in a transdisciplinary initiative, what they perceived as unique aspects of mentorship in a transdisciplinary initiative, and their perceived competence at addressing societal problems using transdisciplinary research approaches. A trained member of the study team conducted interviews and focus groups in person. All TREC II investigators and trainees who were invited to complete the web-based survey were also invited to participate in an interview. All participants were recruited via email, provided written consent, agreed to be audio-recorded, and received a $20 gift card for their time. Study procedures were approved by the Fred Hutchinson Cancer Research Center IRB.

Individual and focus group interviews were professionally transcribed. Each transcription was checked for accuracy, de-identified, and uploaded into Atlas.ti (Version 8) for coding and analysis. We first reviewed all transcripts, then applied a directed content analysis to characterize, summarize examples, and determine the relevance of the proposed transdisciplinary outcomes to solving complex public health problems (71). We sought to determine if and where revision of the proposed outcomes—and their conceptualization—was necessary by developing a list of pre-determined codes that included each of the nine proposed transdisciplinary outcomes and a general code "relevance" to describe the outcome's relevance to solving public health problems. Two coders performed axial coding (72), in which they first applied the initial set of codes to the same five interviews, then met to discuss interpretations, assess inter-coder reliability, add sub-codes, and refine the codes as needed. Coders consulted with the larger study team throughout the coding process, resolved issues of disagreement through group discussion, and built consensus on quote interpretation and emergent themes. This process clarified the "new research methods and models" outcome and leading to two new codes reflecting "integrated theoretical framework development" and "development and adaptation of new statistical models." Additionally, a new code was created to reflect the outcome "new transdisciplinary team and consortia formation", which encompassed the original "new cross- and within-center

collaborations" and "building awareness of the transdisciplinary approach". Finally, all participants received a report of findings from interviews and focus groups conducted at their center. Participants were invited to provide feedback, such as additional interpretations. Members of the TREC II Steering Committee and Collaboration and Outcomes Working Group also had the opportunity to discuss qualitative findings and provide alternative explanations and interpretations.

2.4 Results

Between January and February 2014, 23 (88%) of invited TREC II members completed the web-based survey; 26 (100%) invited members participated in a one-on-one interview; and 23 (74%) invited TREC II trainees participated in one of four focus groups (**Table 2.2**). Interviews and focus groups lasted approximately one hour (range: 48-75 minutes). Based on survey results, directed content analysis, and study team review, we refined the original outcomes resulting in the nine described in **Table 2.3**. **Table 2.4** provides additional quotes from study participants representative of each outcome. All investigators were asked to discuss public policy outcomes and consortia-building. Interview questions and focus groups included questions about training. Thus, these sections of the results include more extensive reporting.

2.4.1 Outcome 1: New Transdisciplinary Team and Consortia Formation

Respondents said that one critical outcome of funded transdisciplinary teams is that connections formed have led to long-term collaborations between researchers representing multiple and often disparate disciplines that otherwise would not have occurred. They said that transdisciplinary teamwork fosters innovation and creativity from study design to implementation, analysis, and dissemination that has implications for real world application. A human behavior researcher reported that adopting transdisciplinary approaches to science:

> *makes you think about things in a way you normally wouldn't. I find when I talk to basic scientists or investigators who work with mice that [we] approach the question in different ways and I think it helps for a better outcome in terms of a research question.* (Participant 4103)

The collaboration of TREC II's four research centers, a coordination center, and NCI enabled investigators to draw upon resources and expertise across the initiative. Several investigators, such as below, described their experiences as team members in a cross-center development project, in which each site contributed uniquely to the success of the project:

> *Our site's expertise is that we had an ongoing cohort study [with…] participants who were very likely to adhere to study protocols […and…] expertise in the GIS side, in terms of layering on spatial information. At [another institution] they had a lot more experience with accelerometry and GPS in very small studies and cleaning that data. [Investigator] at [institution] is a world expert in physical activity research. And then, [institution] has a lot of expertise in GIS and other kind of novel objective measures too. So [this team] definitely expanded our reach in terms of measures into areas that were not within the expertise at this site*. (Participant 4240)

Investigators reported that transdisciplinary team science has the capacity to extend to a much wider audience than does monodisciplinary teams. They reported utilizing opportunities to present in new settings, where they were able to share results from their disciplinarily integrated studies and develop connections with investigators outside of the initiative. Senior investigators related that for transdisciplinary consortia "to be relevant to the community", institutions—not necessarily individuals—should engage those outside the research institution in their work, and specifically have an "*obligation to communicate results and broader implications back to stakeholders, which at some level are the taxpayers*." (Participant 4100) An investigator noted that center's focus on involving diverse stakeholders to achieve greater public health impact:

> *We're again bringing in people who have not thought about interacting with other investigators the way we're doing now. The other thing is, we're trying to disseminate the work by research papers, but also editorials and other kind of writing that leads to transdisciplinary thinking and trying to inform the community about different ways they could have an impact, you know, giving them examples of how we've done it, how they can have an impact that might be larger than what their individual discipline is giving them. (Participant 4450)*

2.4.2 Outcome 2: Integrated Theoretical Frameworks

The teams and consortia formed as a consequence of TREC II provided investigators with the diverse expertise to think about public health problems in new ways. Participants reported that these teams propelled them to develop new theoretical frameworks that bridged multiple conceptual domains. These frameworks guided and unified individual research projects as part of each TREC II center. A senior investigator commented that center's framework, "*If we push hard enough, [the framework] gets us to integrate all the projects across the whole of our center. And that has everyone thinking at new levels [about how to] model obesity and cancer risk and outcomes across a life course*." (Participant 4100) Another investigator described his center's multidimensional framework that was designed to "have direct public health and clinical relevance" on healthy aging. He explained, "[*The] unified framework […] is bridging basic science, epidemiology, and clinical research*." (Participant 4200) A trainee who participated in a cross site pilot project described a framework the team developed to "*integrate measures of physical activity, sedentary behavior, sleep, [and] location," anticipating that subsequent frameworks could "layer on other spatial data, [like] air pollution, so that we can build more personal measures of air pollution […] green space […] and land use data*." (Participant 4240) This information could then help inform an intervention model to target multiple levels of influence on obesity and related health problems. Another investigator noted that "TREC and the collaborative itself has really opened the doors to improving the comfort level of approaching [new] groups." Specifically, this investigator had connected with researchers with expertise in obesity, public health nutrition, behavior change, community health, and geospatial analysis to address the relationship between sleep and obesity among children. Their collaboration led to the development of a "*conceptual framework to broaden our sense of what are some mechanistic pathways*" between sleep and obesity. (Participant 4220)

2.4.3 Outcome 3: Multi-Level Intervention Model Development and Testing

TREC II investigators noted that transdisciplinary interventions should be designed to address multiple levels of influence on health outcomes. One approach by which TREC II researchers addressed energetics and cancer was by developing, implementing, and evaluating multi-level intervention models. Such models consider a range of individual, interpersonal, organizational, community, and policy-level factors. Several investigators cited the importance of applying evidence from observational studies to inform multi-level interventions. To that end, investigators across centers had obtained both internal and external funding to translate the findings of TREC II observational studies into the development of interventions. They noted that development of multi-level intervention models and their implementation arose from projects within their individual centers and through cross-center pilot projects and working groups. At one center, investigators developed an intervention to determine the extent to which exercise and/or weight loss affects breast cancer-related lymphedema outcomes among survivors, and what, if any, economic benefit resulted. A basic scientist, a behavioral interventionist, and an expert in emerging technology who had met through TREC proposed a project to reduce extended sitting time among older adults, a serious risk factor for cancer and chronic disease. Their multi-level intervention model addressed individual factors such as behavior change and community-level factors such as altering work environments. Representing what one investigator described as "a whole other area of new interactions of interdisciplinary work," they planned to assess biomarker response, racial/ethnic differences, and objective measures of movement based on tracking device data.

2.4.4 Outcome 4: Development and Adaptation of Relevant Statistical Models

Investigators said their involvement in transdisciplinary research projects propelled them to consider the value of developing and adapting statistical models to analyze associations, interrelationships, and mutual influence between biological, genetic, environmental, social, and behavioral factors. TREC II members noted the initiative requirement that each research center include a biostatistics core served as an invaluable resource in advancing their transdisciplinary research. They

reported that statisticians within and across TREC II research centers challenged investigators to ensure they used appropriate statistical methodologies, to analyze their data in new ways, and to apply statistical models in new ways. Statisticians reported that having access to other statisticians working on similar topics of cancer and energy balance was a new experience attributable to the collaborative structure of TREC. Sharing ideas with statisticians across TREC II Centers prompted a deeper understanding of measurement of complex variables. Investigators recognized that while some statistical approaches might not be new, their application in the realm of cancer and energetics research was unique; thus, an investigator reported "*I'm not sure they're novel statistical designs, but they're new for us, which is exciting*." (Participant 4306) As an example, in one study, statisticians developed a bio bridge design in which multiple imputations were used to examine biomarkers as intermediate endpoints for a randomized controlled trial to predict and prevent breast cancer recurrence. Another statistician described that team's approach to addressing the correlated error inherent with diet self-report and the lack of biomarkers for puberty. Investigators said that applying adapted statistical models yielded discoveries that advanced their understanding of complex problems and positioned them for future cross-disciplinary collaboration. In one study, a clinician investigating the effect of maternal diet on prostate tumor proliferation in male mice teamed with a population health biostatistician who was:

> *shocked that we had so few animals […] so he came up with this new Bayesian model to look at our data. […] When he looked at the different variables, obviously, maternal diet made a big difference on proliferation, but the second most important thing was the number of male mice in the cage. The more mice that were in the cage, the more likely the mice were to get the hyper proliferation as opposed to the mice that were either housed singly or just with one other mouse.* (Participant 4120)

In this example, the biostatistician's contributions to the team revealed unique results that the others asserted they otherwise would not have known. These unanticipated results catalyzed future collaborations and novel research questions.

2.4.5 Outcome 5: Translation of Findings Across Levels of Influence

Although few investigators reported having taken part in research to translate animal studies into human studies and vice versa, some interviewees identified evaluating and applying findings across the translational continuum from biomedical to clinical to policy as an essential outcome of transdisciplinary research. At one TREC II center, investigators in psychology, animal research, biomarkers, exercise science, behavioral interventions, health disparities, and endocrinology at all career levels proposed a project to translate findings about fasting, circadian rhythm, and breast cancer risk from a mouse model into a human observational study. They sought to determine if nightly fasting among Latinas and non-Latina white women may predict similar outcomes of inflammation and insulin resistance, which are associated with increased breast cancer risk. One project investigator noted that this work:

> *could translate immediately into public health guidelines. You should have a fasting period at night […] so you don't disrupt your circadian clock. Right now, we really have no evidence-based guidelines for like meal frequency or timing. […] Assuming it is replicable, it's straight to guidelines.* (Participant 4300)

A senior investigator described the primary research projects and ancillary projects at their TREC II Center as part of a systems science modeling approach. Biological data from animal and human models, data from intervention studies, and data from studies of the built environment would contribute to a broader exploration of where to intervene to reduce cancer risk. This investigator referenced the integrated theoretical model that guided work at that TREC center, relating "*our center challenge is to bring it to the, if you will, the integration of the center rather than leave the projects as disparate activities*." (Participant 4100) Another investigator emphasized the value of transdisciplinary teams' consideration of the full translational continuum to maximize public health impact.

2.4.6 Outcome 6: Public Policy Influence

Investigators agreed unanimously that a central role of research is to build the evidence base to inform policy. They said the nature of transdisciplinary collaboration specifically in TREC facilitated a drive to make systematic, structural policy changes. This investigator illustrated this concept, stating:

> *There's this hole in the middle of our efforts to try to actually change things. The investigators who are building the evidence base build the evidence base and stop. The public health people focus on changing policy and stop. The physicians focus on applying the best evidence that they can without actually changing their infrastructure and stop. The health services people are focused on high level changes. Transdisciplinary researchers say, 'We have a new evidence base. How do we change the clinical infrastructure?'* (Participant 4100)

Participants were cognizant of the ethical challenges of using preliminary evidence to inform policy, citing the amount of time it takes to conduct studies and test evidence as one challenge to influencing public policy. They noted that their exposure through TREC II to diverse research, community, and government stakeholders who had expertise in dissemination and implementation propelled them to think critically about the societal implications of their work and specifically, "*how public policy works […] so we are not overclaiming what we might be able to do with what we've discovered in our work*." (Participant 4330) Senior investigators described their engagement in policy development, recommendations, and advocacy through their membership and contributions to location and national boards, working groups, and advising bodies, in which they provided technical insight into evaluation methodology, or presented evidence in their area of expertise. At one center, investigators were able to develop guidelines and public policies ranging from removing sugar sweetened beverages from school cafeterias, informing school start times based on children's need for sleep, and developing a federal policy on affordable housing, all of which may impact later risk of obesity and cancer. Although junior investigators did not report membership on boards or guideline committees, they recognized the importance of engaging with those outside of research and academic institutions, ideally during study design, to "*understand what challenges they face, and what's realistic, so that my research can be as*

applied as possible." (Participant 4102) Investigators at all stages acknowledged the relevance of their role as researchers in policy, as this investigator expressed, *"…the research and the policy […] is all part of a continuum. You can't have the policy changes responsibly without the research behind it*." (Participant 4421) Another investigator highlighted the complexity of determining and involving the relevant stakeholders to inform policies: "*Physical activity policies come from an area that isn't strictly physical activity in nature, or health in nature. […] You really need the education sector and the transportation sector involved to make that work. […] There's a whole economic aspect*." (Participant 4110) These stakeholders were seen as critical to developing appropriate conceptual frameworks whose application could eventually guide policy efforts. Investigators described multiple challenges of engaging in policy work as academic researchers. Investigators perceived conflicting expectations of transdisciplinary researchers and university policies. Some investigators noted that while policy work is inherent in transdisciplinary research, it is seldom rewarded in academic institutions and not emphasized in many degree programs; thus, investigators are not equipped with the tools to translate the relevance of their work to audiences outside of research institutions. Senior investigators perceived a shift in universities in which the role of policy researchers was becoming more important as researchers are held accountable to funders. "*There's this spectrum of people who have the skills and get them over time and others who thought epidemiologists shouldn't talk about policy. Those days, I think, are disappearing.*" (Participant 4100)

2.4.7 Outcomes 7 and 8: Scholarly Productivity—Transdisciplinary Manuscript Publication and Transdisciplinary Grant Awards

Respondents recognized that publications and independent research funding, while not unique to transdisciplinary research, are the accepted benchmarks of successful research. They did, however, describe two major challenges: first, identifying journals that would favorably review and accept transdisciplinary publications (i.e., those reflecting multiple disciplines), and second, finding the additional time required to collaborate across disciplines, departments and institutions to develop

integrated frameworks and implement projects, analyze results, and disseminate and translate findings. Investigators described a collaboration across TREC II centers to develop new grant applications that addressed multi-level components of the impact of exercise and weight loss on breast cancer co-morbidities like lymphedema. This cross-center team designed a study to examine whether racial/ethnic disparities in severity and progression of lymphedema result in higher costs for minority group members This effort relied on a framework that integrated biological, community, and economic theory that investigators said was made possible through TREC II collaborations. One investigator described the process of convening researchers with diverse expertise and a unifying interest and developing a grant application to address health disparities in breast cancer. This investigator perceived this practice as different from non-transdisciplinary approaches based on the project's focus to create a framework that linked theories and expertise from multiple disciplines. The framework could inform a multi-level intervention to improve disparate breast cancer outcomes.

2.4.8 Outcome 9: Training the Next Generation of Transdisciplinary Researchers

Trainee focus group participants said transdisciplinary research requires new skills, such as working in cross-disciplinary, often dispersed teams, and developing novel conceptual models and analytic approaches with an overall goal to yield public health impact. Thus, they underscored the importance of preparing investigators to conduct this type of work. Each TREC II research center was required to support an Education and Training Core. In addition, TREC II supported a Training and Education Working Group that spanned the initiative and was led by an investigator from the Coordination Center. Trainees said these opportunities facilitated their career development and built a sense of community across investigators from different departments and disciplines at their institutions. These relationships led to productive research and mentorship collaborations that trainees said positioned them to both understand multiple levels of influence on obesity and cancer and to determine where to intervene to improve population health. One trainee commented, "*Every project that I work on*

is a team approach. It's not just me and my mentor working on something, but we involve people from all different levels [of science] that are like a mini group of experts." (FG4300)

Senior investigators emphasized the importance of leveraging TREC II human and financial resources to facilitate growth among trainees. To that end, proposals involving trainees were prioritized for pilot project funds. Trainees across all centers recognized the value of having access to those funds and their corresponding research opportunities. One trainee reported, "*If you have an idea, if somebody's excited about a new project, it's actually feasible to figure out how to make it happen. […] There are funds specifically dedicated to our development and developing new ideas*." (FG4400) Another participant reflected on the value of having access to data from multiple projects across the TREC II research centers, saying, "*Since TREC has been going on for some time now there's data available across sites that as a trainee you have access to. If we're interested, we're welcome to join in [analysis and manuscript writing]*." (FG4200) Trainees said that as TREC II members, they benefitted from mentorship with experts that spanned disciplines from basic science to population health. A mentor summarized the importance of training scholars to pursue transdisciplinary research, despite the difficulties such training may present.

> *Most innovation happens at the intersections—not in the center—of disciplines. In the center of disciplines is repetition. You do what you know, what your mentor did. If you really want innovation, you have to be at an intersection, an interface. These days, doing what you did just isn't sufficient. You just cannot come in with incremental science anymore. You've got to come in with something new. […] There's not a good future for very, very generally unidisciplinary research, especially in human research.* (PD4300)

2.5 Discussion

In this study, we applied a multistage, mixed method approach to establish, define, and characterize a set of outcomes of the transdisciplinary approach based on TREC II perspectives. This process resulted in nine final outcomes: 1) new transdisciplinary team and consortia formation; 2) integrated theoretical framework development; 3) multi-level intervention model development and testing; 4) development

and adaptation of relevant statistical models; 5) translation of findings across levels of influence; 6) public policy influence; 7) transdisciplinary manuscript publication; 8) transdisciplinary grant awards; and 9) training the next generation of transdisciplinary researchers.

Although publishing manuscripts and securing grants is always a desired outcome, the quality and magnitude of disciplinary integration distinguishes transdisciplinary manuscripts and grants from other cross-disciplinary and monodisciplinary approaches. Conducting bibliometric analysis is an objective approach to measuring growth in publications. The Transdisciplinary Tobacco Use Research Centers (TTURC) evaluation team proposed quantitative measures (i.e., number of disciplines represented, levels of analysis, number of disciplines represented by co-authors) to assess the degree of integration of a publication or grant (57). Furthermore, transdisciplinary initiatives with a coordination center and leaders with previous experience guiding transdisciplinary centers demonstrated higher publication rates than those without (43). Similarly, translating findings from observational studies into interventions could also be a goal of monodisciplinary approaches. However, TREC II investigators emphasized the importance of developing and testing interventions that target multiple levels of influence on energy balance and cancer, an endeavor best undertaken by teams of scientists representing biological, genetic, behavioral, and social sciences.

Despite utilizing different approaches, some of our outcomes overlap those proposed by others who explored the outcomes of the transdisciplinary approach. For example, Carew and Wickson's (37) and Mitchell and colleagues' (34) presentations of transdisciplinary outcomes emphasize "mutual and transformational learning" that occurs for participants in transdisciplinary projects. Stokols and colleagues identified "scientific integration," an intermediate outcome area that includes transdisciplinary integration, methods, and scientific models; they described policy implications, health outcomes, translation to practice and improved interventions as aspects of a long-term "health impacts" outcome (35). Our investigation revealed that the teams and consortia formed through TREC II relied on

"mutual and transformational learning" among teams to develop integrated frameworks. The formation of these teams and frameworks served as the foundation for all subsequent outcomes described by TREC II members and distinguished these outcomes from other research approaches. Respondents in our study added to the "interventions" outcome proposed by Stokols by stating that improved interventions that result from a transdisciplinary approach necessarily address multiple levels of influence and focus on accelerating translation from basic science to clinical practice and policy.

TREC II participants also proposed distinct outcomes, such as forming consortia and influencing public policy. They emphasized the importance of bridging academic disciplines, political stakeholders, and community partners as a means of sustaining programs that aim to improve public health outcomes. Because this work is time consuming and can potentially rely on extensive resources, transdisciplinary investigators must be appropriately trained to partner and collaborate across both academic disciplines and community sectors and be supported by their university's administrations. Although awarding transdisciplinary grants is the decision of funding agencies, these decisions are influenced to some extent by investigators' ability to take advantage and build awareness of the approach. Investigators from all career stages said that replicable, repeated evidence generated from transdisciplinary research should necessarily inform policies, and that transdisciplinary research teams are ideally equipped to become engaged in policy processes. However, while some mid-stage investigators reported that they were experienced in translating evidence into practice, they were unsure which avenues to take to translate such findings into public policy. Early career investigators particularly reported not having the support, training, or skills to engage in policy work, representing an area of further consideration for incorporation into transdisciplinary training programs.

2.5.1 Limitations

We made multiple and diverse attempts to characterize the experience and perspectives of TREC II investigators at all levels and corroborate findings regarding transdisciplinary outcomes. However, the

data only represents those who participated in the study and may not be representative of the entire TREC II initiative. Furthermore, the experiences of TREC II investigators may differ from investigators in other transdisciplinary initiatives. Thus, further research should investigate if and how such outcomes may pertain to other transdisciplinary initiatives, and what factors may constrain or facilitate their achievement.

2.5.2 Conclusion

The nine refined transdisciplinary outcomes described in this work contribute to our understanding of the relevance of transdisciplinary research for addressing complex public health problems. Although the outcomes identified overlap somewhat with those expected in non-transdisciplinary approaches, they are distinguished by the involvement of team members who represent diverse disciplines, reliance on integrated theoretical frameworks, and the explicit goal to address a societal problem of interest. These transdisciplinary outcomes can serve as a starting point for assessing the value added by transdisciplinary research approaches.

Table 2.1 Research phases, purposes, methods used, and products generated

Phase	Purpose	Method	n	Analytic Approach	Product
1	Propose outcomes of TD research	TREC steering committee session on evaluation	10	Content analysis of meeting notes	**9 TREC TD outcomes:** 1| new cross-and within-center collaborations 2| building awareness of the TD approach 3| multi-level intervention models 4| new statistical models 5| translation 6| public policy influence 7| TD manuscript publication 8| TD grant awards 9| TD training
2	Determine which outcomes TREC members perceived themselves to have contributed	Web-based survey among TREC investigators	23	Calculate basic descriptive statistics	Quantitative data on TREC participant engagement in proposed TD outcomes
3	Define and characterize TD outcomes in TREC, based on TREC member experiences	Semi-structured interviews among TREC investigators Focus groups among TREC trainees	26 22	Directed content analysis with axial coding of transcripts, iterative group discussion	**9 revised TREC TD outcomes defined and characterized:** 1| new TD team and consortia formation 2| integrated theoretical framework development 3| multi-level intervention model development and testing 4| development and adaptation of relevant statistical models 5| translation of findings across levels of science 6| public policy influence 7| TD manuscript publication 8| TD grant awards 9| training the next generation of TD researchers

Table 2.1. Research phases, purposes, methods used, and products generated

Phase	Purpose	Method	n	Analytic Approach	Product
1	Propose outcomes of TD research	TREC steering committee session on evaluation	10	Content analysis of meeting notes	**9 TREC TD outcomes:** 1| new cross-and within-center collaborations 2| building awareness of the TD approach 3| multi-level intervention models 4| new statistical models 5| translation 6| public policy influence 7| TD manuscript publication 8| TD grant awards 9| TD training
2	Determine which outcomes TREC members perceived themselves to have contributed	Web-based survey among TREC investigators	23	Calculate basic descriptive statistics	Quantitative data on TREC participant engagement in proposed TD outcomes
3	Define and characterize TD outcomes in TREC, based on TREC member experiences	Semi-structured interviews among TREC investigators Focus groups among TREC trainees	26 22	Directed content analysis with axial coding of transcripts, iterative group discussion	**9 revised TREC TD outcomes defined and characterized:** 1| new TD team and consortia formation 2| integrated theoretical framework development 3| multi-level intervention model development and testing 4| development and adaptation of relevant statistical models 5| translation of findings across levels of science 6| public policy influence 7| TD manuscript publication 8| TD grant awards 9| training the next generation of TD researchers

Table 2.2. TREC II research center interview and focus group respondents (n=48)

Interviewees	n
Center Directors/Co-Director	5
Project Manager/Administrative Role	4
Primary Project Investigator or Co-I	11
Pilot Project Investigator	12
Core Leader	6
Early Career Investigator (postdoc or junior faculty)	7
Total interviewees	26*
Focus Groups (n=4)	
Trainees**	22

**Some individuals interviewed hold multiple roles in the TREC initiative. This number reflects the total number of TREC individuals interviewed.*

***TREC members who participated in focus groups self-identified as TREC trainees*

Table 2.3. Relevance and examples of TREC II transdisciplinary outcomes

Outcome		Relevance for solving complex societal problems	Examples of TREC members' achievement of TD outcomes*
1	New transdisciplinary team and consortia formation	Forming consortia that bridge academic disciplines, political stakeholders, and community partners can lead to long term collaborations that foster innovation, creativity, and sustainability. Venues for consortium building may include but are not limited to conferences, symposia, or town hall meetings.	◆ New collaborations established through presentation of transdisciplinary findings at non-TREC scientific meetings, such as American Association for Cancer Research, Dissemination and Implementation, or veterinary conferences ◆ Presented at other academic, research, and/or community institutions ◆ Presented at Medical School Grand Rounds ◆ Hosted institution-wide TREC symposia ◆ Co-hosted joint meeting of two transdisciplinary initiatives, TREC and Centers for Population Health and Health Disparities
2	Integrated theoretical framework development	Frameworks that combine concepts and draw on expertise from more than one discipline guide transdisciplinary research and form the foundation for subsequent outcomes of the approach.	◆ Integrated biological, environmental, and policy data into a systems model to determine obesity and cancer health outcomes across life course ◆ Developed a unified framework of basic science, epidemiology, and clinical research to improve quantity and quality life of cancer survivors ◆ Mixed measures of physical activity, sedentary behavior, sleep, and location to address multiple levels of influence on obesity
3	Multi-Level intervention model development and testing	Multi-level intervention models consider a range of individual, interpersonal, organizational, community, and policy-level factors that influence complex public health problems. Such models follow naturally from a TD approach in that they cover many of the diverse levels of analysis in understanding the interaction between biological, behavioral, and socio-environmental factors.	◆ Tested association between environmental exposures and biomarkers of cancer risk ◆ Tested effect of individual- and community-level intervention to reduce sitting time on obesity and biomarkers of cancer risk ◆ Proposed intervention for mother/newborn dyads to reduce obesity across the lifespan ◆ Tested an intervention delivered at individual, family, and health care system level to reduce obesity through sleep improvement

4	Development and adaptation of relevant statistical models	New statistical methods and new uses for existing statistical methods are required to determine associations, interrelationships, and mutual influence that biological, genetic, environmental, social, behavioral dimensions have on each other and on public health overall.	◆ Applied the method of triads to address correlated error in self-reported dietary data ◆ Developed a bio bridge design in which multiple imputations were used to look at biomarkers as intermediate endpoints for breast cancer recurrence ◆ Determined new applications for the method of triads
5	Translation of findings across levels of science	Transdisciplinary teams comprise investigators and stakeholders who aim to integrate findings from across levels of influence to speed translation from basic science to clinical practice and policy.	◆ Translated evidence from mouse model study to determine impact of nightly fasting on breast cancer outcomes among diverse women ◆ Expected to inform public health guidelines for types of activity needed for optimal health based on integrated SenseCam, GPS, and accelerometer data
6	Public policy influence	Transdisciplinary research approaches champion scientific innovation and discovery. By involving academic and community, and government stakeholders, transdisciplinary teams apply these discoveries through policy changes that impact the public health challenges of concern.	◆ Informed economic savings from behavioral interventions for cancer incidence reduction ◆ Expected public health guidelines for gut rest; resist eating at night to stave off obesity ◆ Informed clinical guidelines to include prioritizing sleep to reduce obesity risk ◆ Proposed public policies to improve environmental influence on physical activity (e.g., sidewalks, safety)
7	Transdisciplinary manuscript publication	Transdisciplinary research is conducted by teams of investigators, which can result in higher publication rates compared to single investigator-initiated research. Publications and grants representative of the transdisciplinary approach exhibit high degree of disciplinary integration. Publications that highlight findings from transdisciplinary approaches raise awareness among the academic community and can lead to greater interest and investment in transdisciplinary research.	◆ Obtained grants to test multi-level components of impact of exercise and weight loss on breast cancer co-morbidities ◆ Obtained funding to examine racial/ethnic disparities in cost based on severity and progression of lymphedema
8	Transdisciplinary grant awards		

9	Training the next generation of transdisciplinary researchers	Complex public health problems such as the relationships between diet, physical activity, and cancer require innovative, integrated scientific solutions. Thus, efforts must be made to train investigators who are able to work across disciplines to develop novel conceptual models and research methodologies, as well as to translate and integrate findings across levels of influence.	♦ Prioritized developmental pilot funds for trainees to forge new research areas ♦ Formed cross-center WGs (e.g., Education and Training) to generate project ideas, encourage interaction, and build trainee TD competency ♦ Provided training in TD research conduct (e.g., disciplinary integration, communication) ♦ Supported cross-disciplinary and cross-institution multi-mentor models for trainee development

**examples provided are representative but not exhaustive of those across the TREC II initiative*

Table 2.4. Representative quotes characterizing TREC transdisciplinary outcomes

Outcome		Representative quotes
1	New transdisciplinary team and consortia formation	*"It is important to showcase the contributions of transdisciplinary projects to other investigators. I've been in so many different venues where I present on the really consistent evidence that we are finding in TREC around sleep and obesity. There are so many different ways that it then triggers another investigator in the room to come up to me and say, 'I'm just beginning a cohort. I hadn't thought about including sleep or including questions about sleep.' And I see that as a direct result of presenting in these national forums and kind of getting the word out, to then have someone in the room, or other researchers in the room, consider adding sleep into their studies." (PPN4220)*
2	Integrated theoretical framework development	*"[The] unified framework […] is bridging basic science, epidemiology, and clinical research. That's [Investigator]'s project on animal models for healthy aging. [...] We have also developed statistical approaches to analyze predictors of healthy aging in large cohort studies. We wanted to identify dietary factors, lifestyle factors and genetic factors for healthy aging. For a clinical component we have a project to look at the effects of physical activity and metformin among cancer survivors, [...] We want to prolong the life of the cancer survivors and improve both the quality and the quantity of their lifespan. [...] This is a relatively novel area that we have developed. (4200)*
3	Multi-Level intervention model development and testing	*The statistical work that was done on our main TREC project [an exercise/weight loss intervention] data previously was done by exercise scientists [with participants] in the lab. […] As an interventionist, a behavior scientist, I think about the data in such a different way […] How might GPS data--the data that puts you in an environment--affect the algorithms and the whole picture? […] So in that way, the neighborhood piece comes into it. [We] have applied machine learning algorithms to free living data, not lab data. The computer scientists [are] not public health people so they haven't thought about collecting free living data either. […] They might have developed algorithms to be able to detect X, Y, Z, but not with a purpose in mind. [We think about how] this algorithm can help somebody do X, Y. (CLN4330)*
4	Development and adaptation of relevant statistical models	*"You have a surrogate measure and gold standard measure of diet, and you have a biomarker, the method of triads. There's a mathematical way of using those three pieces of data to come up with a measurement error correction, even if there is correlated error… So what we've done is take that general concept of the method of triads and find new applications for them. So the fact that it has an application with nutritional epidemiology doesn't mean that there's other areas where it cannot be used. And as long as the statistical principles of the method applies to any other problem, this can be used for any other problem." (CLN4220)*
5	Translation of findings across levels of science	*Transdisciplinary teams "should be mentoring basic scientists in a way that helps us to translate to humans…mentoring human researchers in a way that helps them to understand animal models…training both of those sets of scientists in understanding health policy and changing policy, dissemination science." (4400)*

6	Public policy influence	*"It is a dilemma. When I first started talking about [engaging in policy work], I had very traditional researchers in this university saying, 'that's not for you to do. You're too junior to be thinking about affecting policy. You should be very focused and that's a distraction.'" (PPN4330)*
7 & 8	Transdisciplinary manuscript publication and Transdisciplinary grant awards	*"We've already talked with NIH and NCI about looking at the community, neighborhood characteristics, and cancer outcomes and how they might be related. We're applying for a cross-TREC pilot grant [to gather] preliminary information to look at this. […] The luxury of working with the two different sites [is that] we can look in Philadelphia and in St. Louis and compare across populations to see if there are similarities or not, then move forward into intervention work." (TRN4440)*
9	Training the next generation of transdisciplinary researchers	*"Rather than me try to mentor on something that I'm good at but not a specialist in, I can say 'You need to go talk to [investigator name]'. […] You don't have to be the know-all and end-all of something. You have relationships based on shared scientific questions that make it easy to ensure [trainees] get what they need." (PD4300)*

Chapter 3. Shifting attitudes towards transdisciplinary research: A longitudinal study of collaboration in the Transdisciplinary Research on Energetics and Cancer initiative

3.1. Abstract

Collaborative teams of investigators representing multiple disciplines are increasingly being mobilized to address the multi-level factors that influence complex public health problems like obesity and cancer. Understanding how attitudes towards and behaviors that support transdisciplinary functioning change over time by career stage and discipline is a critical step to understanding which processes may be linked to the long-term health outcomes and impact of the approach. In this study, we report on attitudes and early transdisciplinary behaviors associated with transdisciplinary functioning among investigators participating in the Transdisciplinary Research on Energetics and Cancer (TREC) II initiative. At four timepoints between 2011-2015, we administered a survey consisting of three previously developed and tested scales: 1) Transdisciplinary orientation, 2) Interpersonal collaboration, and 3) Collaborative activities. We employed a linear mixed-effects model to analyze data in which investigators were nested within TREC centers over time. Approximately 80% of invited TREC II investigators who represented eight diverse discipline areas and five TREC centers completed the survey at each of four timepoints. Baseline mean scores for all scales varied across individuals, career stages, and disciplines and increased at a constant rate over time. Trainees and mid-career investigators demonstrated lower mean scores than senior investigators on all scales. Compared to four other discipline categories, investigators in the social-behavioral sciences and public health practice discipline category demonstrated higher mean scores in transdisciplinary orientation and participation in collaborative activities, but lower mean scores over time in attitudes towards interpersonal collaboration. As collaborative activities gain momentum in public health research and practice, empirical evidence about team functioning over time contributes to our understanding of how to

prioritize resources, foster institutional support, and enhance training efforts to promote effective transdisciplinary collaboration that will ultimately improve population health.

3.2. Introduction

Collaborative teams of investigators representing multiple disciplines are increasingly being mobilized to address the multi-level factors that influence complex public health problems like obesity and cancer. Monodisciplinary approaches rely on theories and methods from a single discipline (36), and have made possible robust scientific advances in our understanding of both obesity and cancer. However, with few exceptions, efforts to curb the obesity epidemic in the United States (U.S.) have traditionally addressed a single dimension of the problem, such as administering treatments focused on individual-level behavior change, which have proven unsuccessful in reducing the obesity burden (73). Transdisciplinary research integrates diverse disciplinary perspectives to combine theories, models, and frameworks across disciplines, and represents an alternative approach to solving obesity and other multidimensional public health problems (4, 10, 13, 53, 74). The goal of transdisciplinary science is to create new scientific approaches through fostering intellectual exchanges between disciplines (4, 10, 13, 53), and thus to increase our ability to address complex phenomena like obesity and cancer.

In the last two decades, United States (U.S.) agencies have invested hundreds of millions of dollars to stimulate collaborative transdisciplinary public health research initiatives, such as the Transdisciplinary Tobacco Research Centers (TTURC; 1999-2009) (52), the Centers for Population Health and Health Disparities (CPHHD; 2003-2008, 2010-2015) (8), the Transdisciplinary Research on Energetics and Cancer (TREC; 2005-2016) (5), and the Obesity-Related Behavioral Intervention Trials (ORBIT; 2009-2014) (75). In addition to the overall goal to improve population health, each initiative was required to apply collaborative, transdisciplinary approaches to achieve their respective population health goals. These transdisciplinary centers were funded under the premise that they could comprehensively

investigate and address complex, multidimensional public health problems to build upon scientific discoveries made possible through monodisciplinary approaches.

Transdisciplinary research holds promise for new and more impactful scientific, policy, and public health outcomes. However, these outcomes take decades to emerge and evaluate. Health sciences scholars have grappled with how to evaluate transdisciplinary research for over two decades. This work has resulted in several theories, measurement tools, and identification of outcomes specific to transdisciplinary research (32, 41, 49, 52, 65, 76). Such outcomes may include products such as new collaborations, integrated scientific methods and models, better interventions, and improved communication (49). Identification and measurement of factors that may facilitate achievement of these outcomes across multiple transdisciplinary initiatives is a critical step to understanding which collaborative, transdisciplinary processes may be linked to the long-term impacts of the approach.

Contextual factors, such as the social, physical, and organizational environment in which investigators conduct transdisciplinary research, can influence collaborative capacity and satisfaction (36, 77). Results from year one of the first of two rounds of TREC funding, for example, suggested that the longer an investigator participated in cross-disciplinary projects the more positive their attitudes towards interpersonal collaboration and collaborative productivity (36). Outside the realm of cancer, a transdisciplinary agricultural project that measured collaboration at two timepoints found that attitudes towards collaboration improved from baseline to mid-project for all participants except graduate students (78). This and other related studies offer insight into progress toward the conduct of transdisciplinary research in publicly- funded transdisciplinary initiatives and provide tools to assess that progress in subsequent initiatives like the second round of TREC. Nonetheless, few longitudinal studies of collaborative, transdisciplinary functioning have been conducted, and to our knowledge none has measured change over time across all research centers participating in an initiative.

In the current study, we examine changes in attitudes towards collaboration and participation in collaborative activities over time (five years) between career stages and primary disciplines in the second round of the TREC initiative (2009-2016). Our goal is to extend earlier assessments of transdisciplinary research to further our knowledge of the phenomenon. Understanding how attitudes and behaviors of investigators change over the entire course of the initiative like TREC II can clarify factors that may promote long-term scientific and policy outcomes and public health impact. Such information could inform how and where to direct training efforts and resources to bolster capacity of those involved in transdisciplinary projects to promote achievement of collaboration outcomes, specifically to attitudes towards and behaviors that support transdisciplinary team functioning.

Organizational research has found that improved team processes are key mechanisms for enhancing team effectiveness (79). Evidence that elucidates the interpersonal and intrapersonal attributes and processes by which transdisciplinary outcomes occur is needed. This information contributes to knowledge about how and where to maximize investments in the approach. A clearer understanding of these team and individual factors and how they may change over the course of an initiative will position the research and practice community to better support the goals of transdisciplinary public health research to create new intellectual spaces and improve health outcomes.

3.2.1. The TREC initiative

The TREC initiative was established by the National Cancer Institute (NCI) in 2005 to foster transdisciplinary integration of social, behavioral, and biological sciences to examine the relationships among obesity and cancer (5). Between 2005 and 2010, four research centers and a coordination center were funded to facilitate this mission. We refer to this iteration as TREC I. The same coordination center and four different institutions were funded in a second iteration from 2011-2016. This round of funding, referred to as TREC II, is the focus of the current study.

Each of the four TREC II centers involved investigators from diverse academic disciplines and different career stages in three to four primary research projects over the course of the initiative. Transdisciplinary collaboration across sites was fostered in three primary ways: First, annual funding supported developmental transdisciplinary research projects that involved investigators representing multiple disciplines and, often, multiple TREC sites (Table 3.1). These projects aimed to develop and/or test novel theories, methods, models, or interventions that would contribute to knowledge about the relationship between energetics and cancer. Second, 15 cross-center working groups were convened to address scientific priorities and interests related to cancer and obesity (e.g., collaboration and outcomes, education, health disparities, survivorship, spatial-contextual models). Third, the TREC coordination center aimed to support collaboration to promote the goals of TREC II, including fostering transdisciplinary training and evaluation. The coordination center included five cores: 1) leadership and administration; 2) developmental projects; 3) data and bioinformatics; 4) education and training; and 5) integration and self-evaluation. Prior work by Hall and Stokols and colleagues (35, 36, 48) motivated the inclusion and informed the design of the integration and self-evaluation core for TREC II.

The TREC II coordination center integration and self-evaluation core, in cooperation with the cross-center collaboration and outcomes working group and steering committee, led the evaluation of transdisciplinary research in the TREC II initiative. The TREC II evaluation team used existing tools to assess transdisciplinary processes and outcomes in TREC II and to build upon those tools to create new measurement opportunities. Transdisciplinary research, specifically, requires integration of theories, methods, and frameworks to create a common approach to a societal problem that transcends any individual discipline (10).

3.3. Methods

3.3.1. Survey

This study uses data from a TREC II initiative evaluation survey administered to TREC investigators four times over the five-year period of funding: 2011 (baseline), 2013, 2014, and 2015. Approximately one

year elapsed between waves of survey administration. All investigators participating in the TREC initiative at any one point in time received an email invitation at each time point that contained a personalized link to the password-protected survey hosted on Qualtrics. Investigators who were new to the initiative—for example, those who were awarded developmental project grants or those who replaced departing investigators—were invited to participate upon joining the initiative. The survey took between 20-30 minutes to complete. All study procedures were approved by the TREC Steering Committee and the Fred Hutchinson Cancer Research Center Internal Review Board.

3.3.2. Survey measures

Three scales that measure constructs hypothesized to contribute to transdisciplinary functioning were determined *a priori* and employed in the current study: 1) Transdisciplinary Orientation Scale, 2) Interpersonal Collaboration Scale, and 3) Collaborative Activities Scale. These scales were designed, tested, and administered in previous transdisciplinary initiatives (36, 49, 78). Table 3.2 shows each scale and its respective items.

Transdisciplinary orientation. Hall and colleagues developed the *transdisciplinary orientation* scale for use in TREC I (49), based on Rosenfield's theory of disciplinary integration (10). The scale includes 5 questions aimed at determining investigators' orientation towards transdisciplinarity. Each item has five response options (strongly disagree to strongly agree).

Interpersonal collaboration. We administered the *interpersonal collaboration* scale (36) to measure change in attitudes towards perceptions of collaborative research productivity, trust between colleagues, social cohesion, and perception of leadership to foster collaboration. The scale included five items with five response options (strongly disagree to strongly agree).

Collaborative activities. Engaging in behaviors such as reading publications outside one's primary field, participating in working groups with the intent to integrate ideas with others, and establishing collaborations with colleagues from different disciplines have been shown to promote cross-disciplinary

cooperation (36, 77, 80) Thus, we used the *collaborative activities* scale (36, 49) to measure frequency of participation in such activities that promote transdisciplinary integration. The scale included six items with seven response options (never to weekly).

One question with four response options queried participants' career stage (in training, early-, mid-, senior-career). Fewer than 10 participants identified as *in training*, so for the purposes of analysis, we collapsed *in training* and *early career* into a single category. Participants selected a primary discipline that best represented their work from a list of 37 discipline categories. The 37 disciplines were collapsed into five discipline areas: 1) social behavioral science and public health; 2) biochemistry, genetics, and medicine; 3) statistic and systems science; 4) Epidemiology; and 5) Exercise science, nutrition, and metabolism. Participants' reported career stage and primary discipline at survey entry were employed as predictor variables in the analysis. (81).

3.3.3 Analysis

We first conducted analyses to characterize the sample, examine the distributions of the outcome measures over time, to calculate time-specific sample means, and examine missing data. Based on empirical evidence of the scales' construction and use in previous studies (36, 49, 78), we calculated a mean score for each scale. The mean score was employed as a response variable, and each scale was analyzed separately. All analyses were conducted with SPSS (Version 25). Missing data were classified as missing completely at random. Under this assumption, a likelihood-based complete case analysis results in valid inference (82).

We employed a linear mixed-effects model analysis of variance, which is robust to unbalanced designs, missing data, and a small number of clusters (83). To adjust for the possible autocorrelation due to multiple investigators at each TREC site, investigators were nested within TREC sites and modeled as a random effect. The between-subjects factors were *career stage* and *primary discipline*, and the within-subjects factor was *time*.

3.4 Results

Between 2011 and 2015, approximately 80% of invited TREC II investigators completed the survey at each of four timepoints. Table 3.3 reports response rates and respondent characteristics at each year of survey administration. The number of investigators varied by TREC center and ranged from six (Center 4) to 29 (Center 2). *Senior*-career investigators represented most respondents in 2011 (37.2%), but *in training or early career* investigators were the majority in 2013, 2014, and 2015 (39.5%, 41.7%, 40.4%). Social-behavioral Science and Public Health Practice was the discipline category with the greatest proportion of respondents over time, followed by Epidemiology. Below, we report the within- and between-group changes over time for each scale, which are summarized in Table 3.4.

3.4.1. Transdisciplinary orientation

Figure 3.1 illustrates the change over time in mean *transdisciplinary orientation* across career stages and primary disciplines. Mean *transdisciplinary orientation* for early career investigators who indicated *social-behavioral sciences and public health practice* as their primary discipline is represented by the intercept (3.86). The results indicated that mean *transdisciplinary orientation* increased by 0.04 points as the year of survey administration increased; however this change over time was not statistically significant. The difference between *early career investigators* and all other investigator stages was significant, where *mid-career investigators*, on average, demonstrated a 0.25-point higher mean ($p<.03$) and senior career investigators demonstrated a 0.49-point higher mean ($p<.001$) *transdisciplinary orientation.* Regardless of career stage, investigators who identified *social-behavioral sciences and public health practice* as their primary discipline demonstrated significantly higher mean *transdisciplinary orientation* than all other discipline categories, with the exception of *statistics and systems science.*

3.4.2. Interpersonal collaboration

Figure 3.2 illustrates the change over time in mean attitudes towards *interpersonal collaboration*. Mean *interpersonal collaboration* for early career investigators who indicated *social-behavioral sciences and public health practice* as their primary discipline was 3.63 on a scale of one to five. *Senior career*

investigators demonstrated a significantly higher *interpersonal collaboration* score than early career investigators by 0.32 (p=.04). Investigators whose primary discipline was *statistics and systems science* and *epidemiology* demonstrating significantly higher *interpersonal collaboration than social-behavioral sciences and public health practice.*

3.4.3. Collaborative activities

Figure 3.3 illustrates the change over time in mean participation in *collaborative activities.* The baseline mean score for participation in *collaborative activities* for *early career investigators* in *social-behavioral science and public health practice* was 4.15. Mean participation in *collaborative activities* increased by .03 points each year; there was no statistically significant evidence this differed over time (p=.53). The difference between *early career investigators* and all other investigator stages was significant, where *mid-career investigators*, on average, demonstrated a 0.51-point higher mean (p=.02) and senior career investigators demonstrated a 0.96-point higher mean (p<.001) *collaborative activities* score. *Social-behavioral sciences and public health practice* investigators demonstrated the lowest observed *collaborative activities* score, but differences did not vary significantly across discipline categories.

3.5. Discussion

In this study, we examined changes over the five years of the TREC II initiative in attitudes towards and behaviors that support collaborative transdisciplinary research. We collected survey data in four annual waves and compared findings over time within and between investigators at different career stages at all participating centers in the TREC II initiative. Our results indicate that attitudes towards and behaviors that support collaborative, transdisciplinary research change over time, and those changes vary based on investigator career stage and research center with which an investigator is affiliated.

Changes over time. All scale means remained relatively high throughout the four waves of survey administration, and were comparable to scores from a single time point in a previous assessment of transdisciplinary research attitudes and behaviors (49) and higher overall than those reported from a

study that measured these constructs at two points (78). In addition to high scores over time, all three scale means trended slightly upward across the 5-year period. Our findings with previous work that measured transdisciplinary attitudes and behaviors of investigators at one center in the TTURC initiative (77), and to a pre- and mid-study assessment of these constructs in an agricultural transdisciplinary project (78). Both found an improvement in transdisciplinary attitudes and behaviors; however, the measurement period for both was two years, compared to the 5-year period in our study. This indicates that attitudes towards and behaviors that support collaborative transdisciplinary functioning in a large, complex initiative can be sustained over a longer period of time.

The first three waves of the TREC II survey administration coincided with the growth in network ties demonstrated in earlier TREC II evaluation work (81), which included formation of new teams to implement transdisciplinary within- and cross-center pilot projects. As the network ties in TREC increased (81), so did attitudes towards and behaviors that support transdisciplinary collaboration among investigators decreased, despite the documented challenges inherent in transdisciplinary research conduct. For instance, transdisciplinary research necessarily involves investigators from different disciplines who must first convene to define and develop a shared understanding of a problem (28). In monodisciplinary work, investigators are bonded by their shared culture, cognition, and familiar methods, frameworks, and "thought-styles" (79, 84). The early phases of team processes in transdisciplinary collaboration, however, can result in confusion, misinterpretation, and disagreement about methods, approaches, truth, and rigor in research (28, 84). Our data suggests that these challenging team phases do not necessarily translate to reduced participation in or poorer attitudes towards collaborative transdisciplinary research activities.

In addition to being disciplinarily dispersed, transdisciplinary teams that are geographically separated—such as those collaborating across TREC II centers—are required to address additional challenges of bridging time and space (85). The TREC within- and cross-center collaborations spanned

departments, schools, community and public sectors, academic and research institutions, and TREC II centers (29). Such long-distance collaborations come at the cost of reducing opportunities for collaborators to meet face-to-face, which has been found to promote trust, improve communication, and increase scientific productivity (86, 87). Previous theoretical and empirical work has found that contextual factors, such as geographic separation and differing policies between collaborating entities influence collaboration satisfaction (51, 77, 88). Our study found that attitudes towards collaboration and participation in collaborative activities remained positive over the 5-year reporting period and TREC II collaborations resulted in the development of robust training programs (29, 69, 89), new methods and frameworks (47, 90), and increased publications each year over time (81), previously identified outcomes of transdisciplinary research (34, 37, 77).

Rosenfield initially proposed that as the level of disciplinary integration increases, so too do the subsequent innovations and their impacts to society (4, 10, 13, 45, 53). A study of TTURC investigators similarly found that investigators with higher greater transdisciplinary orientation developed products with more practical, policy, and translational relevance than those with lower transdisciplinary orientation. Our findings indicate that it is possible to both maintain high levels of transdisciplinary orientation and measure this construct over the course of an initiative. Future research is needed to determine if the positive attitudes and participation in activities that support transdisciplinarity are the result of an initiative-level effect or if these factors can be sustained over time as investigators become involved in different research projects and teams.

Differences between career stages. A persistent trend over time was evident between career stages, in which *senior* investigators scored highest on each scale, followed by *mid-career* investigators. *Early career or in training* investigators consistently scored lowest on all scales over time. Contextual factors, such as grant requirements and institutional culture and policies influence attitudes towards transdisciplinary research (51). In this case, the structure of TREC II, and academic tenure and promotion

policies may, in part, explain the differences over time and between career stages for these measures. In addition, junior investigators are at a point in their careers in which they are developing their own areas of expertise, and are often required to demonstrate independence, including publishing first-author manuscripts to be promoted or considered for tenure (51, 91). Such expectations may be difficult to meet given the collaborative nature of most transdisciplinary research. Previous work has found that in addition to training junior investigators in transdisciplinary research conduct itself, bolstering investigators' capabilities in interpersonal and intrapersonal communication and collaboration can enhance research competency and scholarly productivity (68, 77) and contribute to project success (92, 93). Senior investigators' higher means on these measures indicates their increased collaborative capacity, and an opportunity to extend training opportunities for senior investigators—who are leading collaborative, transdisciplinary initiatives—to facilitate environments where collaboration is encouraged and rewarded.

Differences between primary discipline categories. Unlike career stages, consistent patterns were not apparent across scales for primary discipline categories. The mean *transdisciplinary orientation* and *collaborative activities* scores over time for the *social-behavioral science and public health practice* discipline category were higher than all other discipline categories. For the *transdisciplinary orientation* scale, differences were significant for all comparative discipline categories except *statistics and systems science,* and the greatest differences emerged between *social-behavioral science* and the *exercise science, nutrition, and metabolism* category, which demonstrated the lowest *transdisciplinary orientation* scores over time. This scale measured participants' integration of perspectives, theories, and models from other disciplines into their own work. Conversely, those in the *social-behavioral science* category demonstrated a lower mean score on *interpersonal collaboration,* a scale that measured perceptions of mutual trust, social cohesion, and transdisciplinary training and research success. The results are likely reflective of differing disciplinary orientations towards collaboration in research, in

which *social-behavioral science and public health practice* are interdisciplinary by nature, whereas *exercise science, nutrition, and metabolism* rely on basic science approaches, which have historically not rewarded collaborative efforts. Although differences emerged between discipline categories in *collaborative activities,* none were significant. This could be due to respondents' involvement in the initiative itself, in which opportunities to participate in collaborative activities were provided, encouraged, and rewarded.

This study has several strengths. It is the first to evaluate changes over time across all participating centers in a transdisciplinary initiative from baseline to the end of the initiative. The multi-level mixed model enabled us to account for unbalanced design and missing data and compare findings across investigator stages and primary disciplines, while considering the correlation within and between observations, groups, and time. We employed scales previously developed and administered in other transdisciplinary initiatives to assess constructs hypothesized to contribute to transdisciplinary functioning, thus adding to our knowledge base of measurement in the science of collaborative transdisciplinary team science.

3.5.1. Limitations

Despite its strengths, there are several limitations to this study. First, no comparison group of investigators was surveyed; therefore, we could not evaluate differences between TREC investigators' attitudes and behaviors over time and investigators from non-transdisciplinary initiatives that are addressing similar public health problems. The small sample size and measurement variability in this study influenced statistical results and data organization. For instance, the absence of statistically significant differences in changes over time may be due to low power. In addition, because few investigators identified as *in training*, we collapsed this category with the *early career investigator* career stage. Although these investigators are proximal in career stages, those *in training* included graduate students and postdoctoral fellows, who may have unique attitudes, behaviors, and

experiences compared to early career investigators, most of whom were assistant professors. Future research is needed to distinguish the specific needs, experiences, and outcomes for trainees in a transdisciplinary initiative from those at other career stages. Due to the small sample size, we collapsed 37 primary disciplines into five discipline categories. Although we grouped similar disciplines together, there may have been differences in attitudes and behaviors towards transdisciplinary collaboration within each discipline category that were not captured. Finally, data for all investigators was not available for all years as the composition of the TREC network changed over time.

3.5.2. Conclusion

Interpersonal, social, organizational, and behavioral factors influence the success of teams (36, 49, 51, 77, 79). These factors include the attitudes and behaviors assessed in this study. Our study demonstrated that attitudes towards and behaviors that support collaborative transdisciplinary research increased over time: attitudes were overall positive and frequency of participation in collaborative activities was high throughout the five-year TREC II initiative. Our study demonstrates that despite the challenges of conducting transdisciplinary research, TREC II investigators perceived an environment of trust and respect, maintained a transdisciplinary orientation and took advantage of opportunities to participate in collaborative activities. Organizational research has found that improved team processes are key mechanisms for enhancing team effectiveness (79). As collaborative activities gain momentum in public health research and practice, empirical evidence about team functioning over time contributes to our understanding of how to prioritize resources and training efforts to promote effective transdisciplinary collaboration that will ultimately improve population health.

Table 3.1. TREC II research projects

Primary research projects
Harvard University
Sleep Duration, Childhood Energy Balance, and Insulin Resistance in Children
Environmental and Lifestyle Factors, Obesity and Cancer-related Biomarkers
Energetic Factors, Fatal Prostate Cancer and Survivorship
Impact or Exercise and Metformin on Hyperinsulinemia in Colorectal and Breast Cancer Survivors
University of California, San Diego
Role of Inflammation and Insulin Resistance in Mouse Models of Breast Cancer
Diet Composition and Genetics: Effects on Weight, Inflammation, and Biomarkers
Obesity-related Mechanisms and Mortality in Breast Cancer Survivors
Assessment of Energy Expenditure in Women with Increased Breast Cancer Risk
University of Pennsylvania
Impact of Exercise and Caloric Restriction on Cancer Recurrence in Mice
Women in Steady Exercise Survivor Trial
Breast Cancer-related Lymphedema: Cost of Illness and Cost Effectiveness of Alternative Management Strategies
Washington University in St. Louis
Transgenerational Animal Models of Nutritional Impact on Cancer Predisposition
Energy Balance and Post-Radical Prostatectomy Urinary and Sexual Function
Worksite Policies and Neighborhood Influences on Obesity and Cancer Risk
Social Determinants in the Link Between Obesity and Cancer
Cross-center pilot projects
Integrating Measures of Physical Activity, Sedentary Behavior, Sleep, and the Built Environment
Obesity, C-peptide and Lethal Prostate Cancer
Inflammation markers and body mass index in breast cancer
Lipidomic Profiling of Energetics-Associated Cancer Models in Mice
The Use of Obesity Profiles in the Prediction of Breast Cancer
Transgenerational effect of maternal diet on methylation of cancer related genes
Obesity and Weight Loss in Endometrial Cancer Survivors: A Randomized, Multisite Trial
Assessing the Impact of Spatial Uncertainty on the Relationships between the Built Environment and Physical Activity and Sedentary Behavior
Physical Activity to Reduce Breast Cancer Risk Associated with Delayed Parity
DNA Methylation Response to Diet Composition in Obese Insulin Resistant Women

TREC: Transdisciplinary Research on Energetics and Cancer

Note: The TREC II Coordination Center did not implement primary research projects; within-center pilot projects are not listed

Table 3.2. TREC II evaluation survey scales items

Transdisciplinary orientation
I believe that benefits of collaboration among scientists from different disciplines usually outweigh the inconveniences and costs of such work.
In my own work, I typically incorporate perspectives from disciplinary orientations that are different from my own.
Although I was trained in a particular discipline, I devote much of my time to understanding other disciplines in order to inform my research.
In my collaborations with others I integrate research methods from different disciplines.
In my collaborations with others I integrate theories and models from different disciplines.
Interpersonal collaboration
I am confident that our center will be successful in achieving its transdisciplinary research goals.
I am confident that our center will be successful in achieving its transdisciplinary training goals.
The members of our center have a high level of mutual trust in each other.
The members of our center are a socially cohesive group.
The PI/Director/Leader of our center is effective in promoting a climate of collaboration and trust.
Collaborative activities
Read journals or publications outside of your primary field
Attend meetings or conferences outside of your primary field
Participate in working groups or committees with the intent to integrate ideas with other participants
Obtain new insights into your own work through discussion with colleagues who come from different fields or disciplinary orientations
Modify your own work or research agenda as a result of discussions with colleagues who come from different fields or disciplinary orientations
Establish links with colleagues from different fields or disciplinary orientations that have led to or may lead to future collaborative work

TREC: Transdisciplinary Research on Energetics and Cancer

All scale responses measured on a five-point Likert scale ranging from strongly disagree (1) to strongly agree (5) except the collaborative activities scale, which was measured on a seven-point Likert scale ranging from never (1) to weekly (7)

Table 3.3. TREC II survey respondent characteristics, 2011-2015

Year	2011	2013	2014	2015
Invited	100	92	72	70
Respondents (rate%)	78 (78.0)	76 (82.6)	59 (81.9)	57 (81.4)
Respondents by TREC II center	n (invited)			
Center 1	22 (27)	24 (25)	15 (15)	14 (20)
Center 2	19 (29)	13 (22)	10 (20)	10 (15)
Center 3	20 (25)	20 (25)	19 (22)	18 (20)
Center 4	5 (6)	6 (6)	5 (5)	5 (5)
Center 5	12 (13)	13 (14)	10 (10)	10 (10)
Respondents by career stage	n (% of total at timepoint)			
In training or early-career	23 (29.5)	30 (39.5)	24 (40.0)	23 (40.4)
Mid-career	26 (33.3)	23 (30.3)	17 (29.0)	17 (29.8)
Senior-career	29 (37.2)	23 (30.3)	18 (31.0)	17 (29.8)
Respondents by discipline¥	n (% of total at timepoint)			
Social/ Behavioral Science & Public Health Practice	19 (24.4)	16 (21.1)	14 (23.7)	17 (29.8)
Biochemistry/Genetics & Medicine	17 (21.7)	13 (17.1)	10 (16.7)	6 (10.5)
Statistics and System Science	10 (12.8)	9 (11.8)	5 (8.3)	5 (8.8)
Epidemiology	14 (17.9)	19 (25.0)	13 (21.7)	14 (24.6)
Exercise Physiology, Nutrition, & Metabolism	14 (17.9)	12 (15.8)	11 (15.2)	9 (15.8)

TREC: Transdisciplinary Research on Energetics and Cancer

**This analysis relied on career stage reported at survey entry*

¥*Totals may not add to total responses for that year due to missing data*

Table 3.1. Results summary: coefficient estimates β and standard errors (SE)

	Transdisciplinary orientation		*Interpersonal collaboration*		*Collaborative activities*	
Predictor	Coef β	SE (β)	Coef β	SE (β)	Coef β	SE (β)
Time	0.04	**0.03**	0.07*	0.03	0.03	0.04
Early career (reference group)	3.86	0.14	3.63***	0.19	4.15	0.25
Mid-career	0.25*	0.12	0.23	0.16	0.51*	0.22
Senior career	0.49***	0.12	0.32*	0.16	0.96***	0.22
Social-Behavioral Science and Public Health Practice (reference group)	3.86	0.14	3.63	0.19	4.15	0.25
Biochemistry, Genetics, and Medicine	-0.28*	0.14	0.30	0.19	-0.14	0.25
Statistics and Systems Science	-0.29	0.17	0.49*	0.22	-0.03	0.29
Epidemiology	-0.33**	0.13	0.33*	0.17	-0.03	0.22
Exercise Science, Nutrition, and Metabolism	-0.42***	0.14	0.22*	0.19	-0.10	0.24

*p<.05; **p<.01; ***p<.001

All scale responses measured on a five-point Likert scale ranging from strongly disagree (1) to strongly agree (5) except the collaborative activities scale, which was measured on a seven-point Likert scale ranging from never (1) to weekly (7)

Figure 3.1. Changes over time in *transdisciplinary orientation* by career stage and primary discipline

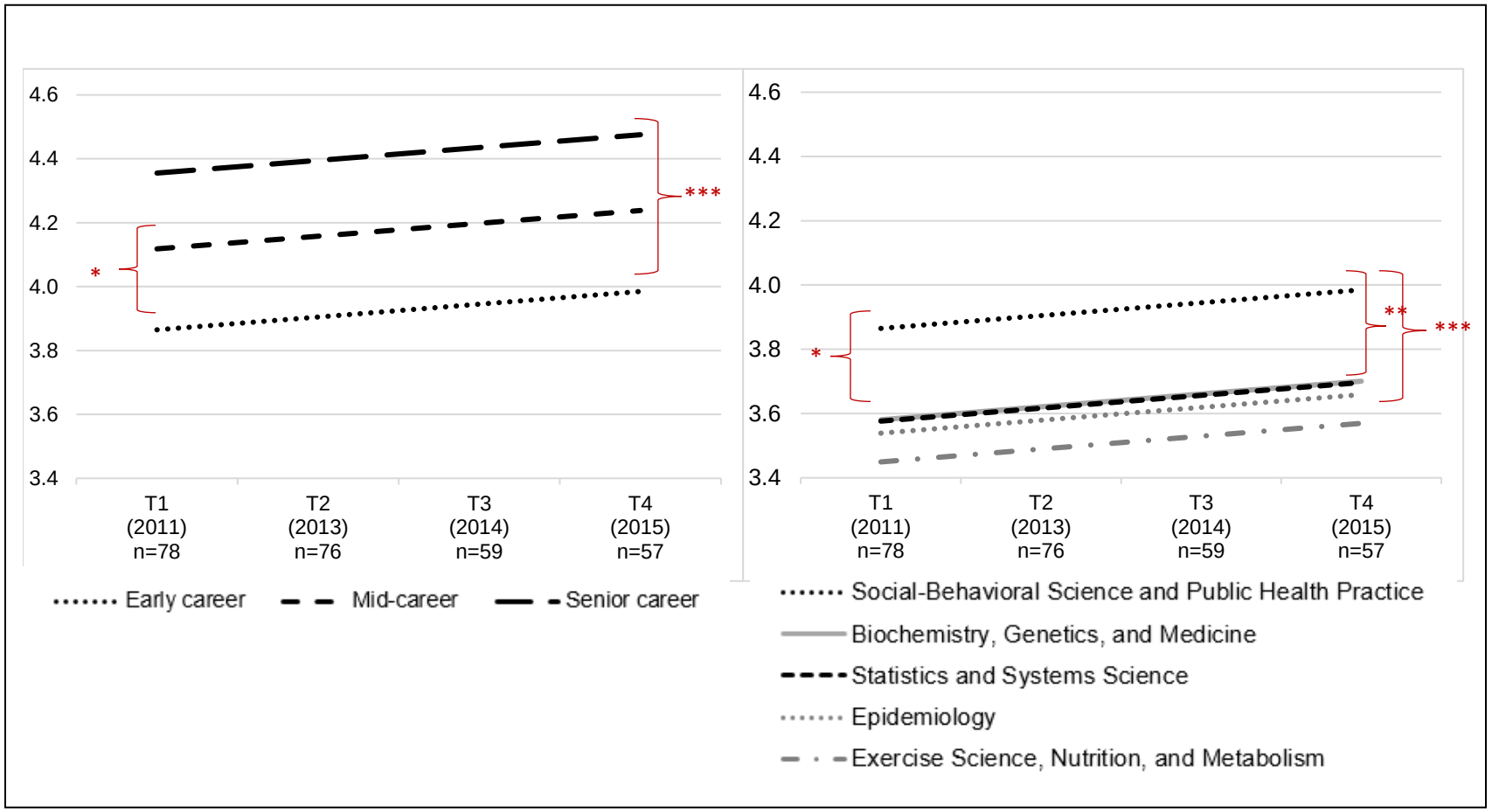


Figure 3.2. Changes over time in *interpersonal collaboration* by career stage and primary discipline

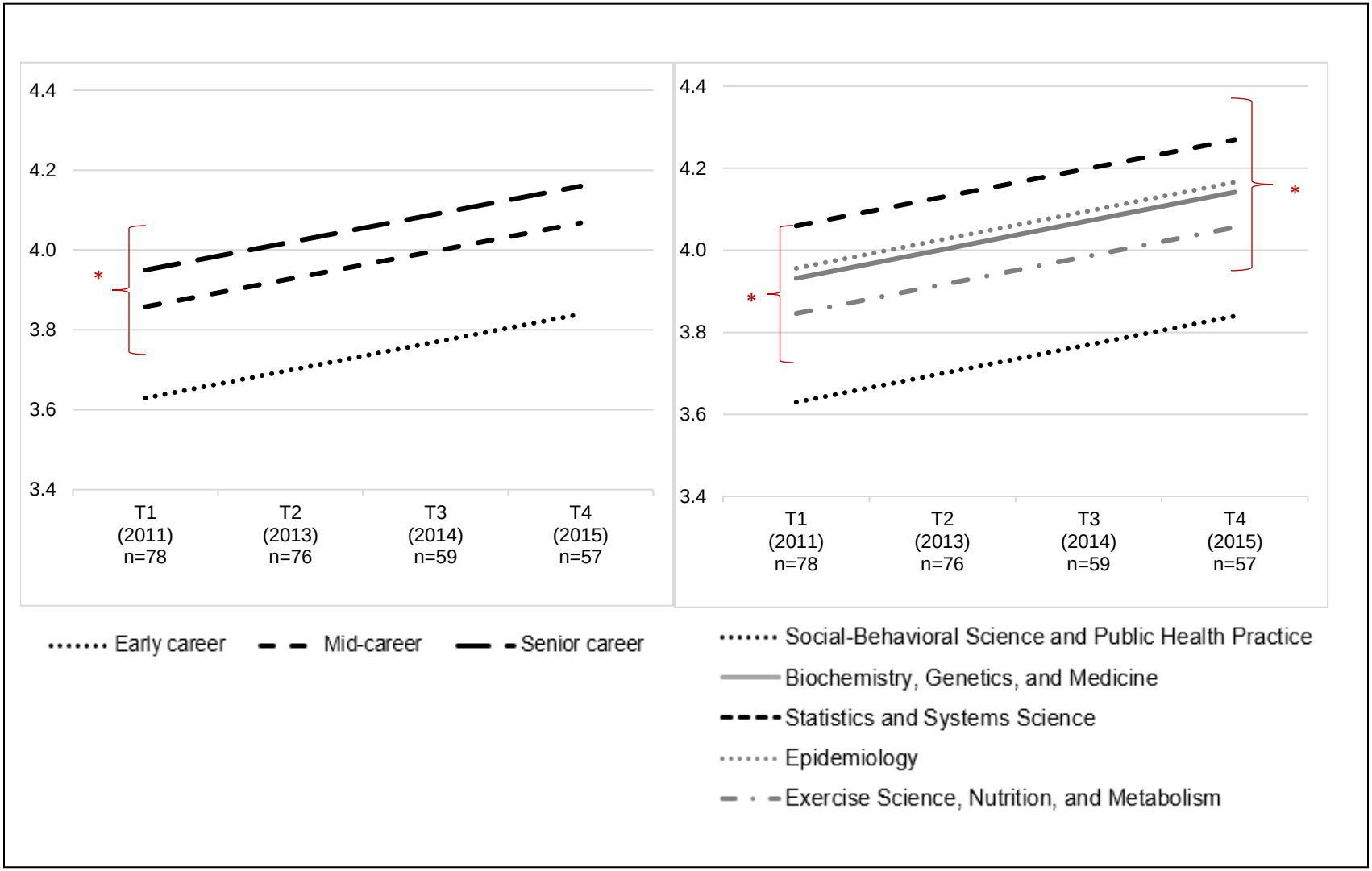


Figure 3.3. Changes over time in *collaborative activities* by career stage and primary discipline

Chapter 4. Roadmap to transdisciplinary outcomes: A constant comparative analysis of two National Institutes of Health-funded initiatives

4.1. Abstract

We present a comparative framework of transdisciplinary outcomes and their influencing contextual factors for two National Institutes of Health (NIH)-funded center grant initiatives: Transdisciplinary Research on Energetics and Cancer (TREC) and the Centers for Population Health and Health Disparities (CPHHD). Using a sequential, two-phase qualitative study design, we collected and analyzed data from document reviews and qualitative interviews with 51 TREC and CPHHD investigators and NIH program staff members. We applied a constant comparative analysis to qualitative data, in which emergent concepts from each data source were iteratively compared to identify potential relationships between contextual factors and transdisciplinary outcomes within and between the TREC and CPHHD initiatives. Four outcomes were common to TREC and CPHHD: 1) culture shifts to achieve collaborative transdisciplinary functioning; 2) integrated theoretical frameworks; 3) multilevel investigations; and 4) transdisciplinary training programs. Organizational, environmental, and intra/interpersonal contextual factors, such as federal funding levels, presence of a coordination center, and investigators' capacity and willingness for transdisciplinary collaboration influenced the differences in each outcome between the two initiatives. We built on previous research that explored transdisciplinary team science by comparing how contexts and subsequent outcomes of transdisciplinary research differ between two center initiatives. Our results offer evidence regarding where to invest resources to promote desired transdisciplinary research outcomes and foster innovation to solve complex public health problems. Our findings have the potential to inform academic support for transdisciplinary research to increase public health impact.

4.2. Background

For nearly fifty years, classical theorists, philosophers, physicists, engineers, and critical scholars have used transdisciplinary research to investigate complex societal issues (1-4). More recently, in response to the recognition that valuable knowledge generated from monodisciplinary research has not resulted in expected population health benefits, health scientists have adopted transdisciplinary approaches to address multifactorial health challenges like cancer and other chronic diseases (5-8). Transdisciplinary research aims to integrate concepts from multiple disciplinary perspectives with a goal of developing more effective solutions to complex problems (35). This approach differs from other cross-disciplinary studies in which investigators from different disciplines work separately and/or sequentially on a research problem. Specifically, transdisciplinary investigators work concurrently to integrate theories, methods, and concepts from multiple disciplines (10, 13, 74).

Public investment in team-based transdisciplinary research to address multifactorial public health problems has increased over the last two decades (5-8, 35, 75). Early evaluations of transdisciplinary functioning in US federally funded research initiatives have contributed theories of transdisciplinarity and team process models (28, 35, 51), quantitative scales to measure collaborative processes integral to transdisciplinary research (36, 94), and frameworks for evaluating large, transdisciplinary initiatives (32, 41, 49, 95, 96). Studies of transdisciplinary research in the health sciences have primarily described and measured collaborative processes. Less work has focused on outcomes unique to the approach. An initial evaluation of three of the Transdisciplinary Tobacco Research Centers (TTURCs) proposed a working conceptual model of transdisciplinary collaboration that listed concepts, interventions, training programs, and organizations as desired outcomes (35). Although the outcomes were not explicitly characterized, the model proposed that their achievement was influenced by the contextual factors described in Stokols and colleagues' typology of contextual influences on transdisciplinary collaboration, which include *inter- and intrapersonal* (e.g., attitudes

towards collaboration, leadership, communication, social cohesion), *organizational* (e.g., incentives for collaboration, range of disciplinary expertise), *environmental* (e.g., geographic proximity of collaborators), *technologic* (e.g., technology infrastructure and team proficiency), and *sociopolitical* factors (e.g., multifactorial challenges that require transdisciplinary collaboration to address; policies to support knowledge sharing) (51).

Although prior work offered perspectives on single research projects or initiatives with limited organizational structures, no study to our knowledge has compared transdisciplinary outcomes and contextual influences between two concurrently funded initiatives that addressed different health problems. A clearer understanding of multi-project, multi-site transdisciplinary research is necessary to develop a comprehensive framework of transdisciplinary research success for public health researchers, the practice community, and funding agencies. Such information could determine whether transdisciplinary outcomes are similar across initiatives and which contextual factors might yield such outcomes. This multi-method study utilized diverse data sources to compare the transdisciplinary outcomes and contexts of two National Institutes of Health (NIH)-funded transdisciplinary research initiatives, the Transdisciplinary Research on Energetics and Cancer (TREC) initiative and the Centers for Population Health and Health Disparities (CPHHD). Our goal was to identify common outcomes of transdisciplinary research and compare those outcomes across two federally funded, US-based initiatives; further, we investigate contexts that influenced each outcome.

4.3. Methods

4.3.1. Study design

Using a sequential, two-phase qualitative study design, we collected and analyzed data through document reviews and qualitative interviews. Review of the initial Request for Applications (RFA) and agenda of scientific meetings of TREC and CPHHD provided background regarding each initiative's response to sociopolitical factors outside of the initiatives, (i.e., rising incidence in energy-balance-related cancer, increasing health disparities in cancer and cardiovascular disease, insufficiency of

findings from single disciplines to equitably mitigate these public health problems. The documents also supplied data to describe organizational, environmental, and technologic contextual factors (e.g., grant requirements, policies, collaborative incentives, scientific meeting format) that influenced outcomes in each initiative. Review of the center abstracts served to characterize the transdisciplinary research conducted. Interviews were used to determine investigators' perceptions, experiences, and specific examples of outcomes they perceived as unique to transdisciplinary research, and which contextual factors might have influenced those outcomes. Three questions guided the analysis: 1) What unique outcomes emerged from the transdisciplinary approach to promote public health in each initiative? 2) What contextual factors influenced those outcomes? 3) How did contexts and outcomes compare across the initiatives?

4.3.2. Study setting

Table 4.1 summarizes key aspects of TREC and CPHHD. TREC was established by the National Cancer Institute (NCI) in 2005 and has been described in depth elsewhere (5, 29, 69). Broadly, TREC's goal was to "integrate diverse disciplines to find effective interventions across the lifespan to reduce the burden of obesity and cancer and to improve public health" (64). This study focuses on the second funding cycle of the TREC initiative (2011-2016). The Fred Hutchinson Cancer Research Center served as the Coordination Center (CC) for both TREC funding cycles. The CPHHD was a multi-center inter-institutional initiative supported by the NCI, the National Heart, Lung, and Blood Institute (NHLBI), and the Office of Behavioral and Social Sciences Research (OBSSR) (38). The CPHHD fostered transdisciplinary science among clinical, basic, and population scientists to address health inequities related to cancer and cardiovascular disease (38). Investigators were required to utilize principles of Community Based Participatory Research (CBPR), an approach that promotes engagement with community members at each phase of the research process, from identification of the problem to be addressed, to

conceptualization of community-relevant research questions, study design, analysis, and interpretation (97). This analysis focuses on the second cycle CPHHD funded (2010- 2015) (8).

4.3.3. Document review

We drew data from three document sources to characterize and assess the TREC and CPHHD context: 1) the RFA for both initiatives; 2) scientific meeting agendas; and 3) primary research project summaries for each initiative. Two members of the study team first reviewed each RFA and all meeting agendas. We applied content analysis to all documents (71). In an inductive process, we applied codes that matched Stokols' typology of contextual factors influencing transdisciplinary scientific collaboration (51, 72). To compare project characteristics across initiatives, we applied also applied deductive coding to compare characteristics beyond contextual factors (i.e., intervention/observational study, macro- and micro- factors addressed) across primary research project summaries (72).

4.3.4. Interviews

Interview questions were designed to identify and explore investigators' perspectives of transdisciplinary outcomes and the contextual factors that influenced those outcomes. We applied purposeful, maximum variation sampling, whose goal is to capitalize on heterogeneous perspectives by identifying common patterns across a diverse sample (98). Accordingly, we recruited investigators from every TREC and CPHHD center and each funding agency (i.e., NCI, NHLBI, and OBSSR). Potential respondents received a recruitment email to explain the study and schedule one-on-one telephone interviews. Interviews with TREC investigators were conducted face-to-face at each TREC Center; interviews with TREC funding agency staff members and CPHHD investigators and staff were conducted via telephone. Participants provided written (in-person interviewees) or oral (telephone interviewees) consent, which included permission to print direct quotes. All non-funding agency participants received a $25 gift card for their time.

All interviews were audio-recorded, professionally transcribed, de-identified and uploaded into Atlas.ti (Version 8). The study team developed an initial coding framework based on outcomes identified

in previous TREC evaluation efforts and Stokols' typology of contextual factors influencing transdisciplinary scientific collaboration (51). Three coders applied a constant comparative analytic approach (99) to the data, in which a conceptual phrase/code representing a transdisciplinary outcome or its facilitating or constraining contextual factor(s) was attached to segments of text. By iteratively comparing emergent concepts from each data source to those coded and analyzed previously, we generated hypotheses about the relationships between concepts (99) and created visual representations of the data. The study team communicated regularly to discuss interpretations, agree on a final coding structure, and finalize visual interpretations of the data. The final codebook was applied across all interview transcripts, where two coders jointly coded 16 (31%) transcripts. Member checking can improve a study's validity and credibility (100); thus, preliminary results were shared via program reports and discussed with TREC and CPHHD investigators on steering committee calls and at scientific meetings. Study materials were approved by the Fred Hutchinson Cancer Research Center Internal Review Board and the TREC and CPHHD steering committees.

4.4. Results

Between June 2015 and January 2016, 51 investigators and NIH program staff members from TREC (n=26) and CPHHD (n=25) participated in interviews lasting between 37-75 minutes. Respondent affiliations are described in Table 4.2. All data sources described *intra/interpersonal, organizational,* and *environmental*, contextual factors that influenced similarities and differences in transdisciplinary outcomes across the two initiatives. Investigators highlighted four outcomes that they perceived distinguished transdisciplinary approaches from mono- and multi-disciplinary research approaches: 1) culture shifts for collaborative transdisciplinary research conduct; 2) integrated theoretical frameworks; 3) multilevel investigations; and 4) transdisciplinary training programs. Figure 4.1 characterizes each transdisciplinary outcome and compares their differing contextual influences in TREC and CPHHD. Below, we characterize each outcome that investigators described as unique to transdisciplinary

research and compare the outcome between TREC and CPHHD. Then, we discuss contextual influences on those transdisciplinary outcomes across the two initiatives.

4.4.1. Culture shifts for collaborative transdisciplinary research conduct

TREC and CPHHD investigators described the traditional organizational culture of their institutions as failing to incentivize or offer sufficient support for collaboration across disciplines and sectors. However, they highlighted a transformation that occurred in their personal and their institution's prioritization of collaborative transdisciplinary. They perceived this cultural transformation as both a unique outcome of their transdisciplinary work and a catalyst for future transdisciplinary collaboration. Although levels of commitment varied across institutions, investigators emphasized a greater organizational and institutional commitment to collaborative activities, evidenced by changes in language and guidelines for promotion and tenure that included recognition for teamwork and cross-sector collaboration, institutional funding for collaborative activities, and prioritizing cross-sector and community participation in research.

TREC investigators described both an intra/interpersonal and organizational orientation that was beginning to shift from championing monodisciplinary and single-investigator research to inclusion and integration of multiple academic disciplinary perspectives. One investigator noted, *"I had never interacted between basic [science], epidemiology and social work, whereas I could leave OB-GYN and go to cell biology or biochemistry […] TREC has broken down silos between social science, basic science, and clinical research here."* **(TREC 6)** Investigators, such as this one, described TREC Center leadership as catalyzing a culture shift towards a transdisciplinary orientation in academic institutions: "*Within the medical school, [center co-director drove] efforts to engage in thinking through transdisciplinarity as a key component of being responsive [to grants]. Now, other groups and the dean of the school of social work are advocating for transdisciplinary approaches."* **(TREC 25)**

Across the CPHHD projects, investigators noted shifting values in their schools or departments to focus specifically on improving health for the underserved by integrating community insight as a discipline in research projects. Moreover, they said the CPHHD program highlighted the significance of involving community members on research teams as a way to address health disparities. Illustrative of sentiments among a few CPHHD investigators, this investigator—whose institution had been funded by CPHHD for both five-year grant cycles—said "*We have an institutional commitment to health disparities and the underserved…[to] making sure the community has a voice in the research projects."* **(CPHHD 28)** These were unique concepts that CPHHD investigators speculated had not previously been traditionally recognized or valued in academic institutions.

4.4.2. Integrated theoretical frameworks

Transdisciplinary theoretical frameworks are those that transcend any single discipline by mixing concepts from multiple disciplines to create a new conceptualization of a problem. Each TREC and CPHHD center implemented between 3-5 primary research projects. To do so, they relied on frameworks that bridged concepts across scientific areas and levels of analysis, with a goal of improving outcomes in cancer, cardiovascular disease, and/or health disparities. In TREC, the new frameworks also bridged concepts from disciplines represented across projects and research centers. Investigators reported that this type of blending multiple disciplinary perspectives to "go beyond" a single orientation was not common in projects without a transdisciplinary emphasis.

The TREC initiative was designed to address multiple macro/contextual- and micro/individual-level factors that influence energy balance and cancer, illustrated by an encompassing conceptual model developed by TREC leadership early in the initiative (5). Additionally, project summaries illustrated center-specific conceptual models that theorized how integrated basic, social, and implementation science approaches could address cancer and obesity across the life-course. Investigators said that leveraging complementary strengths of different disciplines spurred more creative thinking to ask

questions and generate new solutions to improve obesity-related cancer outcomes. This engineer offered a specific example:

> *"The transdisciplinary part, creating this space where people can ask questions and form new questions just wouldn't have existed without TREC. In engineering, looking at things in the frequency domain is just standard. As we try to build these models, we ask, 'Well, why I am looking at this particular model this way, but [name] is looking at it a different way, [name] is looking at it a third way? What am I bringing to that picture?' It forces me to think differently, 'Oh, that's because epidemiology is generally done from a time domain, not a frequency domain, if we're looking at trends. So how could we leverage looking at things from the frequency domain to understand and inform prevention strategies that are specifically tied to social determinants of health?"* ***(TREC 2)***

The Warnecke ecological model for analysis of population health and health disparities (8), served as a uniting framework across CPHHD Centers. Project summary and interview data indicated CPHHD researchers' commitment to investigating and intervening at multiple levels of influence (e.g., biological, behavioral, socio-environmental). Reflective of the multilevel approach, this investigator described what others also expressed:

> *"We know that disparities are multiple in origin at different levels from cells to society and policy, so monocausal hypotheses are very narrow. Understanding the role of each level contributing to disparities is an advantage, from genetics to policy. So you have to intervene in a way that interrupts the social context and not just the individual behavior."* ***(CPHHD 25)***

Some CPHHD investigators described extensive formative work conducted with the communities the research intended to benefit, resulting in theoretical frameworks that drew together constructs that were meaningful and relevant to all collaborators. This investigator provided one such example:

> *"One paper developed theoretical framework for the cancer journey. It was developed by nurses. We had a series of papers that came out from the Hopi, one of the tribes we work with, that explained exercise and physical activity in terms of cultural and historical values and preferences.*" **(CPHHD 37)**

4.4.3. Multilevel investigations

Investigators described their development of new multilevel investigations—those that tested the relationships between constructs and variables identified in the integrated theoretical frameworks

that guided their work—as products unique to a transdisciplinary research approach. TREC projects were largely observational; the majority examined biological responses and pathways between obesity and cancer, whereas most CPHHD projects included a human intervention, as required by the RFA. Most TREC observational projects considered the influence of both biological and behavioral factors on cancer incidence and survivorship. This investigator described a cross-center TREC project that mixed such concepts to determine modifiers of breast cancer risk:

> *"Alcohol consumption from menarche to first pregnancy is associated with increased risk of breast cancer. In modern society the time interval during those two reproductive events is becoming longer and longer. […] Lifestyle behaviors may modify the time interval from menarche to first pregnancy. We want to use the human data and the animal model to test our hypotheses that exercise and alcohol consumption may modify the risk of breast cancer [for these women]."* **(TREC 5)**

Although intervention projects were less common in TREC primary research projects, investigators described spinoff projects that included interventions that spanned disciplines and targeted multiple levels of influence. These projects were funded by within-TREC resources (i.e., pilot projects) and beyond-TREC resources (e.g., NIH, state and local health departments, institutional funding). This investigator described an intervention that combined psychology, computer science, oncology, and health services, and targeted individual and health-systems level changes:

> *"What's most exciting for me is translating some stuff we [psychologists] do into clinics and giving women wrist Fitbits during chemotherapy. What does their activity look like? What is the feasibility of using wearable sensors during active treatments? I'm working with the oncologists; they're excited about how it may help them monitor breast cancer patients."* **(TREC 18)**

Community-engaged, multilevel interventions were ubiquitous across CPHHD centers. Project summaries and interview data revealed the diversity of multilevel interventions across the initiative, reflected in the locations (e.g., rural or urban community clinics, participant homes, schools, local business churches) target populations (e.g., children, families, patients) and their demographic characteristics (e.g., rural Appalachians, urban African Americans, urban Puerto Ricans, rural American Indians/Alaska Natives, urban and rural Latinos), and the outcomes of interest (e.g., changes in biology,

behavior, systems). This investigator summarized the complexity of the projects of that CPHHD to reduce cervical cancer in rural Appalachian women:

> *"[We intervened] at the medical center and at home, in the family structure, teaching parents [about] the HPV vaccine, seeing if they would interact with the medical system and if that would produce a behavior, which was getting their child vaccinated. […] We developed the psychoneuroimmunology model that we put forth to say how place—where they live—and the conditions of place impact risk of cervical cancer. So how do these multiple influences fit?"* **(CPHHD 29)**

Investigators said the CPHHD challenged them to think about and address disparities more broadly. This investigator elaborated:

> *"In the health disparities field, [risk factors are] more complex than [those found in] studies [of] more educated or more income-secure populations. There're so many other things going on in terms of stress, of inadequate resources. You can give them education, but if they don't have access to food…Without considering all these things, you can misunderstand your data. So it has to be this way for health disparities, and it was very hard and it's going to continue to be very hard to move forward with small R01s, because this ability to put it all together has made a huge difference in health outcomes."* **(CPHHD 35)**

4.4.4. Transdisciplinary training programs

"It's on the center [initiative], not an individual, to make sure the trainee is involved in an enterprise." **(TREC 25)** Investigators nearly unanimously cited training of a new cadre of transdisciplinary cancer, CVD, and health disparities researchers as a unique and a compelling outcome of the initiatives. Although postdoctoral fellows and junior faculty were officially considered "trainees" in these initiatives, one way in which investigators distinguished transdisciplinary training programs from others is because they value training at all career stages, given the relatively new emphasis for most investigators on transdisciplinary and community-engaged research. Early career investigators were able to assume leadership roles and conduct transdisciplinary research with the support and mentorship of multiple, cross-disciplinary experts across research sites. Investigators from both initiatives described the benefit of breadth and depth of training that trainees obtained that they perceived would position them more competitively than their peers trained outside of a non-transdisciplinary center grant. These two investigators illustrated:

> *"When you come into a [transdisciplinary project] and your background is in exercise physiology in humans, and then you learn to study animals while you're doing your post-doc, and you learn to really see the world from the perspective of both human and animal science and then you get some coursework in epidemiology, you're able to see the solar system, if you will, as opposed to only having focused on the planet before."* **(TREC 20)**

> *"The training component is a major crowning achievement. A lasting impact is likely to be the doctoral students and the junior faculty we have trained. They leave with a kind of a mindset that is different from people who generally follow these things from one simple perspective. [Trainees] leave with a different kind of a mindset and appreciation for multidisciplinary perspectives*. **(CPHHD 51)**

TREC and CPHHD investigators perceived the involvement of trainees in activities such as exchange programs and pilot projects as a cost-effective approach to promoting academic productivity and subsequent career development.

> *"Compared to a T32 or R grant, in which trainees are off doing their siloed research […trainees] do not have normally the focus of a major working group and resources to support training and travel for new investigators as we do in TREC. You do not have opportunities to pull newer investigators from across different sites and engage them in real data-driven projects that build the foundation for them to move to the next level of academic competition and grantsmanship. […TREC's] new investigators represent a new pool of talent. […] A very modest level of resources then became a dynamic area of really moving forward opportunities in transdisciplinary science."* **(TREC 24)**

> *"Trainee exchange programs are very cost-effective […] Expanding those would be another way for cross-fertilization. Student exchange works fantastic because the PIs are so busy that to get something going between centers, that requires dedicated effort and time, and the best way to do that is to involve junior [investigators] to support their careers and help keep the communication going."* **(CPHHD 35)**

CPHHD investigators highlighted two major themes about training that TREC investigators did not. First, several CPHHD investigators said that although the scientific meetings provided valuable opportunities to learn how other centers approached CBPR and transdisciplinary research, they could have benefitted from explicit cross-center training in these research approaches, which most said could have been facilitated by a coordination center, had one existed. Second, most CPHHD investigators underscored their role in training and capacity building (e.g., in research, grant writing, health education, health services) among community members with whom they worked. This investigator summarized:

> *I would say for our center [the most compelling product was] developing new models for engaging communities and mobilizing youth and community intervention research. […] And [demonstrating] how to develop training programs for the next generation of young Latino health scholars and interventionists. We have a number of publications that are coming out of the center, but I'm going to be honest with you. The biggest thing that's come out of our center has been the training.* **(CPHHD 30)**

TREC and CPHHD investigators broadly asserted that the culture shifts, integrated theoretical frameworks, new multilevel models and transdisciplinary training programs they described could only be achieved through large, transdisciplinary center grants. Several considered transdisciplinary research "*a new science"* for public health problems. They noted that grants to fund such collaborative work represent an important opportunity to challenge and transcend *incremental approaches*, or, "*a bunch of little projects that, by themselves, really aren't going to have any kind of particular large-scale impact*." **(CPHHD 30)**

4.4.5. Contextual influences on transdisciplinary outcomes in TREC and CPHHD

Table 4.3 compares the program summaries and *organizational, environmental,* and *technologic contextual* influences on outcomes, based on TREC and CPHHD RFA and scientific meeting agenda review. Each initiatives' purpose, *goal, problem and population foci represent a response to the sociopolitical factors of rising* energy-balance related cancer incidence (TREC) and increasing health disparities in cancer and cardiovascular disease (CPHHD). The center-grant—compared to a single-investigator-led—structure and focus on disciplinary integration outlined in TREC and CPHHD RFAs represented an organizational factor that required investigators to collaborate across schools and departments within their own institutions. TREC required investigators to sign confidentiality agreements, which investigators said encouraged collaboration in a safe environment to achieve transdisciplinary outcomes. Furthermore, TREC allocated a budget for an electronic shared data repository and funded a coordination center to facilitate communication and integrate efforts across the initiative. These attributes represent *organizational* and technologic factors that influenced how investigators worked towards transdisciplinary outcomes. CPHHD investigators were required to

intervene at multiple levels of influence on health disparities and to partner with communities to conduct their transdisciplinary research. CPHHD investigators perceived the financial support from national agencies (i.e., NCI, NHLBI) as "legitimizing" community-academic partnerships in research at their institutions and nationally. The funding was an example of an *organizational* factor that both brought attention to intersecting influences on health disparities and validated the critical importance of diverse disciplinary and practical expertise to address them. Both TREC and CPHHD required training programs; the TREC RFA required specific components, whereas CPHHD centers had design flexibility, *organizational* factors that specifically influenced the training programs in each initiative. All TREC and CPHHD centers were required to support center-specific training cores. The TREC coordination center also included a training core and led a cross-center training working group that served facilitate cooperation across and build upon training efforts at individual TREC Centers. TREC funds were allocated for trainee exchange opportunities and pilot projects, whereas CPHHD leadership secured *ad hoc* funding for such opportunities that were not originally built into the grant.

Although *inter-* and *intrapersonal* factors were supported through requirements and activities outlined in document data (e.g., scientific meetings, working groups), interview data offered examples of how those requirements supported team capacity to achieve transdisciplinary outcomes. In both initiatives, investigators' transformational leadership—actions that motivated others to make change to support long-term transdisciplinary collaboration and scientific innovation—exemplified *intra/interpersonal* factors that stimulated new incentives for transdisciplinary collaboration at their institutions. Specifically, they leveraged their positions to suggest alternatives to what most investigators perceived as antiquated academic rewards structures that hinder disciplinary integration and collaboration. These activities, in turn, facilitated an environment that fostered the development of integrated theoretical frameworks, new multilevel models, and training programs unique to transdisciplinary research. In the CPHHD, investigators regarded community knowledge as a discipline,

and used the funds from the initiative to build lasting infrastructure to ensure community participation in health disparities research projects. The *interpersonal* and *organizational* contextual factors that influenced transdisciplinary outcomes in TREC and CPHHD were mutually reinforcing. Investigators teamed to develop structures to support longer term transdisciplinary collaboration to improve population health. Such structures offered resources for investigators to convene regularly over time, build trust and respect, share ideas, and develop innovative frameworks, models, and training programs.

4.5. Discussion

In this study, we describe a comparative analysis of transdisciplinary outcomes and their contextual influences in two NIH-funded transdisciplinary center grant initiatives. RFAs, scientific meeting agendas, project summaries, and interview analysis revealed four outcomes that were both common across the TREC and CPHHD and unique to transdisciplinarity: 1) culture shifts for collaborative transdisciplinary research conduct; 2) integrated theoretical frameworks; 3) new multilevel investigations; and 4) new transdisciplinary training programs. Each transdisciplinary outcome was characterized differently between the initiatives, variations that may have been influenced by the organizational, environmental, technologic, and intra/interpersonal contexts in which each initiative operated.

Prior research has identified transdisciplinary research outcomes to include those traditionally rewarded in academic institutions such as publications (58), conceptual outcomes such as new theories and models, and practical outcomes such as new intervention models or policies to promote population health and/or reduce health disparities (35, 37, 101). Although investigators in this study discussed publications as a necessary marker of academic success, they indicated that more compelling, unique outcomes were those that reinforced structures to support transdisciplinary collaboration, new frameworks and models to more accurately characterize public health problems and inform solutions for their resolution, and training programs that prepared collaborators from all career stages and sectors to

conduct transdisciplinary research. A range of organizational, environmental, technologic, and intra/interpersonal contextual factors proposed by Stokols' and colleagues (51) also influenced the nature and achievement of transdisciplinary outcomes in TREC and CPHHD. First, investigators described shifting cultures toward the transdisciplinary and community-engaged (in CPHHD) approaches they utilized to address cancer, CVD, and health disparities. In TREC, culture shifts that resulted in institutional changes to better support cross-department, and cross-center collaboration, such as prioritizing the transdisciplinary approach when responding to funding announcements. Such shifts were made possible by cooperative policies across the initiative, cross-center pilot project funds specified in that initiative's grant structure (organizational factors), and investigators' commitment to working with their individual institutions to highlight the value of the transdisciplinary approach (intra/interpersonal factor). In contrast, the CPHHD's requirement for community-engaged intervention research supported policy changes at some individual institutions' to prioritize health disparities research that aims to directly impact their immediately surrounding communities (environmental factor) and include participating community members as budget line items, even beyond the CPHHD grant initiative (organizational factors). Our results suggest that prioritization of cross-disciplinary, cross-sector research at the institutional level is driven by intra/interpersonal contextual factors, such as leaders who challenge policies and reward structures that do not support transdisciplinary functioning. Moreover, these intra/interpersonal contextual factors are supported by the organizational contexts of center grant initiatives that provide funding for collaborative innovation and disciplinary integration in public health research.

Investigators highlighted their development of integrated theoretical frameworks and multilevel intervention and observational investigations as unique to the transdisciplinary approach, which may be similar to the outcome "concepts" proposed in previous work (35). These transdisciplinary outcomes were driven by grant requirements and were further supported by investigators' willingness to devote

time to learning about how different disciplines approached a common problem (intra/interpersonal factors). Organizational factors that differed across the initiative influenced investigators' team composition and processes, and consequently, the frameworks, models, and training programs they developed. For example, both initiatives required collaboration across research centers. However, compared to CPHHD, TREC had both requirements and funding that supported a greater number of face-to-face meeting opportunities, a requirement that investigators sign confidentiality agreements, ongoing pilot projects, and a coordination center whose role was to facilitate coordination and collaboration, transdisciplinary training, and evaluation in that initiative. Moreover, the CPHHD included more than twice as many research centers and had an annual budget only two thirds that of TREC. TREC investigators described cross-center collaborations as critical to developing new transdisciplinary frameworks and testing new multilevel models to address obesity-related cancer. However, the organizational context limited CPHHD investigators' capacity for cross-center collaboration, and the frameworks and models they described were predominately developed with available expertise within their research sites. However, those frameworks and models included expertise from local community groups with whom CPHHD investigators partnered to conduct their work. These transdisciplinary outcomes consequently carried relevance to the communities the research intended to benefit. Our findings suggest that if investigators are expected to integrate disciplinary expertise, resources, or data from multiple centers within an initiative, a grant requirement for collaboration is necessary but insufficient. Cross-center collaboration and integration requirements must be accompanied by financial and technical resources to incentivize collaboration. For example, studies have found that coordinating centers can facilitate cross-center communication, collaboration, data harmonization, and transdisciplinary training and evaluation (88, 102), Further, if the goal of an initiative is to address a public health problem relevant to the local context and to ameliorate health disparities, theories and frameworks must integrate community insight with academic theoretical perspectives (101, 103, 104).

Thus, training academic researchers and community partners to collaborate is crucial to that goal. Center-specific and initiative-wide transdisciplinary training programs were identified as critical outcomes of each initiatives transdisciplinary approach. Future studies to compare career trajectories of individuals who participated in a transdisciplinary training program and those who did not could provide valuable information regarding the long-term impact of transdisciplinary training on investigators and on the outcomes associated with their research. Practical evaluations conducted of transdisciplinary efforts in the U.S. and abroad have evaluated research process and found, for example, that shared leadership, reductions in hierarchies, and co-learning within teams facilitates success (32, 42, 51, 105-107), co-learning and integration of knowledge perspectives and ways of is critical to transdisciplinarity (32, 108). Our work qualitatively describes these intra/interpersonal factors and provides a framework for future investigation to assess how these factors quantitatively relate to the achievement of outcomes presented here, and how these outcomes may promote gains in population health.

This study has several strengths. Multiple data sources (i.e., documents, interviews) and analytic techniques strengthen the credibility of study findings (100). The perspective of investigators from every center and funding agency in each research initiative and funding agency representatives were gathered in qualitative interviews. These data provided differing, specific, and complementary examples of contexts, transdisciplinary collaboration, and outcomes to address complex public health problems in cancer, cardiovascular disease, and health disparities.

4.5.1. Limitations

Despite its strengths, this study has several limitations. Although TREC investigators who participated in interviews were involved in that initiative's evaluation over a five-year period, with multiple points of interface with the study team, CPHHD investigators were involved only in this comparison study in the final year of the initiatives. Because the CPHHD (10 centers) was so much larger than TREC (4 centers), in most cases, two investigators were interviewed per CPHHD center, compared to 5-7 investigators per

TREC center. The nature of qualitative data is such that experiences are described and not quantified, so hypotheses about causal relationships could be generated but not tested in this work. Further quantitative comparative research could elucidate if the contexts described by TREC and CPHHD investigators promote long term research outcomes, such as new policies and population health improvements. Future studies are needed to quantitatively assess causation between the context and transdisciplinary outcomes described here, and to evaluate the strategic investments in these contexts to produce transdisciplinary outcomes.

4.5.2. Conclusion

In this study, we built on previous research that explored processes of transdisciplinary team science by comparing how contexts and subsequent outcomes of transdisciplinary research differ between two center grant initiatives. As such, our results offer the investigators, funding agencies, and collaborators evidence regarding where to invest resources to promote desired outcomes of transdisciplinary research and foster innovation that can solve complex public health problems. Our findings could help inform academic institutional and departmental support for transdisciplinary research conduct to effectively generate public health impact.

Table 4.1. TREC and CPHHD research centers

Institution	*Center title*
TREC research centers	
Harvard University	Influence of genetic, behavioral, and structural factors on obesity and the biologic mediators between obesity and cancer at multiple stages of life
University of California, San Diego	Insulin resistance and inflammation underlying the association of energetics with breast cancer carcinogenesis
University of Pennsylvania	Advancing science on energetics and cancer survivorship
Washington University in St. Louis	Molecular and social-environmental influences on energetics and cancer throughout the lifespan
CPHHD research centers	
National Cancer Institute-funded CPHHD Centers	
Fred Hutchinson Cancer Research Center	Breast cancer prevention in Latinas
Harvard University	Reducing lung cancer disparities
Ohio State University	HPV vaccine initiation in Appalachia
University of Illinois-Chicago	Disparities in breast cancer diagnosis and treatment
University of Washington	Improving cancer outcomes in Native Americans
National Heart, Blood, and Lung Institute-funded CPHHD Centers	
Johns Hopkins University	Reducing disparities in cardiovascular health
Northeastern University	Diet and CVD in Puerto Ricans
Rush University	Enhanced cardiopulmonary health
University of California, Los Angeles	Dietary change through corner store makeovers
University of North Carolina-Chapel Hill	Reducing risk factors for cardiovascular disease

TREC: Transdisciplinary Research on Energetics and Cancer; CPHHD: Centers for Population Health and Health Disparities; HPV: human papilloma virus; CVD: cardiovascular disease

Table 2. TREC and CPHHD Interview respondents
(June 2015-January 2016)

Role	TREC n	CPHHD n	Total
Center Director or Co-Director	6	13	13
Project investigator or core leader	19	5	19
Early career investigator	5*	4	9
Funding agency representative	1	3	4
Total	26	25	51

TREC: Transdisciplinary Research on Energetics and Cancer
CPHHD: Centers for Population Health and Health Disparities
**TREC early career investigators in this dataset also served as core leaders (n=1) or developmental project investigators (n=4), so total does not equal 26 as these investigators are noted twice.*

Table 3. RFA and scientific meeting agenda summary: comparison of organizational, environmental, and technologic contextual factors that influenced transdisciplinary outcomes in the TREC and CPHHD

	TREC (2011-2016)	CPHHD (2010-2015)
	PROGRAM SUMMARY	
Purpose	• Foster collaboration across multiple disciplines • Encompass projects that cover biology, gen/omics/etics of energy balance to behavioral, socio-cultural, and environmental influences on energetics and cancer risk • Establish transdisciplinary teams with appropriate expertise	• Promote transdisciplinary research in health inequities • Improve health outcomes and quality of life for populations with higher disease burden • Conduct interventions as primary objective
Goal	• Enhance knowledge of mechanisms underlying association between energy balance and cancer • Explore & integrate etiology of obesity and health behavior theories, with broad population impact at the social-environmental and policy levels for obesity prevention and control	• Understand pathways that result in disparate health outcomes • Develop comprehensive models of how various social, economic, cultural, environmental, biological, behavioral, physiological, and genetic factors affect individual health outcomes and their distribution in populations • Aid development of effective multilevel interventions to that promote health and/or reduce disease burden
Problem focus	Obesity, energetics and cancer	Individual and contextual factors underlying health disparities in cancer and cardiovascular disease
Population focus	Children, groups at high risk for obesity, cancer survivors	Population groups with differences in incidence, prevalence, mortality, and disease burden
	ORGANIZATIONAL FACTORS	
Funders (funded programs)	NCI (4 research centers; 1 coordination center)	NCI (5 centers); NHLBI (5 centers); OBSSR (meetings)
Budget (year $)	Annual: $15M (2010)	Annual: $10M (2009)
Funding mechanism	Research Project Cooperative Agreement (U54) Substantial funding agency programmatic involvement as partner, not directorship	Specialized Center (P50) Emphasizes a multi-disciplinary approach to a specified problem; centers serve as resources for research topic area

ORGANIZATIONAL, ENVIRONMENTAL, TECHNOLOGIC FACTORS		
Grant requirements	• 4 cores (recommended): administrative, bioinformatics, training, pilot projects• Define training program, budget required for trainee exchange and outreach activities• Collaborate across TREC Centers• Develop centralized resources with coordination center and NCI • Allocate budget for centralized data collection archived at coordination center• Sign confidentiality agreements; share knowledge, data, research materials with TREC investigators	• 1 core (recommended): administrative, others to Centers' discretion• Conduct minimum 1 multilevel intervention project• Develop training component, design defined by Centers• Participate in data harmonization activities• Interact with other CPHHD centers to share information (measures, protocols, methods), collaborate, identify opportunities for common measures
Resources and activities	• 8 face-to-face scientific meetings; 1 additional annual face-to-face Steering Committee meeting • Funded coordination center to integrate efforts of individual research centers • Trainee conference travel funds; investigator exchange funds managed by coordination center • Annual within- and cross-center pilot funds for ancillary research projects • 15 cross-center working groups	• 5 face-to-face scientific meetings; additional annual face-to-face Steering Committee meetings • Contracted scientific program coordinator to manage cross-center communication and administration • Ad-hoc funds for trainee exchange programs • Ad-hoc funds for ancillary pilot projects • 7 cross-center working groups

RFA: Request for Applications; TREC: Transdisciplinary Research on Energetics and Cancer; CPHHD: Centers for Population Health and Health Disparities; NCI: National Cancer Institute; NHLBI: National Heart, Lung, and Blood Institute; OBSSR: Office of Behavioral and Social Science Research

Table 4.1. TREC and CPHHD research centers

Institution	*Center title*
TREC research centers	
Harvard University	Influence of genetic, behavioral, and structural factors on obesity and the biologic mediators between obesity and cancer at multiple stages of life
University of California, San Diego	Insulin resistance and inflammation underlying the association of energetics with breast cancer carcinogenesis
University of Pennsylvania	Advancing science on energetics and cancer survivorship
Washington University in St. Louis	Molecular and social-environmental influences on energetics and cancer throughout the lifespan
CPHHD research centers	
National Cancer Institute-funded CPHHD Centers	
Fred Hutchinson Cancer Research Center	Breast cancer prevention in Latinas
Harvard University	Reducing lung cancer disparities
Ohio State University	HPV vaccine initiation in Appalachia
University of Illinois-Chicago	Disparities in breast cancer diagnosis and treatment
University of Washington	Improving cancer outcomes in Native Americans
National Heart, Blood, and Lung Institute-funded CPHHD Centers	
Johns Hopkins University	Reducing disparities in cardiovascular health
Northeastern University	Diet and CVD in Puerto Ricans
Rush University	Enhanced cardiopulmonary health
University of California, Los Angeles	Dietary change through corner store makeovers
University of North Carolina-Chapel Hill	Reducing risk factors for cardiovascular disease

TREC: Transdisciplinary Research on Energetics and Cancer; CPHHD: Centers for Population Health and Health Disparities; HPV: human papilloma virus; CVD: cardiovascular disease

Table 4.2. TREC and CPHHD Interview respondents (June 2015-January 2016)

Role	TREC n	CPHHD n	Total
Center Director or Co-Director	6	13	13
Project investigator or core leader	19	5	19
Early career investigator	5*	4	9
Funding agency representative	1	3	4
Total	26	25	51

TREC: Transdisciplinary Research on Energetics and Cancer

CPHHD: Centers for Population Health and Health Disparities

**TREC early career investigators in this dataset also served as core leaders (n=1) or developmental project investigators (n=4), so total does not equal 26 as these investigators are noted twice.*

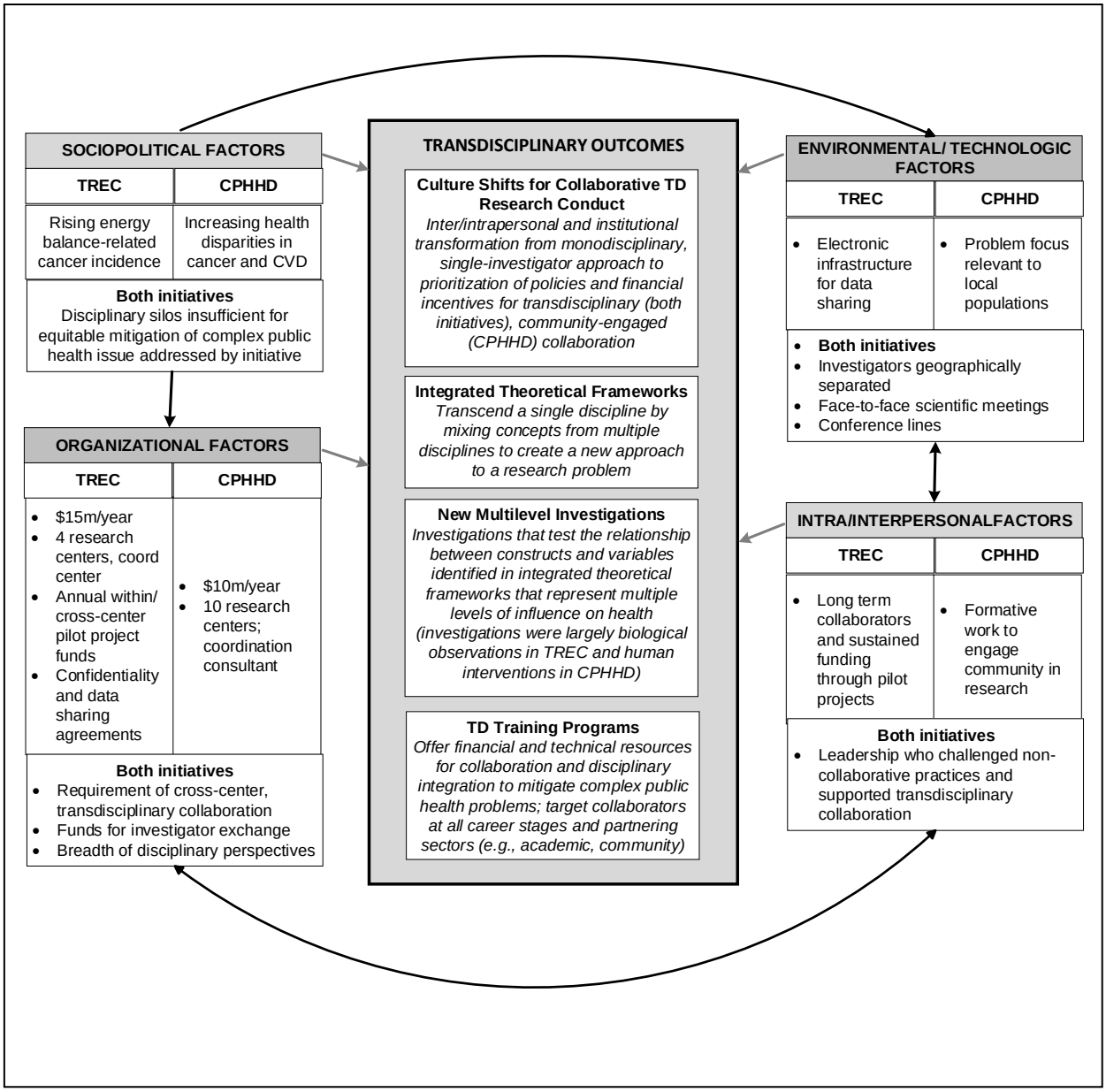
Table 4.3. Comparison of contextual factors that influenced transdisciplinary collaboration and outcomes in the TREC and CPHHD

	TREC (2011-2016)	CPHHD (2010-2015)
	PROGRAM SUMMARY	
Purpose	• Foster collaboration across multiple disciplines • Encompass projects that cover biology, gen/omics/etics of energy balance to behavioral, socio-cultural, and environmental influences on energetics and cancer risk • Establish transdisciplinary teams with appropriate expertise	• Promote transdisciplinary research in health inequities • Improve health outcomes and quality of life for populations with higher disease burden • Conduct interventions as primary objective
Goal	• Enhance knowledge of mechanisms underlying association between energy balance and cancer • Explore & integrate etiology of obesity and health behavior theories, with broad population impact at the social-environmental and policy levels for obesity prevention and control	• Understand pathways that result in disparate health outcomes • Develop comprehensive models of how various social, economic, cultural, environmental, biological, behavioral, physiological, and genetic factors affect individual health outcomes and their distribution in populations • Aid development of effective multilevel interventions to that promote health and/or reduce disease burden
Problem focus	Obesity, energetics and cancer	Individual and contextual factors underlying health disparities in cancer and cardiovascular disease
Population focus	Children, groups at high risk for obesity, cancer survivors	Population groups with differences in incidence, prevalence, mortality, and disease burden
	ORGANIZATIONAL FACTORS	
Funders (funded programs)	NCI (4 research centers; 1 coordination center)	NCI (5 centers); NHLBI (5 centers); OBSSR (meetings)
Budget (year $)	Annual: $15M (2010)	Annual: $10M (2009)
Funding mechanism	Research Project Cooperative Agreement (U54) Substantial funding agency programmatic involvement as partner, not directorship	Specialized Center (P50) Emphasizes a multi-disciplinary approach to a specified problem; centers serve as resources for research topic area

ORGANIZATIONAL, ENVIRONMENTAL, TECHNOLOGIC FACTORS		
Grant requirements	• 4 cores (recommended): administrative, bioinformatics, training, pilot projects• Define training program, budget required for trainee exchange and outreach activities• Collaborate across TREC Centers• Develop centralized resources with coordination center and NCI • Allocate budget for centralized data collection archived at coordination center• Sign confidentiality agreements; share knowledge, data, research materials with TREC investigators	• 1 core (recommended): administrative, others to Centers' discretion• Conduct minimum 1 multilevel intervention project• Develop training component, design defined by Centers• Participate in data harmonization activities• Interact with other CPHHD centers to share information (measures, protocols, methods), collaborate, identify opportunities for common measures
Resources and activities	• 8 face-to-face scientific meetings; 1 additional annual face-to-face Steering Committee meeting • Funded coordination center to integrate efforts of individual research centers • Trainee conference travel funds; investigator exchange funds managed by coordination center • Annual within- and cross-center pilot funds for ancillary research projects • 15 cross-center working groups	• 5 face-to-face scientific meetings; additional annual face-to-face Steering Committee meetings • Contracted scientific program coordinator to manage cross-center communication and administration • Ad-hoc funds for trainee exchange programs • Ad-hoc funds for ancillary pilot projects • 7 cross-center working groups

RFA: Request for Applications; TREC: Transdisciplinary Research on Energetics and Cancer; CPHHD: Centers for Population Health and Health Disparities; NCI: National Cancer Institute; NHLBI: National Heart, Lung, and Blood Institute; OBSSR: Office of Behavioral and Social Science Research

Figure 4.1. Transdisciplinary outcomes and contextual influences in TREC and CPHHD



Chapter 5. Conclusions

5.1 Summary of findings

The health of whole populations benefits from collaborative efforts to address the interacting biological, social, behavioral and environmental factors that influence public health problems and their outcomes. However, the prevailing approach to examining public health challenges has been to examine them within the confines of a single discipline, representing a gap between the nature of societal problems and the multifactorial approaches potentially available for their resolution. (18, 19). Although the contributions of individual disciplines have addressed many public health challenges and are critical to developing integrated frameworks capable of addressing factors across levels of influence, many complex health problems remain unresolved and would benefit from a transdisciplinary approach.

In this work, we utilized mixed- and multi-method qualitative and quantitative study designs and diverse analytic approaches to illustrate and empirically substantiate a conceptual model of transdisciplinary research. The work draws from diverse initiative documents as well as the rich experiences of investigators and funding agency representatives, and program staff from two NIH-funded initiatives, TREC and CPHHD. We used an approach in which members of these initiatives contributed to each phase of the research process to develop, critique, and compare transdisciplinary outcomes across multiple public health center grant initiatives. This work also evaluated longitudinal data to examine transdisciplinary behaviors and attitudes, which may help clarify the process of becoming transdisciplinary. The approach enabled systematic analysis of diverse perspectives across individuals from varying career stages, disciplinary backgrounds, and research initiatives to characterize transdisciplinary outcomes and expand the field of transdisciplinary public health research. The first study defined and characterized nine outcomes of the transdisciplinary approach to improve energy-balance-related cancer outcomes based on experiences of investigators in the TREC initiative: 1) new transdisciplinary team and consortia formation; 2) integrated theoretical framework development; 3) multi-level intervention model development and testing; 4) development and adaptation of relevant

statistical models; 5) translation of findings across levels of influence; 6) public policy influence; 7) transdisciplinary manuscript publication; 8) transdisciplinary grant awards; and 9) training the next generation of transdisciplinary researchers. The second study revealed that attitudes towards and behaviors that support collaborative, transdisciplinary research changed across TREC investigators over time, and that early career investigators had lower scores related to these measures compared to mid- and senior-career investigators. Furthermore, mean scores varied between disciplines. That study found that attitudes towards collaboration and participation in collaborative activities remained positive over the 5-year reporting period. These attitudes coincide with research that demonstrates that TREC II collaborations resulted in the development of robust training programs (29, 69, 89), new methods and frameworks (47, 90), and increased publications each year over time (81), previously identified outcomes of transdisciplinary research (34, 37, 77). The third study of this dissertation offered a comparative framework of transdisciplinary outcomes and their contextual influences in two NIH-funded transdisciplinary center grant initiatives. The study revealed four outcomes that were both common across the TREC and CPHHD and unique to transdisciplinarity: 1) culture shifts for collaborative transdisciplinary research conduct; 2) integrated theoretical frameworks; 3) new multilevel models; and 4) new transdisciplinary training programs. Each transdisciplinary outcome was characterized differently between the initiatives, variations that were likely influenced by the organizational, environmental, technologic, and intra/interpersonal contexts in which each initiative operated.

5.2 Implications

Altogether, the three studies in this dissertation make use of diverse data sources that include quantitative surveys, program documents, semi-structured interviews, and focus groups. Triangulation of the data sources and integration of findings across the three studies contribute to a more holistic understanding of transdisciplinary outcomes and the factors in the two NIH initiatives that facilitate or constrain achievement of those outcomes from the perspective of those involved. The conceptual

model we have developed and substantiated in this work can be used to facilitate systematic planning and implementation of transdisciplinary projects, assist in evaluating transdisciplinary research, determining if a transdisciplinary approach is suited for a research question, and, perhaps most importantly, assess the value of transdisciplinary approaches to resolving complex public health problems and promoting gains in public health.

5.3 Limitations

As each study highlighted, this work has several limitations. Two of these studies utilized qualitative techniques to analyze data from in-depth interviews and focus groups. Consequently, transdisciplinary outcomes were characterized based on experiences and perceptions of investigators from two initiatives only, which may not be representative of investigators across transdisciplinary initiatives in general. The nature of qualitative data is such that experiences are described and not quantified, so hypotheses about causal relationships can be generated but not tested in this work. Study three compared outcomes across TREC and CPHHD. However, the qualitative data only represent those who participated in the study and may not be representative of the entire TREC II or CPHHD II initiatives. In study two, no comparison group of investigators was surveyed to; therefore, we could not evaluate differences between TREC investigators' attitudes and behaviors over time and investigators from non-transdisciplinary initiatives that are addressing similar public health problems. In that study, the sample size was small, and data for all investigators was not available for all years as the composition of the TREC network changed over time.

5.4 Future research

This work presents several opportunities for future research. First, our work identifies transdisciplinary outcomes and assesses contextual factors that influence their characterization and achievement. We offer a framework for future investigation to assess how contextual factors, including attitudes and behaviors, quantitatively relate to the achievement of outcomes presented here, and how these

outcomes may promote gains in population health. The nature of qualitative data is such that experiences are described and not quantified, so hypotheses about causal relationships can be generated but not tested in this work. Further quantitative comparative research could elucidate if the contexts described by TREC and CPHHD investigators promote long term outcomes of transdisciplinary research, such as new policies and population health improvements. Moreover, research is needed to quantitatively assess causation between the context and transdisciplinary outcomes described here, and to evaluate the strategic investments in these contexts to produce transdisciplinary outcomes. Our data demonstrated that early career investigators' experiences, attitudes, and behaviors differ significantly from those at other career stages. Thus, future research is needed to distinguish the specific needs, experiences, and outcomes for trainees in a transdisciplinary initiative from those at other career stages. Such studies could compare career trajectories of individuals who participated in a transdisciplinary training program and those who did not to provide valuable information regarding the long-term impact of transdisciplinary training on investigators and on the outcomes associated with their research. Finally, although this work provides useful tools to advance the transdisciplinary research field, the effectiveness of the use of these tools over long time periods remains unexamined and a subject for future research.

5.5 Conclusion

The comprehensive set of transdisciplinary outcomes established in this dissertation, combined with the understanding of attitudes, behaviors, and contexts that influence transdisciplinary collaboration offer the public health research and practice community three main tools. First, the work offers and illustrates a conceptual framework for planning and evaluation of transdisciplinary research to address public health problems. Second, it demonstrates the diverse data sources and analytic techniques that can be used to evaluate such initiatives. Finally, it provides evidence regarding how and where to invest in and

prioritize resources in a transdisciplinary initiative for the greatest potential of achieving desired outcomes.

References

1. Nicolescu B. Methodology of transdisciplinarity. World Futures. 2014;70(3-4):186-99.
2. Bernstein JH. Transdisciplinarity: A review of its origins, development, and current issues. 2015.
3. Ertas A, Maxwell T, Rainey VP, Tanik MM. Transformation of higher education: the transdisciplinary approach in engineering. IEEE Transactions on Education. 2003;46(2):289-95.
4. Balsiger PW. Supradisciplinary research practices: history, objectives and rationale. Futures. 2004;36(4):407-21.
5. Patterson RE, Colditz GA, Hu FB, Schmitz KH, Ahima RS, Brownson RC, et al. The 2011–2016 Transdisciplinary Research on Energetics and Cancer (TREC) initiative: rationale and design. Cancer Causes & Control. 2013;24(4):695-704.
6. Abrams DB, Leslie F, Mermelstein R, Kobus K, Clayton RR. Transdisciplinary tobacco use research. Nicotine Tob Res. 2003;5 Suppl 1:S5-10.
7. Cooper LA, Ortega AN, Ammerman AS, Buchwald D, Paskett ED, Powell LH, et al. Calling for a bold new vision of health disparities intervention research. American journal of public health. 2015(0):e1-e3.
8. Warnecke RB, Oh A, Breen N, Gehlert S, Paskett E, Tucker KL, et al. Approaching health disparities from a population perspective: the National Institutes of Health Centers for Population Health and Health Disparities. Am J Public Health. 2008;98(9):1608-15.
9. National Center for Health Statistics. Health, United States, 2017: With special feature on mortality. Hyattsville, Maryland: CDC/National Center for Health Statistics Office of Analysis and Epidemiology; 2018.
10. Rosenfield PL. The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. Social Science & Medicine. 1992;35(11):1343-57.
11. Mobjörk M. Consulting versus participatory transdisciplinarity: a refined classification of transdisciplinary research. Futures. 2010;42(8):866-73.
12. Klein JT. Reprint of "Discourses of transdisciplinarity: Looking back to the future". Futures. 2015;65:10-6.
13. Stokols D, Hall KL, Vogel AL. Transdisciplinary public health: definitions, core characteristics, and strategies for success. In: Haire-Joshu D, McBride TD, eds. Transdisciplinary public health: research, methods, and practice. . San Francisco: Jossey-Bass; 2013:3-30.
14. Abrams DB, Leslie F, Mermelstein R, Kobus K, Clayton RR. Transdisciplinary tobacco use research. Society for Research on Nicotine and Tobacco; 2003.
15. Mermelstein R, Kobus K, Clayton R. Transdisciplinary tobacco use research: a decade of progress. Society for Research on Nicotine and Tobacco; 2007.
16. National Institutes of Health 2014;Pageshttp://www.nihorbit.org/.
17. ;Pageshttp://cancercontrol.cancer.gov/populationhealthcenters/cphhd/index.html.
18. Hadorn GH, Biber-Klemm S, Grossenbacher-Mansuy W, Hoffmann-Riem H, Joye D, Pohl C, et al. Handbook of transdisciplinary research: Springer; 2008.
19. Hadorn GH, Pohl C, Bammer G. Solving problems through transdisciplinary research. The Oxford handbook of interdisciplinarity: Oxford University Press New York; 2010:431-52.
20. Pohl C, Hadorn GH. Core terms in transdisciplinary research. Handbook of transdisciplinary research: Springer; 2008:427-32.

21. Wiesmann U, Biber-Klemm S, Grossenbacher-Mansuy W, Hadorn GH, Hoffmann-Riem H, Joye D, et al. Enhancing transdisciplinary research: A synthesis in fifteen propositions. Handbook of transdisciplinary research: Springer; 2008:433-41.
22. Pohl C**.** From science to policy through transdisciplinary research. Environmental Science & Policy. 2008;11(1):46-53.
23. Di Iacovo F, Moruzzo R, Rossignoli CM, Scarpellini P**.** Measuring the effects of transdisciplinary research: the case of a social farming project. Futures. 2016;75:24-35.
24. Serrao-Neumann S, Schuch G, Harman B, Crick F, Sano M, Sahin O, et al. One human settlement: A transdisciplinary approach to climate change adaptation research. Futures. 2015;65:97-109.
25. Lawrence RJ**.** Housing and health: from interdisciplinary principles to transdisciplinary research and practice. Futures. 2004;36(4):487-502.
26. Beland Lindahl K, Westholm E**.** Transdisciplinarity in practice: aims, collaboration and integration in a Swedish research programme. Journal of Integrative Environmental Sciences. 2014;11(3-4):155-71.
27. Vogel A, Stipelman B, Hall K, Nebeling L, Stokols D, Spruijt-Metz D**.** Pioneering the Transdisciplinary Team Science Approach: Lessons Learned from National Cancer Institute Grantees. Journal of translational medicine & epidemiology. 2014;2(2).
28. Hall KL, Vogel AL, Stipelman BA, Stokols D, Morgan G, Gehlert S**.** A four-phase model of transdisciplinary team-based research: goals, team processes, and strategies. Translational behavioral medicine. 2012;2(4):415-30.
29. Gehlert S, Hall K, Vogel A, Hohl S, Hartman S, Nebeling L, et al. Advancing Transdisciplinary Research: The Transdisciplinary Research on Energetics and Cancer Initiative. Journal of translational medicine & epidemiology. 2014;2(2):1032.
30. Vogel AL, Stipelman BA, Hall KL, Nebeling L, Stokols D, Spruijt-Metz D**.** Pioneering the Transdisciplinary Team Science Approach: Lessons Learned from National Cancer Institute Grantees. Journal of translational medicine & epidemiology. 2014;2(2).
31. Jahn T, Bergmann M, Keil F**.** Transdisciplinarity: Between mainstreaming and marginalization. Ecological Economics. 2012;79:1-10.
32. Klein JT**.** Evaluation of interdisciplinary and transdisciplinary research: a literature review. American journal of preventive medicine. 2008;35(2):S116-S23.
33. Lynch A, Thackway R, Specht A, Beggs PJ, Brisbane S, Burns E, et al. Transdisciplinary synthesis for ecosystem science, policy and management: The Australian experience. Science of the Total Environment. 2015;534:173-84.
34. Mitchell C, Cordell D, Fam D**.** Beginning at the end: The outcome spaces framework to guide purposive transdisciplinary research. Futures. 2015;65:86-96.
35. Stokols D, Fuqua J, Gress J, Harvey R, Phillips K, Baezconde-Garbanati L, et al. Evaluating transdisciplinary science. Nicotine & Tobacco Research. 2003;5(Suppl 1):S21-S39.
36. Hall KL, Stokols D, Moser RP, Taylor BK, Thornquist MD, Nebeling LC, et al. The collaboration readiness of transdisciplinary research teams and centers findings from the National Cancer Institute's TREC Year-One evaluation study. Am J Prev Med. 2008;35(2 Suppl):S161-72.
37. Carew AL, Wickson F**.** The TD wheel: a heuristic to shape, support and evaluate transdisciplinary research. Futures. 2010;42(10):1146-55.
38. Bangdiwala SI, Paula CSd, Ramiro LS, Muñoz SR**.** Coordination of international multicenter studies: governance and administrative structure. salud pública de méxico. 2003;45(1):58-66.
39. Hessels LK**.** Coordination in the science system: theoretical framework and a case study of an intermediary organization. Minerva. 2013;51(3):317-39.
40. Lauto G, Sengoku S**.** Perceived incentives to transdisciplinarity in a Japanese university research center. Futures. 2015;65:136-49.

41. Trochim WM, Marcus SE, Mâsse LC, Moser RP, Weld PC. The Evaluation of Large Research Initiatives A Participatory Integrative Mixed-Methods Approach. American Journal of Evaluation. 2008;29(1):8-28.
42. Boardman PC, Corley EA. University research centers and the composition of research collaborations. Research Policy. 2008;37(5):900-13.
43. Gehlert S, Carothers B, Lee J, Gill J, Luke D, Colditz GA. A Social Network Analysis Approach to Diagnosing and Improving the Functioning of Transdisciplinary Teams in Public Health. Transdisciplinary Journal of Engineering and Science. 2015;6:11-22.
44. Ross LF, Loup A, Nelson RM, Botkin JR, Kost R, Smith Jr GR, et al. The challenges of collaboration for academic and community partners in a research partnership: points to consider. Journal of empirical research on human research ethics: JERHRE. 2010;5(1):19.
45. Russell AW, Wickson F, Carew AL. Transdisciplinarity: Context, contradictions and capacity. Futures. 2008;40(5):460-72.
46. Boardman C, Gray DO, Rivers D. Cooperative research centers and Technical innovation: Government policies, industry strategies, and organizational dynamics. New York: Springer Science & Business Media; 2012.
47. Colditz GA, Gehlert S, Bowen DJ, Carson K, Hovmand PS, Lee JA, et al. Toward a modern science of obesity at Washington University: How we do it and what is the payoff? Cancer Prevention Research. 2016;9(7):503-8.
48. Hall KL, Feng AX, Moser RP, Stokols D, Taylor BK. Moving the science of team science forward: collaboration and creativity. Am J Prev Med. 2008;35(2):S243-S9.
49. Mâsse LC, Moser RP, Stokols D, Taylor BK, Marcus SE, Morgan GD, et al. Measuring collaboration and transdisciplinary integration in team science. Am J Prev Med. 2008;35(2):S151-S60.
50. Cummings JN, Kiesler S. Collaborative research across disciplinary and organizational boundaries. Social Studies of Science. 2005;35(5):703-22.
51. Stokols D, Misra S, Moser RP, Hall KL, Taylor BK. The ecology of team science: understanding contextual influences on transdisciplinary collaboration. American journal of preventive medicine. 2008;35(2):S96-S115.
52. Morgan GD, Kobus K, Gerlach KK, Neighbors C, Lerman C, Abrams DB, et al. Facilitating transdisciplinary research: the experience of the transdisciplinary tobacco use research centers. Nicotine & Tobacco Research. 2003;5(Suppl_1):S11-S9.
53. Wickson F, Carew AL, Russell AW. Transdisciplinary research: characteristics, quandaries and quality. Futures. 2006;38(9):1046-59.
54. Flinterman JF, Teclemariam-Mesbah R, Broerse JE, Bunders JF. Transdisciplinarity: The new challenge for biomedical research. Bulletin of Science, Technology & Society. 2001;21(4):253-66.
55. Brownson RC, Chriqui JF, Stamatakis KA. Understanding Evidence-Based Public Health Policy. American Journal of Public Health. 2009;99(9):1576-83.
56. Kobus K, Mermelstein R. Bridging basic and clinical science with policy studies: The Partners with Transdisciplinary Tobacco Use Research Centers experience. Nicotine & Tobacco Research. 2009;11(5):467-74.
57. Mitrany M, Stokols D. Gauging the transdisciplinary qualities and outcomes of doctoral training programs. Journal of Planning Education and Research. 2005;24(4):437-49.
58. Hall KL, Stokols D, Stipelman BA, Vogel AL, Feng A, Masimore B, et al. Assessing the value of team science: a study comparing center- and investigator-initiated grants. Am J Prev Med. 2012;42(2):157-63.
59. Gehlert S. Shaping education and training to advance transdisciplinary health research. Transdisciplinary Journal of Engineering & Science. 2012;3(1):1-10.

60. Hiatt RA, Rimer BK. A new strategy for cancer control research. Cancer Epidemiology Biomarkers & Prevention. 1999;8(11):957-64.
61. Stokols D, Hall KL, Taylor BK, Moser RP. The science of team science: overview of the field and introduction to the supplement. Am J Prev Med. 2008;35(2):S77-S89.
62. Turkkan JS, Kaufman NJ, Rimer BK. Transdisciplinary tobacco use research centers: a model collaboration between public and private sectors. Nicotine & tobacco research. 2000;2(1):9-13.
63. McAneney H, McCann JF, Prior L, Wilde J, Kee F. Translating evidence into practice: A shared priority in public health? Social Science & Medicine. 2010;70(10):1492-500.
64. National Cancer Institute 2006;Pageshttp://trecscience.org/trec/bin/about/archive05.aspx?j=21.
65. Klein JT. Crossing boundaries: Knowledge, disciplinarities, and interdisciplinarities: University of Virginia Press; 1996.
66. Walter AI, Helgenberger S, Wiek A, Scholz RW. Measuring societal effects of transdisciplinary research projects: design and application of an evaluation method. Evaluation and program planning. 2007;30(4):325-38.
67. Okamoto J. Scientific collaboration and team science: a social network analysis of the centers for population health and health disparities. Translational Behavioral Medicine:1-12.
68. Vogel AL, Feng A, Oh A, Hall KL, Stipelman BA, Stokols D, et al. Influence of a National Cancer Institute transdisciplinary research and training initiative on trainees' transdisciplinary research competencies and scholarly productivity. Translational behavioral medicine. 2012;2(4):459-68.
69. Schmitz KH, Gehlert S, Patterson RE, Colditz GA, Chavarro JE, Hu FB, et al. TREC to WHERE? Transdisciplinary Research on Energetics and Cancer. Clinical Cancer Research. 2016;22(7):1565-71.
70. Vogel AL, Hall KL, Fiore SM, Klein JT, Bennett LM, Gadlin H, et al. The team science toolkit: Enhancing research collaboration through online knowledge sharing. American journal of preventive medicine. 2013;45(6):787-9.
71. Hsieh H-F, Shannon SE. Three approaches to qualitative content analysis. Qualitative health research. 2005;15(9):1277-88.
72. Saldana J. The Coding Manual for Qualitative Researchers. 2009 Thousand Oaks. Calif Sage.
73. McTigue KM, Harris R, Hemphill B, Lux L, Sutton S, Bunton AJ, et al. Screening and interventions for obesity in adults: summary of the evidence for the US Preventive Services Task Force. Annals of internal medicine. 2003;139(11):933-49.
74. Jantsch E. Inter-and transdisciplinary university: A systems approach to education and innovation. Higher Education. 1972;1(1):7-37.
75. Czajkowski SM, Powell LH, Adler N, Naar-King S, Reynolds KD, Hunter CM, et al. From ideas to efficacy: The ORBIT model for developing behavioral treatments for chronic diseases. Health Psychology. 2015;34(10):971.
76. Klein JT. The transdisciplinary moment (um). Integral Review. 2013;9(2).
77. Stokols D, Harvey R, Gress J, Fuqua J, Phillips K. In vivo studies of transdisciplinary scientific collaboration: lessons learned and implications for active living research. American journal of preventive medicine. 2005;28(2):202-13.
78. Frescoln LM, Arbuckle Jr J. Changes in perceptions of transdisciplinary science over time. Futures. 2015;73:136-50.
79. Cooke NJ, Hilton ML. Enhancing the effectiveness of team science: National Academies Press Washington, DC; 2015.
80. Klein JT. A taxonomy of interdisciplinarity. The Oxford handbook of interdisciplinarity. 2010;15:15-30.

81. Gehlert S, Lee JA, Gill J, Patterson R, Schmitz K, Nebeling L, et al. The Structure of Distributed Scientific Research Teams Affects Collaboration and Research Output. Transdiciplinary Journal of Engineering and Science. 2017;8:1-19.
82. Beunckens C, Molenberghs G, Kenward MG. Direct likelihood analysis versus simple forms of imputation for missing data in randomized clinical trials. Clin Trials. 2005;2(5):379-86.
83. Diggle P. Analysis of longitudinal data: Oxford University Press; 2002.
84. Pohl C. What is progress in transdisciplinary research? Futures. 2011;43(6):618-26.
85. Fiore SM, Salas E, Cuevas HM, Bowers CA. Distributed coordination space: toward a theory of distributed team process and performance. Theoretical Issues in Ergonomics Science. 2003;4(3-4):340-64.
86. Wilson JM, Straus SG, McEvily B. All in due time: The development of trust in computer-mediated and face-to-face teams. Organizational behavior and human decision processes. 2006;99(1):16-33.
87. Hampton SE, Parker JN. Collaboration and productivity in scientific synthesis. BioScience. 2011;61(11):900-10.
88. Cummings JN, Kiesler S. Coordination costs and project outcomes in multi-university collaborations. Research Policy. 2007;36(10):1620-34.
89. James AS, Gehlert S, Bowen DJ, Colditz GA. A framework for training transdisciplinary scholars in cancer prevention and control. Journal of Cancer Education. 2015;30(4):664-9.
90. James P, Jankowska M, Marx C, Hart JE, Berrigan D, Kerr J, et al. "Spatial energetics": integrating data from GPS, accelerometry, and GIS to address obesity and inactivity. American journal of preventive medicine. 2016;51(5):792-800.
91. Goring SJ, Weathers KC, Dodds WK, Soranno PA, Sweet LC, Cheruvelil KS, et al. Improving the culture of interdisciplinary collaboration in ecology by expanding measures of success. Frontiers in Ecology and the Environment. 2014;12(1):39-47.
92. Kessel F, Rosenfield PL. Toward transdisciplinary research: historical and contemporary perspectives. American journal of preventive medicine. 2008;35(2):S225-S34.
93. Katz JS, Martin BR. What is research collaboration? Research policy. 1997;26(1):1-18.
94. Misra S, Stokols D, Cheng L. The transdisciplinary orientation scale: Factor structure and relation to the integrative quality and scope of scientific publications. Journal of Translational Medicine & Epidemiology. 2015;3(2):1042.
95. Börner K, Contractor N, Falk-Krzesinski HJ, Fiore SM, Hall KL, Keyton J, et al. A multi-level systems perspective for the science of team science. Science Translational Medicine. 2010;2(49):49cm24-49cm24.
96. Quinlan KM, Kane M, Trochim WM. Evaluation of large research initiatives: outcomes, challenges, and methodological considerations. New Directions for Evaluation. 2008;2008(118):61-72.
97. Wallerstein N, Duran B. Community-based participatory research contributions to intervention research: the intersection of science and practice to improve health equity. American journal of public health. 2010;100(S1):S40-S6.
98. Palinkas LA, Horwitz SM, Green CA, Wisdom JP, Duan N, Hoagwood K. Purposeful sampling for qualitative data collection and analysis in mixed method implementation research. Administration and Policy in Mental Health and Mental Health Services Research. 2015;42(5):533-44.
99. Glaser BG. The constant comparative method of qualitative analysis. Social problems. 1965;12(4):436-45.
100. Creswell JW, Plano Clark VL. Designing and conducting mixed methods research. 2nd ed. Thousand Oaks, CA: Sage Publications; 2011.

101. Wallerstein NB, Yen IH, Syme SL**.** Integration of social epidemiology and community-engaged interventions to improve health equity. American Journal of Public Health. 2011;101(5):822-30.
102. Hohl SD, Knerr S, Thompson B**.** A framework for coordination center responsibilities and performance in a multi-site, transdisciplinary public health research initiative. Research Evaluation. 2019.
103. Kastelic SL, Wallerstein N, Duran B, Oetzel JG**.** Socio-ecologic Framework for CBPR. In: Wallerstein N, Duran B, Oetzel JG, Minkler M, eds. Community-Based Participatory Research for Health: Advancing Social and Health Equity. San Francisco, CA: Jossey-Bass; 2017:77-93.
104. Wallerstein NB, Duran B**.** Using community-based participatory research to address health disparities. Health Promot Pract. 2006;7(3):312-23.
105. Morello-Frosch R, Brown P, Brody JG**.** Democratizing ethical oversight of research through CBPR. Community-based participatory research for health: Advancing social and health equity. 3 ed. San Francisco: Jossey-Bass; 2017:215-25.
106. Israel BA, Schulz A, Parker EA, Becker AB, Allen A, GUZ-MAN JR, et al. Critical issues in developing and following CBPR principles. 2008.
107. Wallerstein N, Oetzel J, Duran B, Tafoya G, Belone L, Rae R**.** What predicts outcomes in CBPR. Community-based participatory research for health: From process to outcomes. 2008;2:371-92.
108. Israel BA, Schulz AJ, Parker EA, Becker AB**.** Review of community-based research: assessing partnership approaches to improve public health. Annual Review of Public Health. 1998;19(1):173-202.