INNOVATION AS AN ADAPTIVE MANAGEMENT STRATEGY IN SOCIAL-ECOLOGICAL SYSTEMS

by

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A Dissertation

Submitted to the Faculty of Purdue University

In Partial Fulfillment of the Requirements for the degree of

Doctor of Philosophy

Lyles School of Civil Engineering

West Lafayette, Indiana

August 2019

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I dedicate this work to God; may it bring life and water.

ACKNOWLEDGMENTS

When we, in striving toward insurmountable goals, come to the end of ourselves, we face our own limitations, faults, and weakness and must seek the strengths, abilities, and gifts of those around us. Those giants on who's shoulders we stand, though mortal, appear to shine brighter when we reflect back on that wide gap they filled and high rung they enabled us to reach.

A special thank you to Linda Lee and Suresh Rao for such support and endurance. You saw something in an unlikely undergraduate student a decade ago; since then I have had many homes, many children and now three degrees. It has always been non-traditional, and I thank you for accepting me for me. I am also indebted to Zhao Ma who took a risk (she may or may not regret!) and in the face of many obstacles continued to believe in me and to push and support me throughout. David Yu also took a chance and under a tight timeline we accomplished a tremendous amount, and I will remain changed for the better as he pushed me to improve my way of communicating with the world. Thank you for not giving up on an untraditional student.

During our most difficult times in life, a friend can make the difference between success and failure. Some need many friends, and I am blessed to have such a group. I also acknowledge the comrade, the confidant, and the companion. I am forever thankful for Brandon Ennis, Micah Canfield and Tina Sterling for years of talking me off of ledges, putting out fires (quite literally for Micah), and offering words of encouragement. Let us celebrate!

In an entire league of their own are my ever-growing family. To my parents, Troy and Jamie, and my mother and father-in-law, Deb and Pat: anyone can welcome a college grad back to their basement, but few could welcome that student back three times…especially when the student brings five dependents with them…thank you for always welcoming and encouraging through good times and bad. To my parents, I owe a sense of illogical determination and will, as well as a desire to improve our world by improve the lives of our neighbors near and far. With the deepest love and respect, thank you.

At some point in life, to our surprise, we begin to notice others' feet on our own shoulders and realize that those giants who came to our aid were in fact mortal and faced their own challenges during the service provided. I acknowledge the sacrifice and stand in awe and gratitude. May I continue to carry such a torch as has been placed in my hand. The tiny feet in my life include my four children: Lailyn, Della, Geneva, and Samuel. This is the only life you know, and I look forward to showing you why it was all worth it. Life is found in the pursuit of meaning, wisdom, and love. When you need inspiration, please reread your favorite Narnia passages (especially those involving Reepicheep!). I love each one of you in so many different ways. Thank you.

And to my wife: you are my best friend and companion. The hills and valleys have been many, and the years have yielded closeness. I could not have done it without you. We have made it through, and let us celebrate the victories and look to a time of peace…. ILYSMICETY.

To all those mentioned, and to those whose influence I will never know, I say this: We did it.

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ABSTRACT

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Institution: Purdue University
Degree Received: August 2019
Title: Innovation as an Adaptive Management Strategy in Socio-Ecological Systems
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Innovation is promoted as a means to address global environmental challenges and achieve resilience in the UN Sustainable Development Goals. Innovation allows for adaptation and transformation in socio-ecological systems as part of the adaptive cycle. Within resilience literature, there are myriad definitions of innovation and disagreement about how to motivate diffusion of innovation, making implementation and the sustainability of innovations difficult. Specifically, matching the correct innovation to a given challenge and motivating the adoption of the innovation remains a roadblock to using innovation to address global environmental change. Here we show that there are explicit conflicts among definitions of innovation, and that innovation in the field does not align with some of these definitions. We found that the diverse definitions of innovation show a more complex view of innovation than normative treatment in policy suggests. We also found that several interacting motivations affect long-term participation in certain innovation activities. We discovered that binary views of innovation as either incremental or radical are generally supported in examples of innovation in the field, although some of the most successful examples of innovation better aligned with a continuum view of innovation associated with the adaptive cycle. Our results add to the warm-glow hypothesis that for altruistic tasks, the degree of participation motivated by a warm-glow feeling which can be enhanced by other motivations. Contrary to crowding out theory, our results suggest that monetary incentives result in higher adoption in Malawi where cost of contributing is high. The findings demonstrate the complexity of innovation, the misalignment between policy and practice, and ways in which adoption might be optimized. This research is a starting point to inform discussion about pragmatic innovation typologies. Such a typology could help operationalize the SDGs by framing the innovation dialogue between policy and practice.

1. INTRODUCTION

1.1 Innovation as an Adaptation Strategy

In response to global water challenges, the United Nations' (UN) Millennium Development Goals (MDGs) included a specific goal of reducing water scarcity in highly affected areas such as Africa (UN, 2019), but fell short of that goal, particularly in the poorest areas of Africa (Rigaud et al., 2018) such as Malawi (UNDP-WSP, 2006). The MDG's failure to meet the goals was due, in part to the approach. The MDGs were focused on addressing access to water, but not necessarily on the resilience or sustainability of those systems, but to global challenges such as climate change. Further, water access does not fully describe the diverse uses of water and subjectivity inherent in the volume of water desired by users of a water system. As a result, many newly created systems were built without these considerations in mind resulting in very low sustainability rates (UNDP-WSP, 2006; Adanke et al., 2012; Costanza et al., 2007). In response to these failures and the shortcomings of the original MDG approach, the UN developed the Sustainable Development Goals (SDGs). The SDGs were created to build upon the existing MDGs by leveraging *innovation* (Griggs et al., 2013) to address sustainability and resilience of water systems (UN 2018, Brown and Wyatt, 2010; United Nations, 2015). To effectively leverage innovation to solve global challenges, we must first gain some common understanding of what is meant by "innovation" and the best approaches to implementation. We must clarify important innovation questions such as innovation of what, for what purpose, at what scales and for whom? Of course, this will vary depending on the goals one seeks to accomplish, capacity for innovation and the ability to diffuse innovations.

Addressing large-scale environmental challenges, such as climate change, requires collective action and diffusion of innovation (Ostrom, 2010; Rockstrom et al., 2009; Dickinson, 2013; Holderness and Turpin, 2015; Rogers, 2010) and innovation. This work considers the diverse concept of innovation by synthesizing academic and policy writings on innovation and adaptation, explores empirical examples of innovations through qualitative field interviews in Malawi, and models scenarios of innovation diffusion considering participatory sensing.

The concept of *innovation* has been introduced into every level of academia, mainstream business and government (Ademar, et al., 2017; Mulgan, 2017). Innovation has also been widely

promoted as a means to achieve sustainability (Gassler et al., 2008; Kallerud, Egil, et al., 2013). For example, a number of United Nations' (UN) committees call for innovation to address sustainability across an array of thematic areas such as water, energy, transportation and climate change (UN 2018, Brown and Wyatt, 2010; Griggs et al., 2013; United Nations, 2015). Similarly, innovation has also been suggested as a mechanism to make socio-ecological systems more resilient (Hahn et al., 2006). In 2018, the UN High Panel on Water advocated for innovative approaches at the global, national, and local level to make water management and services more disaster-resilient (UNHLPW, 2018). Specifically, innovation has been considered in some cases as an enabling condition of adaptation (Few, 2017) which are processes to achieve resilience (Walker et al., 2004).

As presented by Rogers (2003), innovation can be defined as undertaking a new practice or incorporating a new technology to adapt to social-ecological change including climate change. Because the terms adaptation, transformation and innovation are often interchanged in the literature and considered interdependent, we cannot study one of the concepts without considering the others.

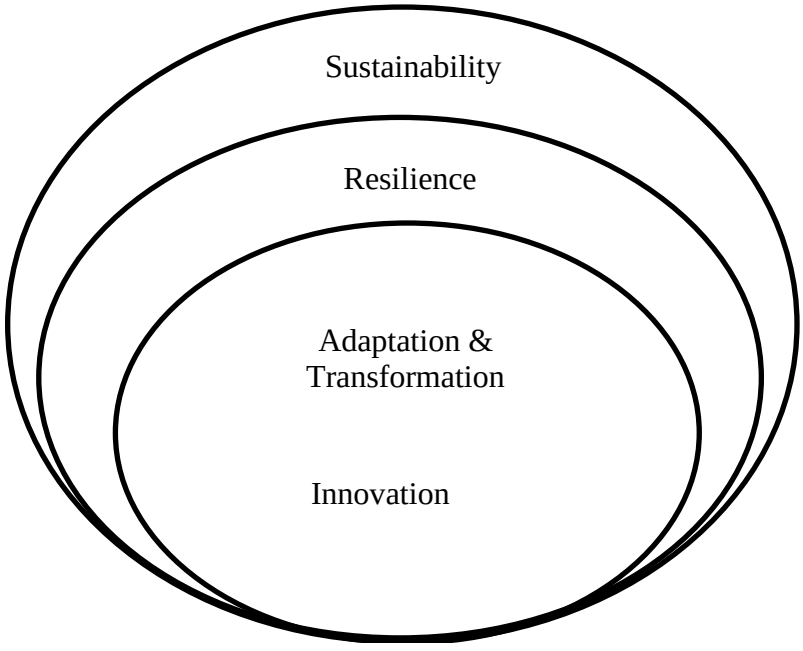

Figure 1-1: Embedded nature of innovation within broader resilience and sustainability concepts, adapted from Griggs et al., (2013) and Folke et al., (2010)

The term *innovation* is now so pervasive that it seems to no longer require definition for operationalization. Definitions of innovation used throughout resilience literature vary and lack consistency, due in part to the diversity of disciplines from which current resilience understanding is derived. The ambiguity and diversity of perspectives has led to confusion in the way ideas surrounding innovation are being, or can be applied, in policy and practice. Ely et al., (2017) state that "There is no consensus on a typology of new models or approaches to innovation in the literature", and "limitations in categorization of distinct innovation approaches" and "ambiguous terms" create a challenge. This diversity is problematic, as many high-level policy documents do not provide context or definition of the term innovation necessary to determine the type of innovation intended (Folke et. al., 2010). The lack of conceptual clarity around the term innovation in scholarly writing leaves interpretation up to the reader. Ambiguity also leaves practitioners—with different interests and visions—little choice but to apply innovation in the way they see fit, which could lead to a range of implementation which, in turn, may not align with the original policy goals.

Although innovation has been mentioned to some extent in the resilience literature, and to a larger extent in the development conversation (Bahadur et al., 2015; Burnharm and Ma, 2016; Mitchell, 2013; Winderl, 2014), it is sometimes treated in a normative way, meaning that some authors use the term innovation without providing a definition. One must interpret the writing or examples provided to ascertain the meaning behand the terms, which is challenging given that widely varying descriptions of innovation are included in other writings. In addition, sustainability problems are poorly formulated, confusing and involve many different actors with conflicting values (Waddock, 2013). In fact, the vagueness of SDGs and contributing factors, such as the normative treatment of innovation, interfered with locals in countries with higher poverty levels, such as Malawi, in meeting the SDGs. Malawi, like other UN member nations, proposed ideas ranging from implementing new technology to changing governance structures (UN, 2015). Although Malawi has made great effort toward the SDGs (Citizens Unite interview, Oct. 15 2014), many water solutions are failing (MWB, 2014). Due to different public, private and business ethics the collaborators' normative orientations will most probably vary and conflict. (Breuer, Henning, and Ludeke-Freund, 2014). In the face of ambiguity, locals are left making choices based more on intuition, subjective values and social norms than on rational use of scientific data. As a result, local people may not make the choices intended by the SDGs and therefore, fail to achieve the

results proposed. Without additional clarity and a working framework for innovation, operationalization of the SDGs will continue to prove challenging.

Previous studies have documented the implementation of innovations and their outcomes. Some have reflected on the normative treatment of innovation in the resilience literature in light of the SDGs. However, no empirical studies could be found that classify the innovations based on the SDGs. This research aims to add empirical insights into the way innovation is implemented at the community level as an adaptation strategy. The research is important, because when innovation is poorly executed as an adaption strategy, it leads to failure to achieve resilience (Few, 2017). We are concerned with examining real cases of adaptive strategies in Malawi and the role of innovation in adaption to increased water scarcity. We consider practices, activities and decision-making processes which might enhance resilience outcomes at scale. The results of SDG efforts have been poor in Malawi, and little is known about how SDGs are translated into practice. By comparing adaptation strategies in the field within a common innovation framework, we aim to gain insight into how policy becomes operationalized in Malawi.

When it comes to innovations, no innovation has transformed the African continent like the mobile phone. This technology has been leveraged for payments, healthcare, international business and has recently been proposed as a platform for participatory sensing. Participatory sensing is one innovation that enables collective action activity by harnessing large numbers of human sensors who actively collect and report data (Silva, 2016). Since this sensing data is free to the public, and can be used by anyone for individual benefit (Khan, 2013), the sensing data collected can be considered public good. Participatory sensing has the potential to improve our understanding of climate change in places such as Africa, where data is most needed (Chan et al., 2014). Africa is likely to be the continent most vulnerable to climate change, increased water stress and increased exposure to disease and other health risks (Parry et al., 2007). People have envisioned ways of using the billions of mobile phones around the world to collect data on the environment and phenomenon of interest. In areas of the world hardest hit by climate change, like Sub-Saharan Africa, people have proposed using mobile phones to collect information of interest such as information on water availability.

While several large pilot projects of participatory sensing have been launched, they have not been successful. This is due, in large part, to the difficulty of user onboarding and retention. Although participatory sensing has been tried in African countries like Malawi, more research is

needed to understand the lack of success due, in part, to low participation (Animal Demography Unit 201; Essoungou, 2010; FEWS NET, 2011; Meier, 2011; Sylla, 2003). One particular challenge related to low participation is the "Cold Start" problem: "in participatory sensing applications refers to the initial stage in service deployment during which service adoption remains sparse and, hence, the collected data does not offer adequate coverage." (Saremi and Abdelzaher, 2016, p. 99). The cold start problem can be caused by low motivations or detracting factors such as cost of sensing activities. Solving these types of participation challenges is critical to addressing the grand challenges facing our world (UN, 2015).

This research considers the diverse concept of innovation by synthesizing academic and policy writings on innovation and adaptation, explores empirical examples of innovations through qualitative field interviews in Malawi, Africa, and models scenarios of innovation diffusion considering participatory sensing in Malawi as a case study. We first provide a synthesis of peer-reviewed resilience literature to better understand how innovation is interpreted and incorporated within the resilience dialogue. With the synthesis we aim to understand how our understanding of innovation, and application of innovation in the field to achieve resilience, are informed by scholarly views of adaptation and transformation. This synthesis explores how several frameworks and typologies regard the key concepts of adaptation, transformation and innovation, and we use them as a reference point to investigate the similarities, differences and overlap among the views on innovation for resilience. We consider how this analysis can further reveal tensions among the descriptive dimensions of innovation which often become particularly noticeable when applying them to address real-world problems. After the synthesis, we focus on how innovation is being operationalized for adaptation using Malawi as a case study. We use data we collected on adaptations to apply a working framework to evaluate actual innovations which have been implemented in Africa. By understanding the role of innovation and how it is operationalized in practice, decision-makers will be able to better communicate needs, goals and desired outcomes and to analyze and select innovations among alternative choices. Finally, we examine how the innovation of participatory sensing can be used in Malawi and under what conditions might such innovations be diffused. Specifically, we address the role of motivation strategy in the adoption and sustained use of participatory sensing. Our paper adds to previous studies on participatory sensing by considering the evolutionary dynamics of a social system in which heterogeneous agents report on the condition of physical phenomenon and in which agents replicate social

behaviors based on the success of neighbors. We first provide a theoretical background on motivation in the context of participatory sensing, then explain why our model likely offers clues to understanding the role of reward, reputation and privacy on the effectiveness of incentive structures. We provide a brief overview of the design of the model, the indicators used to measure outcomes and the analysis of the model.

The results from this collective work on innovation can aid practitioners in identifying and building community capacity for innovation and adaptation. We also suggest a series of statements which can be used by researchers and policymakers to clarify innovation concepts, definitions and goals. Clarifying the intent of policymakers will help practitioners evaluate, interpret and operationalize policies. This work can also improve interdisciplinary approaches to innovation by clarifying concepts and minimizing unintended policy and program outcomes (Johnson et al., 2018). Furthermore, this work can guide future research studies on the role of different types of innovation in resilience (Armitage, 2003). Ultimately, community-level decision-makers will have access to knowledge to be able to take action to make their communities more adaptive to shocks and disturbances to their water systems.

1.2 Research Objectives

To combat the effects of climate change in the Sub-Saharan Africa, many technologies and innovations were implemented to meet the Millennium Development Goal of ending water scarcity. The high failure rate of these efforts demands an examination of the underlying assumption of what it mean to adapt to environmental change and what role innovation has to play. This dissertation research evaluates the current understanding of innovation and use of innovation as an adaptation strategy in meeting the newer Sustainable Development Goals. In conducting the research described under each of the aims, considerable effort was given to explore multiple facets of innovation and diverse views on innovation. To approach this work, I constructed a synthesis of academic and policy writings, conducted empirical qualitative interviews in Malawi, Africa, and performed exploratory modeling of innovation adoption scenarios with Malawi as a case.

Aim 1. Provide a synthesis of the peer-reviewed literature on resilience to better understand how innovation is interpreted and incorporated within the resilience dialogue. Such an analysis can reveal tension among the typologies of innovation, which often become particularly noticeable

when applying them to address real-world problems. Such a synthesis can aid practitioners in identifying and building community capacity for innovation and adaptation. Clarifying the intent of policymakers will help practitioners evaluate, interpret and operationalize policies. Furthermore, this synthesis can guide future research studies on the role of innovation in resilience (Armitage, 2003).

Aim 2. Understand how innovation is being operationalized for adaptation in Malawi, and how well the outcomes align with the goals of the SDGs. I seek to understand what this says about local interpretations and understandings of innovation in Malawi.

Aim 3. a) understand the relationship between motivation strategy and behavioral dynamics, b) identify thresholds for reward that lead to adequate participation while maintaining quality of data, and c) investigate the role of privacy and reputation for sustaining quality and participation. Organization

1.3 Innovation in Malawi: Participatory Sensing

This work consists of 5 chapters including the introduction already presented, 3 chapters representing each of the three main research objectives, and a closing summary chapter.

Chapter 2. This chapter aims to understand how our understanding of innovation, and application of innovation in the field for resilience, are informed by scholarly views on adaptation and transformation. This synthesis explores several frameworks and typologies regarding the key concepts of adaptation, transformation, and innovation, and uses these frameworks and typologies as reference points to investigate the similarities, differences and overlaps across the views on innovation for resilience. Explicitly considering the normative dimensions of innovation enables us to better understand the applications and limitations of the concept, identify opportunities for improving interdisciplinary collaborations, and consider different approaches to minimize unintended policy and program outcomes (Johnson et al., 2018). I also suggest a series of statements which can be used by researchers and policymakers to clarify innovation concepts, definitions and goals.

Chapter 3. In this chapter, I use data I collect on adaptations to apply a working framework to evaluate actual innovations which have been implemented in Africa. By understanding the role of innovation and how it is operationalized in practice, decision-makers will be able to better communicate needs, goals and desired outcomes and to analyze and select innovations among alternative choices. Understanding innovations will help communities leverage innovation to nudge or shift themselves into more desirable regime states, avoiding ramifications that accompany shocks or disturbances to the system. Ultimately, community-level decision-makers will have the knowledge to be able to take action to make their communities more adaptive to shocks and disturbances to their water systems.

Chapter 4. This chapter seeks to quantify the relationship between motivation strategies and adoption of a specific innovation, participatory sensing for public good. I approach this study by modeling a participatory sensing scenario inspired by qualitative research data from Malawi. By analyzing the effects of motivation and privacy on cooperation, our model represents a dynamic population of agents interacting indirectly and reporting data about physical phenomenon in their environment.

Chapter 5. The most important finding from these investigations are summarized along with future work needed.

2. CLARIFYING THE ROLE OF INNOVATION IN RESILIENCE

2.1 Introduction

Once reserved for high-tech companies, inventors and product designers, the concept of *innovation* has been introduced into every level of academia, mainstream business and government (Ademar et al., 2017; Mulgan, 2017). Innovation has also been widely promoted as a means to achieve sustainability (Gassler et al., 2008; Kallerud et al., 2013). For example, a number of United Nations' (UN) committees have called for innovation to address sustainability needs across an

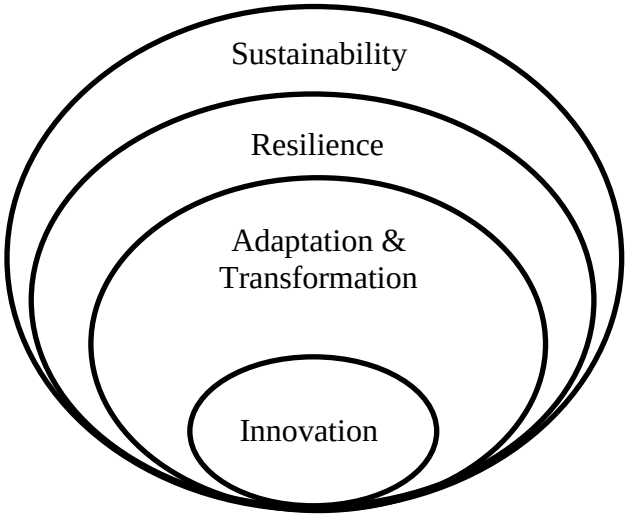

Figure 2-1: Embedded nature of innovation within broader resilience and sustainability concepts, adapted from Griggs et al., (2013) and Folke et al., (2010)

array of thematic areas such as water, energy, transportation and climate (Brown and Wyatt, 2010; Griggs et al., 2013; United Nations, 2015, 2018). Similarly, innovation has been suggested as a mechanism to make socio-ecological systems more resilient (Hahn et al., 2006). In 2016, the UN High Panel on Water advocated for "innovative approaches at the global, national and local level to make water management and water and sanitation services more disaster-resilient." Further, innovation has been considered in some cases as an enabling condition of adaptation (Few, 2017) which is necessary for achieving resilience (Walker et al., 2004). In this context, as defined by Rogers (2003), innovation can be considered as any idea, practice or technology for adapting to social-ecological change including climate change that is perceived as new by an individual or other unit of adoption. Kates et al. (2012) and Klein et al. (2014) also describe innovation as an

activity happening in a different place, location, or geography. In other words, an innovation may have been invented a long time ago, but if potential adopters perceive it as new, it may still be an innovation for them (Rogers, 2003). It has been shown that failure in innovation could lead to failure to achieve adaptation and transformation needed for a resilient system (Herselman et al, 2016; Wentzel and Pouris, 2007; Tschakert and Dietrich, 2010; Shiferaw et al., 2014; Millennium Ecosystem Assessment, 2005). Because adaptation, transformation, and innovation are often used interchangeably in the literature and considered interdependent, we cannot study one concept without considering the others (Figure 2). Within the field of political ecology, which is concerned with relations of power in environmental decision- making (Jones, 2008; Rocheleau et al., 1996) we find a means to approach these embedded concepts. By also leveraging a multi-scalar perspective and sociotechnical transition framework, we can consider the relationship of actors, their diverse innovation goals and environmental context while moving beyond elitism and technology-focused innovation (Figure 2-2) (Lawhon and Murphy, 2012) .

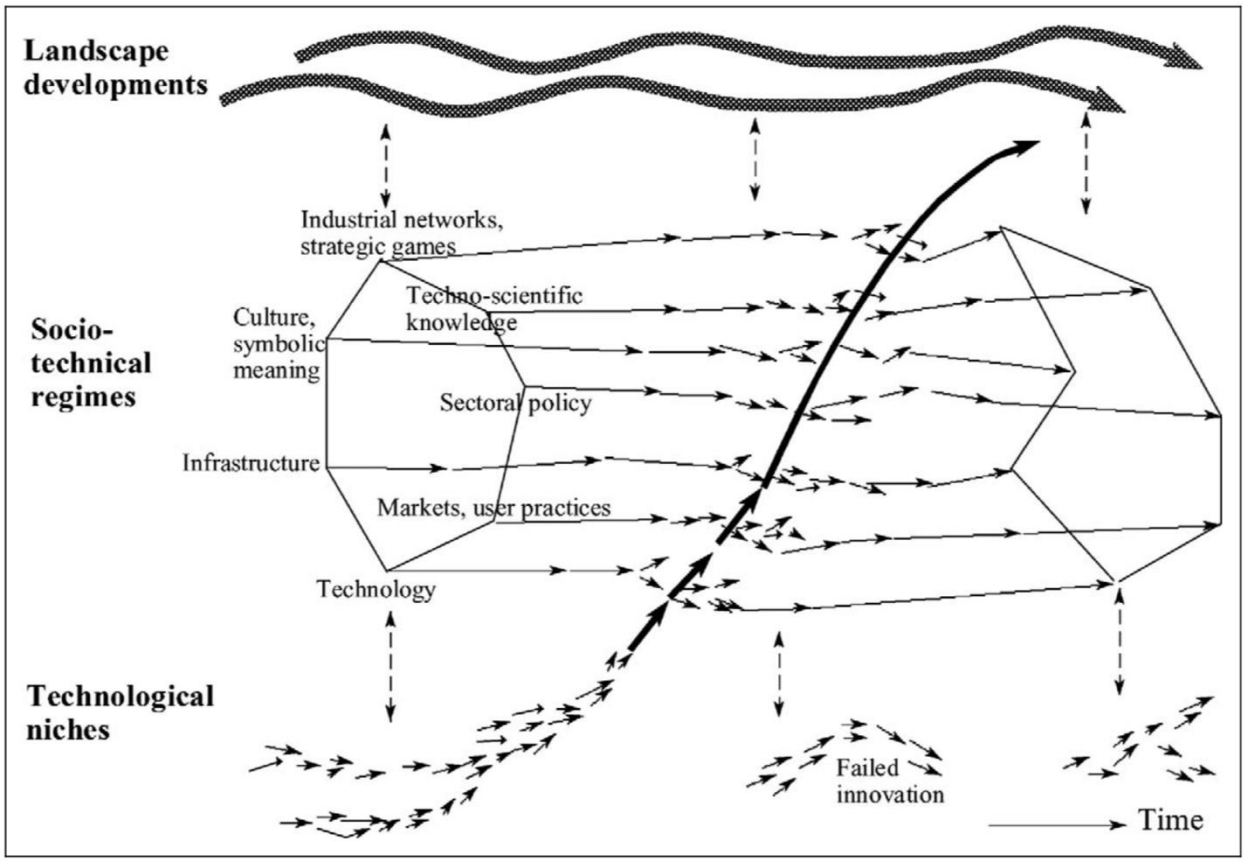

Figure 2-2 The multi-scalar framework for sociotechnical regime transitions Source: Geels (2004)

The term *innovation* is now so pervasive that it seems to no longer require definition for operationalization and often times definitions are absent. However, in the definitions which we do find, and in the examples of innovation provided in articles throughout resilience literature, we can see lack of consistency due, in part, to the diversity of disciplines from which current resilience understanding is derived. The ambiguity and diversity of perspectives has led to confusion in the way ideas surrounding innovation are being, or can be applied, in policy and practice. Ely et al., (2017) state that "There is no consensus on a typology of new models or approaches to innovation in the literature" (p. 4), and "limitations in categorization of distinct innovation approaches" and "ambiguous terms" (p. 4) create a challenge. This diversity is problematic, as many high-level policy documents do not provide context or definition of the term innovation necessary to determine the type of innovation intended (Folke et al., 2010). The lack of conceptual clarity around the term innovation in scholarly writing leaves interpretation up to the reader. Ambiguity also leaves practitioners—with different interests and visions—little choice but to apply innovation in the way they see fit, which could lead to a range of the implementation which may not align with the original policy goals.

The objective of this article is to provide a synthesis of the peer-reviewed literature on resilience to better understand how innovation is interpreted and incorporated within the resilience dialogue. In addition, this article aims to understand how our understanding of innovation, and application of innovation in the field for resilience, are informed by scholarly views on adaptation and transformation. This synthesis explores several frameworks and typologies regarding the key concepts of adaptation, transformation, and innovation, and uses these frameworks and typologies as reference points to investigate the similarities, differences and overlaps across the views on innovation for resilience. Such an analysis can further reveal tension among the typologies of innovation, which often become particularly noticeable when applying them to address real-world problems. Explicitly considering the normative dimensions of innovation enables us to better understand the applications and limitations of the concept, identify opportunities for improving interdisciplinary collaborations, and consider different approaches to minimize unintended policy and program outcomes (Johnson et al., 2018). Such a synthesis can aid practitioners in identifying and building community capacity for innovation and adaptation. We also suggest a series of statements which can be used by researchers and policymakers to clarify innovation concepts, definitions and goals. Clarifying the intent of policymakers will help practitioners evaluate,

interpret and operationalize policies. Furthermore, this synthesis can guide future research studies on the role of innovation in resilience (Armitage, 2003). Although this article is focused on innovation within the resilience literature, the findings may contribute to understanding innovation as discussed to a great extent in innovation studies, business, corporate and economics research, individual resilience, technology and social innovation.

2.2 Overview of Innovation in Resilience Literature

2.2.1 Defining and Categorizing Innovation

Much like the concept of resilience, the term innovation historically draws from a diverse array of disciplines, including technology, sociology and economics, which have shaped the concept over the past several centuries. As a result of this diversity, the literature on innovation is comprised of a myriad of definitions (Edquist, 2004), and determining which definition constitutes innovation depends on the lens through which it is viewed. A list of prominent frameworks shown in Table 1.

The term innovation first appeared around the 13th century but was rarely used until the 20th century (Godin, 2008). Other than a few examples (*The Prince*, 1513; *Of Innovations*, 1625), the word innovation would not come to prominence until it was used in the 18th century in patent law to distinguish plagiarism and imitation (Hilaire-Perez, 2000; Long, 2001; Macleod, 1988; Woodmansee, 1984). By the 19th century, innovation was used in sociology (Tarde, 1902) and anthropology to describe social novelty such as cultural change, agricultural inventions, and political inventions.

In the first half of the 13th century, research was postulated to be the originator of innovation; so claimed the ‘linear model of innovation’ developed by Rupert Maclaurin from MIT (Godin, 2017; Godin, 2008). According to some scholars (Gavin, 2001), the beginnings of a linear model called the Science-Push Model are directly linked with a report titled “*Science: The Endless Frontier*,” prepared for President Roosevelt by Vannevar Bush (1945). In Figure 3, Gust-Bardon (2012) illustrates the linear model as used for innovation in development for social outcomes.

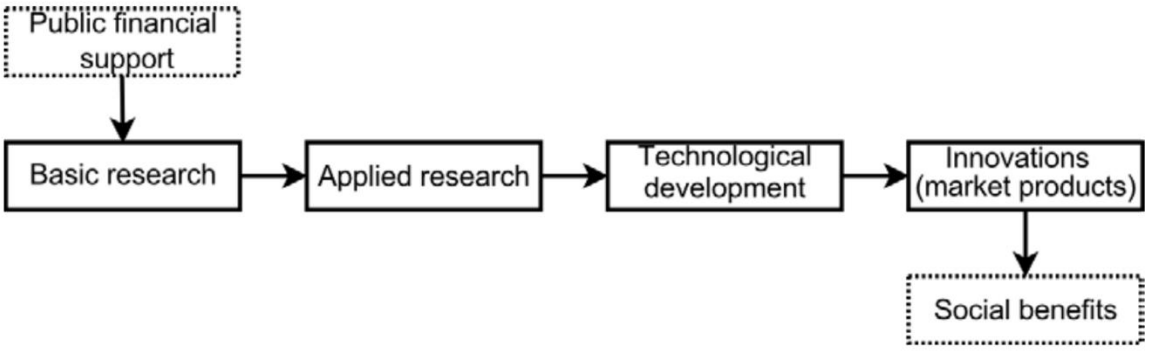

Figure 2-3: Linear Model as Used for Innovation in Development for Social Outcomes

These linear models strongly influenced the rise of industrialization, corporate R&D labs, push for intellectual property and commercialization in academic institutions. Innovation came to predominantly mean technological innovation. By the mid-20th century, anthropologists began to recognize the creativity inherent in diffusion, and described the phenomenon as inventive adaptation (Redfield et al., 1936; Barnett et al., 1954)—meaning adaptation that required new insights. During this time period, the concept of imitating novelty, or diffusion, was debated (Smith et al., 1927). Barnett (1953, p. 103) defied the technological definitions that dominated the field, and instead defined innovation as "any thought, behavior or thing that is new because it is qualitatively different from existing forms." Toward the end of the 20th century, innovation was continually influenced by the practice of technology commercialization, which led to the expansion toward the focus on technology-based innovation and commercialization. As Rogers (1962) states, "The adoption of a new idea almost always entails the sale of a new product" (p. 266). Building upon the work by Rogers, new theories explored the purpose, products and scale of innovation as innovation was adopted into economics and corporate uses. In one example, Kemp (2011) defines innovation as the implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organizational method in business practice. In addition to economics focused and mission-driven innovation, other new forms of innovation have emerged which prioritize social goals. New forms of innovation include: grassroots innovation, pro-poor and inclusive innovation, social innovation, and digitally-enabled open innovation, and collaboration innovation (Ely et al., 2017). Leach et al., (2012, p. 2) argue that innovation is not only "new ways of doing things, in science and technology, but also associated institutions and social practices." Biggs et al., (2010, p. 3) also argue that "social

innovation refers to new concepts, strategies, initiatives, products, processes, or organizations that meet pressing social needs and profoundly change the basic routines, resource and authority flows, or beliefs of the social system in which they arise (Westley et al., 2006, Young Foundation, 2006, p.xx)."

The field of sociology has also made strides to influence the way innovation has been defined beyond technology to broader adaptations. Dale et al., (2010) define innovation as being more than new technology, "Technical ingenuity creates new technology, but social ingenuity reforms old institutions and social arrangements into new ones". These new social perspectives challenge the role of technological innovations, such as alternative crop varieties and water harvesting technologies in drylands (Rickards and Howden, 2012; Rippke et al., 2016) and suggest that technocratic transformations alone do not have the capacity to serve as foundations for societal transformations (Few et al., 2017).

Kates et al., (2012), Few et al., (2017), and others have specifically related innovation to new adaptation activities and resilience. Understanding the relationship of innovation to adaptation is important for more broadly understanding the relationship between innovation and resilience. Each of the different interpretations of innovation uniquely interface with resilience and we must observe interactions of definitions at the adaptation and transformation level to understand the implications.

Table 2-1: Innovation Frameworks and Respective Definitions of Innovation

Name of framework	Definition of innovation
Buenstorf, 2000	None
Dale, Ling, and Newman, 2010	Innovation is more than new technology; technical ingenuity creates new technology, but social ingenuity reforms old institutions and social arrangements into new ones
3 D framework *(Melissa Leach, Johan Rockström, Paul Raskin, Ian Scoones, Andy C. Stirling, Adrian Smith, John Thompson, Erik Millstone, Adrian Ely, Elisa Arond, Carl Folke and Per Olsson)*	New ways of doing things, in science and technology but also associated institutions and social practices—has essential roles to play
Autonomous *(Bahadur and Doczi, 2016)*	The creation of a viable new offering, [which] requires identifying the problems that matter and moving through them systematically to deliver elegant solutions (Keeley et al. 2013).
Disruptive Innovation *(Christensen 1997)*	Innovations can be thought of as falling onto a continuum from evolutionary to revolutionary (Christensen, 1997; Hill and Jones 1998; Tidd et al, 1997; Trott, 1998; Veryzer, 1998) and therefore categorised into two groups: (1) Incremental or evolutionary innovations that improve the performance of established products, services or business models "along the dimensions of performance that mainstream customers in major markets have historically valued" (Christensen, 1997: (2) Revolutionary breakthroughs lie at the core of entrepreneurial activity and wealth creation (Schumpeter 1975) and almost by definition serve as the basis of future technologies, products, services and industries (Tushman and Anderson 1986). Terms such as "disruptive", "radical", "non-linear", "discontinuous", "breakthrough", "paradigm-shifting" and "revolutionary" have all been used to describe what is in essence the opposite of sustaining innovations.
Dahlin and Behrens, 2005	Radical innovation: novel, unique, and adopted
New Forms of Social Innovation *(Ely et al, 2017)*	New forms of social practice and organization, as well as new or improved technological products and processes
Typology of Change and Transformation (Few, 2017)	Completely novel activity or application of an activity in a new location
Eco-Innovation *(Kemp, 2011)*	Innovation: implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organizational method in business practice
Moore and Westley, 2011	Social innovations—that is, any initiatives, products, processes, or programs that change basic routines, resource and authority flows, or beliefs of any social system.
Obrecht, 2016	
Panarchy (Holling et al. 2002). (Alan and Holling, 2008) *Incremental and Radical, Social Innovation* *(Biggs et al, 2010)*	Social innovation refers to new concepts, strategies, initiatives, products, processes, or organizations that meet pressing social needs and profoundly change the basic routines, resource and authority flows, or beliefs of the social system in which they arise (Westley et al. 2006, Young Foundation 2006).
Radical Innovation *(Norman and Verganti, 2016)* *(Norman, 2014)*	
Rogers, 1962; Rogers, 2010	Defined as an idea, practice, or object that is perceived as new by an individual or another unit of adoption
X-Innovation *(Godin, 2017)*	Innovation is the diffusion (adoption to the sociologist; commercialization to the economist) of invention.
10 types of Innovation (Keeley et al, 2013)	

2.2.2 Relationship between innovation and resilience

Some scholars directly relate innovation to resilience as a means of supporting adaptive capacity, enhancing resilience (Adger, 2003) and producing resilient outcomes (Few et al., 2017). Broadly, resilience is defined as "the capacity of a social-ecological system to absorb or withstand perturbations and other stressors such that the system remains within the same regime, essentially maintaining its structure and functions" (http://www.resalliance.org/key-concepts). It describes the degree to which the system is capable of self-organization, learning and adaptation (Holling,

1973; Gunderson and Holling, 2002; Walker et al., 2004). Innovation has been identified as a source of resilience and adaptation across a number of resilience subfields, including urban resilience (Godschalk, 2003; Brown et al., 2012; Chelleri, 2012; Davoudi et al., 2013; Cartalis, 2014; Polèse, 2015), disaster resilience (Paton and Johnston, 2006; Boin and McConnell, 2007; Boin et al., 2010; Zhou et al., 2010) and community resilience (Norris et al., 2008; Twigg, 2009; Magis, 2010; Berkes and Ross, 2013; Skerratt, 2013; Wilson, 2013; Ross and Berkes, 2014). Throughout the literature, the concept of innovation varies typologically and epistemologically by resilience subfields, e.g., the study of disasters, environments, sustainability or communities.

Within the context of socio-ecological resilience, innovation has been defined as "a completely novel activity" (Few, 2017, p.4). By social-ecological systems we mean "complex, integrated systems in which humans are part of nature" (Resilience Alliance, 2019). Klein et al., (2014, p. 31) expand the concept of innovation to include "… new practices and geographic shifts in the location of activities." Novelty is now understood in social-ecological systems as the creation of new things, or new combinations (Allen and Holling, 2010) via natural or human process, and innovation is the process whereby humans develop novelty (Allen et al., 2014). Few (2017) further defines innovation not only as a completely novel activity but also includes the application of an activity in a new location.

Innovation and novelty are operationalized through adaptation and transformation, which are analytical concepts nested within resilience (Walker et al., 2004). Adaption and transformation are often characterized as either binary or two points on a continuum (Johnson et al., 2018), and adaptation, transformation, and innovation have all been described, at times, using the polarizing adjectives "incremental" and "radical". Few (2017) suggests innovation is a mechanism for achieving both incremental and non-incremental or "radical" change. For example, both the incremental adjustments to practices in response to changing conditions (Kates et al., 2012; Denton et al., 2014; Klein et al., 2015) and the fundamental changes inherent in an adaptation activity, or transformation, can be achieved through innovation (Few et al., 2017).

As mentioned, adaptation and transformation have both been used within the resilience literature as interchangeable with innovation. Authors have used certain metrics and indicators to differentiate types of innovation and their relationship to adaptation and transformation. Dahlin and Behrens (2005) have specific criteria to distinguish non-incremental from incremental innovation. To be non-incremental, or what Dahlin and Behrens (2005) call "radical," an

innovation must be novel, unique and adopted. For example, Folke et al., (2010) suggest that adaptation can be instrumental in helping communities survive periods of change or shock, tends to be incremental in nature and can be either localized or systemic (Kates et al., 2012; Pelling, 2010). Few et al., (2017) also consider radical and incremental to be mutually exclusive forms of innovation, separated by scope and scale. Norman and Verganti separate innovation outcomes by degree of technical change and degree of change in social meaning achieved. In their framework, a high degree social meaning change is required for an innovation to be radical, whereas a low degree of meaning change constitutes an incremental change, regardless of degree of technical change that occurs. This aligns well with Few et al.'s (2017) definition of radical change which focuses on a high degree of social change. Adaptation mechanisms, such as innovation, can influence whether or not an adaptation is incremental or a step-change is required for transformation to occur (Few et al., 2017).

Other scholars, like Christensen (1997) view innovation not as binary, but as non-discrete phases in a continuum. Innovations can be thought of as falling onto a continuum from evolutionary to revolutionary (Christensen, 1997; Hill and Jones, 1998; Tidd et al., 1997; Trott, 1998; Veryzer, 1998) and therefore categorized into two groups: (1) incremental or evolutionary innovations and (2) revolutionary breakthroughs which lie at the core of entrepreneurial activity and wealth creation (Schumpeter, 1975). Terms such as "disruptive," "radical," "non-linear," "discontinuous," "breakthrough," "paradigm-shifting" and "revolutionary" have all been used to describe what is in essence the opposite of sustaining innovations." Christensen has been quoted by a number of resilience scholars as a basis for their views on innovation (Leach et al., 2012; Biggs et al., 2010; Moore and Westley, 2011; Westley et al., 2011) Dahlin and Behrens (2005) define radical innovation using three criteria: novel, unique and adopted.

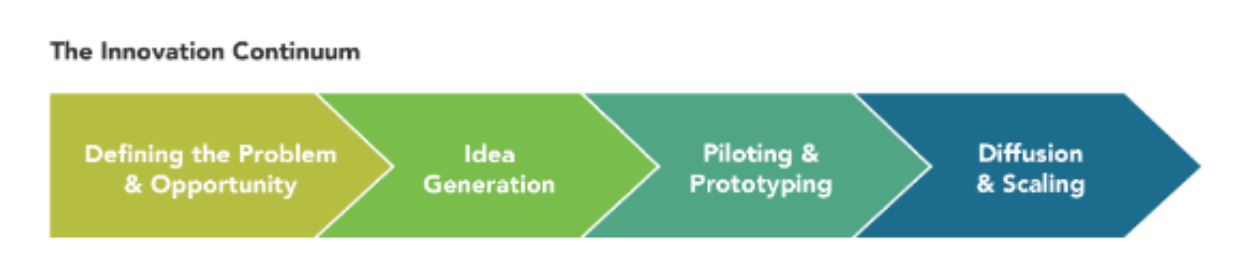

Figure 2-4: Deiglmeier and Greco (2018)'s Innovation Continuum by Which Innovation Scale Up

Still, other scholars see innovation as occurring not as binary or on a linear continuum, but within a cyclical process such as the adaptive cycle (Biggs et al., 2010) which "alternates between long periods of aggregation and transformation of resources and shorter periods that create opportunities for innovation" (Holling et al., 1986, p. 292-317). According to the Resilience Alliance (2019), the adaptive cycle has been proposed as a "fundamental unit for understanding complex systems from ecosystems to societies" and has four phases (Figure 5): 1) growth or exploitation (r); 2) conservation (K); 3) collapse or release (omega); and 4) reorganization (alpha).

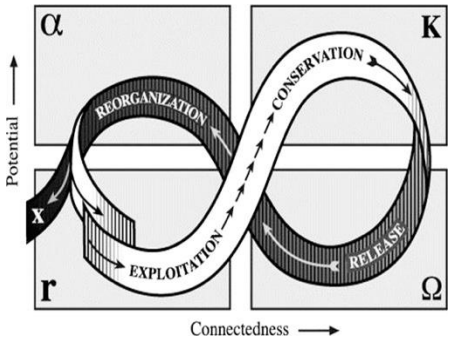

Figure 2-5: The Adaptive Cycle and the Role of Incremental and Radical Innovation

As discussed, innovation has been considered to be another word for adaptation activities and the relationship between incremental and radical innovation can be understood in terms of the adaptive cycle (Holling, 2001; Gunderson and Holling, 2002). The multi-level process of the adaptive cycle includes two major phases. The first, often referred to as the front loop, from r to K, is the slow, incremental phase of growth and accumulation (Resilience Alliance, 2019). "The front loop of the adaptive cycle can be seen as largely characterized by incremental innovation that strengthens the current system or trajectory of change" (Biggs et al., 2010, p. 3). The second, referred to as the back loop, from omega to alpha, is the rapid phase of reorganization leading to renewal. "In contrast, the back loop may be precipitated by, or create a window of opportunity for, radical innovation" (Biggs et al., 2010, p. 3). Figure 6 illustrates the adaptive cycle and the role of incremental and radical innovation (Biggs et al., 2010).

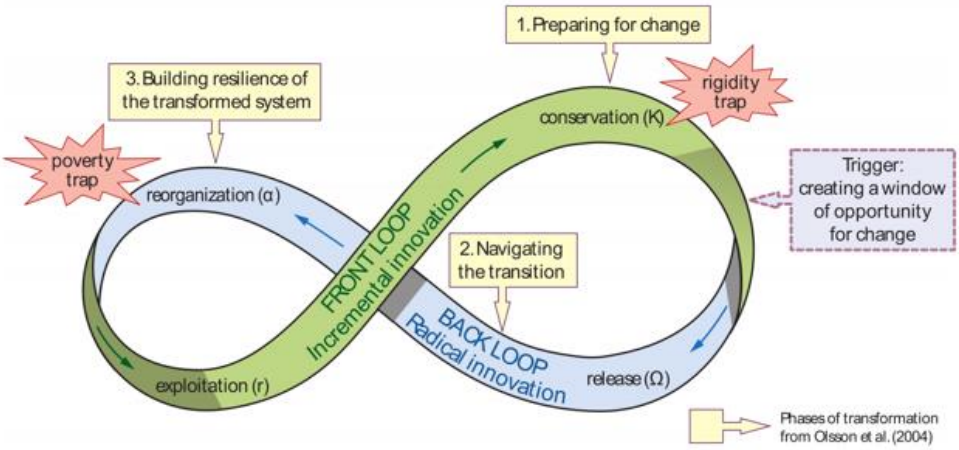

Figure 2-6: The Adaptive Cycle and the Role of Incremental and Radical Innovation (Biggs et al., 2010)

2.2.3 Diffusion and scaling of innovation in resilience

Adaptive cycles are nested in a hierarchy across time and space (Resilience Alliance, 2019). O'Connell et al., (2015, p. 19) believe that "It's all a matter of scale, in time and space…" This hierarchy helps explain how adaptive systems can, for brief moments, generate novel re-combinations that are tested during longer periods of capital accumulation and storage. A nested hierarchy of adaptive cycles represents a panarchy (Resilience Alliance, 2019 Within this panarchy, transformation comes from innovations occurring in the back loop which may lead to fundamental reorganization of the social-ecological systems (Walker et al., 2004; Chapin et al., 2009). Although the radical innovations of the back loop are associated with transformation, some scholars recommend incremental-type innovation from the front loop that can serve as a mechanism to achieve transformation and radical change over time. It could be interpreted that these scholars believe that the processes of localized iteration, evaluation and adjustment can lead to big, incremental changes and transformation while others strongly disagree. Another related concept is the scalability of innovation from small or local scale to larger scales through diffusion (Rogers, 2005) or expansion (Few et al., 2017). Diffusion, or the spread of innovation, depends on many factors such as networks, policy environment and cultural norms (Rogers, 2003). In fact, there is disagreement within the literature concerning the ability of incremental, small changes to lead to transformation either directly or through scaling up.

Many scholars contend that transformation is only possible through more radical innovation that brings new technology and restructures social structure (Pelling et al., 2015). For example, Norman and Verganti (2014, p. 2) believe that incremental innovation, called "hill-climbing," "guarantees continual improvement to the top of the current hill, but it can never lead to another higher hill, much less the highest. In other words, it cannot lead to radical change or innovation." Moore and Westley (2011) make this distinction between transformative or "disruptive" innovations from adaptive innovations by using the breadth of impact and the disturbance the innovations create. Many resilience scholars discredit or overlook small-scale innovation entirely. For instance, Davidson et al., (2016) include innovation as a factor of transformative resilience but did not include innovation as a factor of adaptive resilience. By not distinguishing between incremental and radical change, the reader may be misled unintentionally.

Other studies show that enough incremental change, or incremental change at the right time, can lead to a transformational effect. O'Connell et al., (2015, p. 34) believe that "…actions which are labeled 'incremental adaptation' over the shorter term, may be seen as transformational over the longer term." As an example, Obrecht (2016) would argue that product innovations, such as ready-to-use therapeutic foods (RUTFs), can be transformative by having ripple effects on processes and relationships in humanitarian assistance. Folke et al., (2010, p. 1) state that "transformation does not take place in a vacuum but draws on resilience from multiple scales." Furthermore, Folke (2010, p. 7) believes that "transformational change at smaller scales enables resilience at larger scales, while the capacity to transform at smaller scales draws on resilience at other scales." Another phenomenon, discussed in more detail below, is the embedding of innovation at multiple scales. Sometimes, in order to maintain the same system at one scale, transformations may have to occur at a finer scale (O'Connell et al., 2015). It is important to gain clarity, because these differences can have a large effect on policy and resource allocation. Identifying a working framework for innovation in adaptation and transformation is important in order to apply this knowledge in practice and policy.

2.3 Common Innovation Frameworks

2.3.1 Introduction of frameworks

A number of frameworks have been proposed in the literature which seek to clarify the types of innovation and relationship to change. Authors tend to present innovation types as "X-innovation", in which X represents some descriptive adjective and the type of innovation is distinguished by that adjective (Godin, 2008). Examples include the "eco," "social," or "rapid" in eco-innovation, social innovation or rapid innovation, respectively. Because the concept of innovation owes its epistemological roots to many different disciplines and, as a result innovation is described in many different ways across the literature. Figure 8 highlights a sample of innovation frameworks used in the resilience literature.

Name of framework	Categories of Innovation
Buenstorf, 2000	Process; Product; Incremental; Imitation vs innovation; synonymous with "mutation"; Technological; Economic; Biological
Dale, Ling, and Newman, 2010	Technological and social; incremental; strategic
3 D framework *(Melissa Leach, Johan Rockström, Paul Raskin, Ian Scoones, Andy C. Stirling, Adrian Smith, John Thompson, Erik Millstone, Adrian Ely, Elisa Arond, Carl Folke and Per Olsson)*	Top-down; grass-roots; social; technological; transformative;
Autonomous *(Bahadur and Doczi, 2016)*	Autonomous vs Traditional; improvisation; 'frugal'; jugaad; traditional; simple
Disruptive Innovation *(Christensen 1997)*	Incremental or evolutionary vs distruptive or revolutionary; radical; non-linear; discontinuous; breakthrough; paradigm-shifting
Dahlin and Behrens, 2005	Radical vs incremental; equates invention to innovation
New Forms of Social Innovation *(Ely et al, 2017)*	Mission-oriented; pro-poor and inclusive; grass roots; social; and digitally enabled open and collaborative
Typology of Change and Transformation (Few, 2017)	Instrumental; progressive; radical; transformational; transformative
Eco-Innovation *(Kemp, 2011)*	Normal innovation; eco-innovation; radical; incremental; non-incremental; disruptive
Moore and Westley, 2011	Social; transformative; disruptive; adaptive
Obrecht, 2016	
Panarchy (Holling et al. 2002). (Alan and Holling, 2008) *Incremental and Radical, Social Innovation* *(Biggs et al, 2010)*	Background, Incremental, and Puncuated; radical; Social
Radical Innovation *(Norman and Verganti, 2016)* *(Norman, 2014)*	Category: Radical Sub-categories: Tech-Epiphany, Meaning Driven
Rogers, 1962; Rogers, 2010	Most of the innovations studied are technological in nature, but some are policy or other social-learning innovations.
X-Innovation *(Godin, 2017)*	Maybe high level tech vs social..., then myriad x innovations
10 types of Innovation (Keeley et al, 2013)	Configuration – innovations that focus on the innermost workings of an organization and its business system: 1. profit model: how an organisation makes money 2. network: how an organisation connects with others to create value 3. structure: how an organisation organises and aligns its talent and assets 4. process: how an organisation uses signature or superior methods to do its work Offering – innovations that focus on an organisation's core product or service, or a collection of its products and services: 5. product performance: how an organisation develops distinguishing features and functionality 6. product system: how an organisation creates complementary products and services Experience – innovations that focus on more public-facing elements of an organisation and its business system: 7. service: how an organisation supports and amplifies the value of its offerings 8. channel: how an organisation delivers its offerings to customers and users 9. brand: how an organisation represents its offerings and business 10. customer engagement: how an organisation fosters compelling interactions

Figure 2-7: Innovation Frameworks and Their Respective Categories of Innovation

As influential frameworks, such as Christensen's (1997) disruptive innovation framework, have influenced other scholars, certain terms and concepts in the original frameworks have spread to later frameworks. For instance, Christensen (1997) holds a continuum view of incremental and radical innovation, as well as a focus on the object and outcomes of innovation, concepts which have been adopted by others in the resilience literature. Alternatively, new frameworks, like Bahader and Doczi (2016) which focus on the source of innovation instead of object or outcome, have offered meanings which are quite different from the mainstream and create a rift in the literature. For this synthesis, we seek to understand the relationships among these disparate views to find overlap and underlying disagreement. To best highlight the differences in reference to resilience and the adaptive cycle, we focus on four key aspects: 1) the way in which they define innovation; 2) typology of innovation; 3) indicators and metrics used to describe and categorize; and 4) view of incremental vs non-incremental change.

2.3.2 Definition and typology

Three major types of innovation identified in the literature are relevant to our focus on resilience in socio-ecological systems: social, technological and environmental innovation. Few et al., (2017) provide a typology of change and transformation which includes innovation as a mechanism of transformation. They separate innovation into instrumental, progressive and radical (Few et al, 2017, p. 5). Kemp (2011, p. 3) uses the Oslo Manuel (OECD, 2005) to define innovation as "implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organizational method in business practice." Rogers, who is widely known for exploration of diffusion of innovation (Rogers, 1962; Rogers, 2010), defines innovation as an idea, practice or technology that is perceived as new by an individual or another unit of adoption. Bahadur and Doczi (2016, p. 8), influenced by Keeley et al., (2013, p.6-7), defines innovation as "The creation of a viable new offering, which requires identifying the problems that matter and moving through them systematically to deliver elegant solutions." Rogers (2010) uses innovation and technology as synonyms but acknowledges that innovations can sometimes be social. Dale, Ling and Newman (2010, p. 220) go further and define innovation as more than new technology by stating that "technical ingenuity creates new technology, but social ingenuity reforms old institutions and social arrangements into new ones."

The recent focus on social innovation is in response to the decades-long push for technology. For example, Leach et al., (2012, p.2) define innovation beyond science and technology to also include "…associated institutions and social practices, which have essential roles to play." Moore and Westley (2011), influenced by Christensen (2013), focus on social innovations, which they define as any initiatives, products, processes, or programs that change basic routines, resource and authority flows, or beliefs of any social system. They believe that all innovation is a recombination of older elements. With their typology, Ely et al., (2017) add clarity around the many forms of social innovation. They pose that social innovation means "new forms of social practice and organization, as well as new or improved technological products and processes."

In addition to general social innovation, Kemp (2011) also provides a framework specifically for "eco-Innovation" and defines eco-innovation as "the production, assimilation or exploitation of a product, production process, service or management or business method that is novel to the organization (developing or adopting it) and which results, throughout its life cycle, in a reduction of environmental risk, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives." Biggs et al., (2010) use a hybrid adaptive cycle based on Holling et al., (2002) and Allen and Holling (2008) to study social innovation in the context of resilience in socio-ecological systems. They define social innovation as "new concepts, strategies, initiatives, products, processes, or organizations that meet pressing social needs and profoundly change the basic routines, resource and authority flows, or beliefs of the social system in which they arise" (Westley et al., 2006, Young Foundation, 2006). Biggs et al., (2010) also posit that innovation happens across a nested hierarchy of adaptive cycles, representing a "panarchy" (Allen and Holling, 2008). This multi-scale view of innovation is based on a form of continuum from incremental innovation to radical innovation, but not all scholars subscribe to a continuum view of innovation.

View of Incremental vs non-incremental

The words incremental and radical are used within the literature to distinguish types of incremental and non-incremental change, and these terms also appear in various frameworks but carry with them different conceptual meaning (Few et al., 2017; Norman and Verganti, 2014; Godin, 2008). In addition, the frameworks may use entirely different objects of innovation. By

object of innovation, we mean the "what" of innovation, or what is being innovated upon. They different objects of innovation also carry with them different indicators and metrics used to distinguish and measure types of innovation. In addition to definition, object, and metrics, there is also the debate about whether or not innovation is binary or on a continuum. All of these factors make comparison and interoperability of certain frameworks challenging.

Some scholars hold a binary view of innovation. Some scholars believe that the major difference between incremental and radical methods and outcomes is whether the innovation is perceived as a continuous modification of previously accepted practices (incremental) or whether it is new, unique and discontinuous (radical) (Norman and Verganti, 2014). The nature of incremental and radical innovation as either binary or of continuum nature is also debated: "It is not assumed that one classification is necessarily connected to or leads to another classification: hence the "types," "target outcomes" and the "transformation/transformative" descriptions are in essence describing independent dimensions of an action. Each alternative within those can plausibly be linked to any of the others (as an example, at least in theory, "an innovation could be instrumental, progressive or radical, transformational and transformative" (Few et al., 2017, p.6). Dahlin and Behrens (2005) focus on a binary comparison of radical innovations to incremental innovations and define radical innovation as novel, unique and adopted. Ely et al., (2017) believe that incremental and non-incremental innovation, referred to as transformational innovation, are not necessarily part of same continuum. Few et al., (2017) sees incremental and non-incremental forms of innovation as exclusive and discrete.

On the other hand, many scholars hold a continuum view in which adaptation activities, or innovation are on a continuum – from maintenance, to incremental changes, and then transformation (O'Connell et al., 2015). One article discussed innovation occurring in "transition areas" referred to "continued innovation" (Djalante, Holley, and Thomalla, 2011). Within Autonomous Innovation, Bahadur and Doczi (2016) find that innovation occurs along a gradual continuum as innovations scale-up and do not believe in break-through innovations. Christensen proposes that innovations fall onto a continuum from evolutionary to revolutionary (Christensen, 1997) and "therefore categorized into two groups: incremental or evolutionary innovations and revolutionary breakthroughs" (Thomond and Lettice, 2002, p. 1). Moore and Westley (2011), also influenced by Christensen, separate innovation into transformative or disruptive and adaptive based on the breadth of impact and degree of disturbance they create. Moore and Westley (2011)

see innovation types as discrete and different types along a continuum. Kemp (2011) uses several metrics to describe innovation, including adoption and scale, degree of novelty, and impact on environment. Kemp (2011) also believes innovation is on a continuum based on level of adoption and degree of impact. Biggs et al., (2010) differentiate incremental from radical by degree of novelty, which they define as "the creation of new things, or new combinations (Allen and Holling, 2010) via natural or human processes." Leach et al., use the direction, diversity, and distribution of the innovation as indicators to categorize innovations within a multi-scale, panarchical manner which can be seen as a form of cyclical continuum.

Finally, although the frameworks presented defined types of innovation, in reality multiple types of innovation might be embedded in one another. As Obrecht (2016, p. 15) suggests, "some innovation processes can involve multiple types of innovation". The Community-based Management of Acute Malnutrition (CMAM) Report case study offers "an example of a product innovation – a new software - embedded within a broader paradigm innovation – a new way to think about the categories and indicators used to monitor the performance of acute malnutrition interventions" (Obrecht, 2016, p. 32). Another kind of embedding happens across temporal scales. For example, frameworks like RAPTA that seem to have contradictory methods and goals might simply be assuming that change occurs over long time scales. O'Connell et al., say that "…a sequence of actions which are labeled "incremental adaptation" over the shorter term, may be seen as transformational over the longer term.

Dahlin and Behrens (2005) introduce three criterion which can be used to separate radical from incremental: "Criterion 1: The invention must be novel: it needs to be dissimilar from prior inventions; Criterion 2: The invention must be unique: it needs to be dissimilar from current inventions; Criterion 3: The invention must be adopted: it needs to influence the content of future inventions." Buenstorf (2000) separate incremental from non-incremental by the degree of novelty and degree of diffusion. Moore and Westley (2011) separate transformative or disruptive innovations from adaptive innovations in terms of the breadth of impact and the disturbance the innovations create.

2.3.3 Sources of innovation as differentiator

Some scholars use on the source or genesis of innovation to distinguish incremental from non-incremental. Godin (2008) and Rogers (2010) assume that radical innovations usually come

from outsiders, a view that is quite different from other frameworks of autonomous, local or indigenous innovation, which hold that local people have capacity for radical innovation and transformation Bahadur and Doczi (2016). Ostrom (2010) found that utilization of local and multiple sources of knowledge can lead to better adaptation and innovation. The concept of autonomous innovation is one approach for enhancing local resilience to a range of shocks and stresses, including climate change. Autonomous innovations have five key characteristics: 1) they are inductive (bottom-up); 2) they are indigenous and suited to local cultural norms; 3) they are inexpensive and frugal; 4) they are developed through subjective processes that rely on the innovator's intuition; and 5) they entail a high degree of iteration through trial and error. This is in contrast with innovations arising from structured, expert-led research and development processes and the standardized business procedures of incremental innovations (Bahadur and Doczi, 2016).

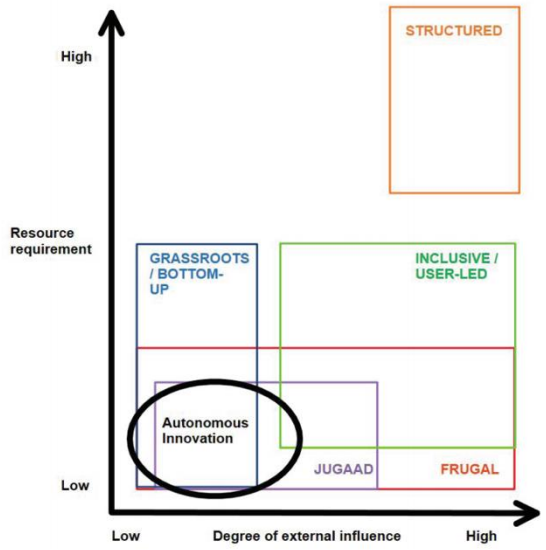

Figure 2-8: Innovation types according to resource requirement and degree of external influence, from Bahadur and Doczi (2016)

Literature on autonomous innovation emphasizes the importance of grassroots initiatives and entrepreneurialism while wrestling with the challenge of scaling in a top-down way. According to some scholars "…understanding past and current autonomous adaptations can help give insight into…particular adaptive strategies" however, those same scholars then prescribe that these insights be used for "planned adaptations," "policy" and "projects" which tend to be top-down (Batterbury and Forsyth, 1999; Carr, 2008; Droogers, 2004). The overvaluation of institutionalized solutions brings the discussion full-circle back to a "grand design scheme", albeit

one based on what were once small, local innovations (Thompson et al., 1986). Bahadur and Doczi (2016) attempt to overcome these logical pitfalls by using autonomous examples and network diffusion effects, but ultimately prescribe the use of training and experts that diffuse information and best-practices. Other scholars and policymakers have had similar challenges translating the theory into reality.

To illustrate some of the differences between frameworks, see Figure 11 and consider two frameworks: one by Godin (2008) and the other by Norman and Verganti (2012; 2014). Both include the language of “incremental” and “radical” innovation, but hold different views on the object of innovation, or what is being innovated, and the relationship between incremental and non-incremental forms of innovation. For instance, Norman and Verganti (2014) believe that incremental innovation can lead to more advanced versions of an innovation but cannot lead to a new radical form of innovation, which they refer to as "hill climbing”. Godin (2008) also uses the word radical innovation but has a different concept in mind. Figure 10 shows the contrasting indicators used to identify incremental innovation vs radical innovation. Norman and Verganti categorized innovation as incremental or radical by the degree of change in technology (Y axis) and meaning (X axis). Godin (2008) uses incremental and radical to describe change in technology (X axis), but the Y axis measures whether or not institutions and practices are sustained or disrupted, which is more pragmatic than simply changes in meaning or understanding which are more subjective in Norman and Verganti (2014). Kemp (2011, p. 4) asks whether or not the innovation is technologically radical and institutionally radical, the latter being innovations “that do not fit with existing rules and practices that require changes in the institutional set up.” Because the frameworks use different objects of innovation, they are difficult to compare.

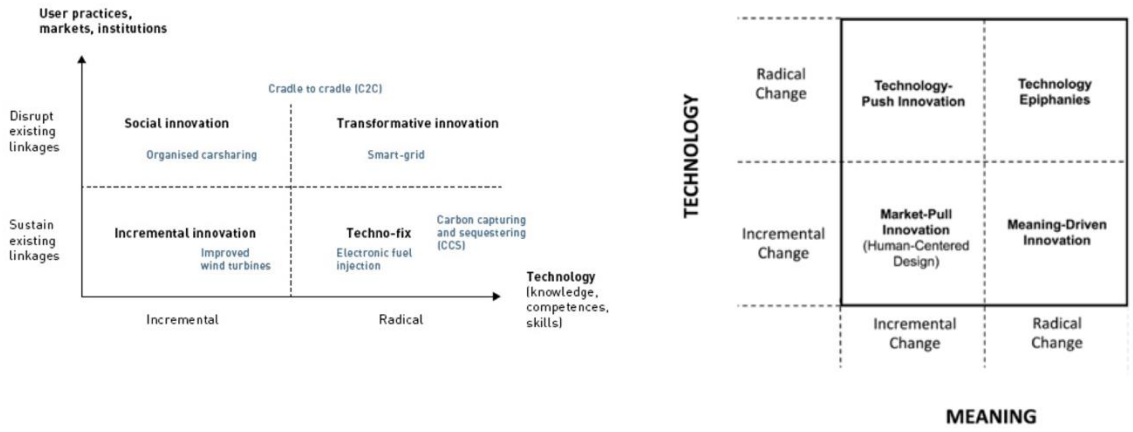

Figure 2-9: Institutional disruption vs. Technology advance: Kemp (2011), based on Clark (1985) and Arundel et al., (LEFT) and Radical Innovation Framework Proposed by Norman and Verganti with technology and meaning as axis of change (RIGHT).

Name of framework	Indicators and Metrics
Buenstorf, 2000	
Dale, Ling, and Newman, 2010	Novelty; diffusion
3 D framework *(Melissa Leach, Johan Rockström, Paul Raskin, Ian Scoones, Andy C. Stirling, Adrian Smith, John Thompson, Erik Millstone, Adrian Ely, Elisa Arond, Carl Folke and Per Olsson)*	Creativity; diffusion
Autonomous *(Bahadur and Doczi, 2016)*	Direction, diversity, distribution
Disruptive Innovation *(Christensen 1997)*	Inductive (bottom-up); indigenous and suited to local cultural norms; inexpensive and frugal; developed through subjective processes that rely on the innovator's intuition; and entail a high degree of iteration through trial and error.
Dahlin and Behrens, 2005	It begins its success by meeting the unfulfilled needs of an emerging or niche market. • Its set of performance attributes, highly rated by niche market customers, are not initially appreciated by mainstream markets. Mainstream market customers as well as competitors value different performance attribute sets and therefore view the innovation as substandard. • Niche market adoption enables investment in the product, service or business model to increase its performance. It can then create or enter new niche markets and expand customer numbers. • Awareness of the product, service or business model increases, forcing and influencing change in the mainstream markets perception of what it values • The change in the mainstream market's perception of what it values is the catalyst that enables the innovation to disrupt and replace existing mainstream products, services or business models.
New Forms of Social Innovation *(Ely et al, 2017)*	Criterion 1: The invention must be novel: it needs to be dissimilar from prior inventions. Criterion 2: The invention must be unique: it needs to be dissimilar from current inventions. Criterion 3: The invention must be adopted: it needs to influence the content of future inventions.
Typology of Change and Transformation (Few, 2017)	Predominant actors; priority values; principal incentives/drivers; sources of investment; forms of appropriability; sites of innovation; predominant forms of knowledge; emblematic technological fields
Eco-Innovation *(Kemp, 2011)*	Mechanisms and Objectives: Scope; object of innovation; and technical or behavioral adaptation action
Moore and Westley, 2011	Adoption; scale; novelty; implact on environment
Obrecht, 2016	Breadth of impact and disturbance they create
Panarchy (Holling et al. 2002). (Alan and Holling, 2008) *Incremental and Radical, Social Innovation* *(Biggs et al, 2010)*	
Radical Innovation *(Norman and Verganti, 2016)* *(Norman, 2014)*	
Rogers, 1962; Rogers, 2010	Degree of change in Technology Degree of change in meaning
X-Innovation *(Godin, 2017)*	Innovations that are perceived as (a) relatively advantageous (over ideas or practices they supersede); (b) compatible with existing values, beliefs, and experiences; (c) relatively easy to comprehend and adapt; (d) observable or tangible, and; (e) divisible (separable) for trial, are adopted more rapidly (Rogers, 2003).
10 types of Innovation (Keeley et al, 2013)	

Figure 2-10: Innovation Frameworks and Metrics for Distinguishing Types of Innovation

2.4 Implications and Challenges

Scholars are not aligned with what constitutes innovation, whether there are distinct types of innovation, the relationship of various types and associated outcomes. There is also lack of alignment pertaining to the origin or source of innovation. Because of this vagueness, lack of description and clarification of intention, policymakers and practitioners in the field lack common understanding and alignment. These challenges present obstacles in implementing innovation as policymakers intended. Therefore, when addressing the need for better policy, it is difficult to engage in meaningful dialogue.

2.4.1 Implications for implementation

Innovation is most effective at the community scale, with community being defined broadly as communities of practice, professional affiliation, shared interests and networks and virtual communities (Dale et al., 2010). When policy turns into practice at the local or community level, different interpretations take on concrete forms. Many scholars seemingly assume that innovation is a de facto positive force for resilience (Andries et al., 2004; Folke et al., 2010; Stafford-Smith et al., 2010), but there are many examples of negative disturbance and harmful innovation in the field (Allen and Holling, 2008).

Misalignment and misunderstanding

Misalignment between intended outcomes and innovation practices could be caused by alternate interpretations of the type of change desired; the rate of change needed; the innovation process which is prescribed; participants in the innovation process; as well as the scalability or diffusion of innovation. If scholars and policymakers' intentions are not clear, then local practitioners will make decisions based on interpretation, "subjective values", or "social norms" which may not reflect best practices or "rational reflection on scientific data" (Ryan and Gross, 1943, Coleman et al., 1957, Rogers, 2003). This can have concrete implications in practice. For illustrative purposes, consider a statement about innovation, "Innovation is needed to allow for a sustainable future." Such a statement might be found in a policy document which encourages innovation. Now assume that this statement does not elaborate to include a definition of innovation. Following are scenarios that illustrate how misalignment could result in alternative innovation practices, and misallocation of funding.

- Because the word *innovation* is not defined in the document, it may be read and understood to mean an incremental type of innovation. Based on this interpretation of the policy, a programmatic course of action may likely focus on practical tools for generating new ideas with immediate impact and market demand. A focus will be on technological solutions that can be applied locally.
- The innovation was intended to mean a radical, non-incremental type of innovation that can lead to transformation. If incremental innovations were prioritized and funded programmatically, the outcomes intended may not transpire.
- The reader properly understood the call for innovation to mean radical, non-incremental innovation that might lead to transformation and large-scale impact. However, the UN further intended to mean autonomous local innovation and not top-down innovation. The reader, when attempting to apply innovation, does so in a top-down manner. In this case, the reader may have the correct goal of radical innovation, but the wrong method—planning instead of relying on emergent and autonomous or indigenous innovation.

To illustrate using an example, assume that the same reader who understands the call for innovation to mean radical—non-incremental innovation that could lead to transformation and large-scale impact, might employ or promote a recommended method like Design-Thinking in communities because such methods are often promoted for generating innovation. However, such methods are known to be inherently incremental and may not lead to the radical results desired.

Conservative or equity-reducing methods

The result of incremental methods may be a resilient solution but encourage a conservative view of social conditions such as unequitable gender roles in the community. The Design Thinking method which, as discussed, can be inherently conservative, may be resilient, promote but may not be considered sustainable or equitable. By encouraging a conservative view of social conditions, it may thus promote gender inequality. The data itself can be misused or could contribute to unjust power dynamics (Chambers, 2006). Water issues in Malawi are deeply tied to gender hierarchies, socio-economic power dynamics and colonization of data; the research information rarely goes back to local people (van Wijk, 2001). In order to build collaborative, participatory, and equitable partnerships, more learning is needed to understand how communities

at various scales envision their future and implement both technical and social change (Miller et al., 2014). Processes such as Design Thinking also emphasize the role of empathy in designing solutions to grand challenges. Empathy here means "the co-experience of another's situation"; not only "emotion sharing" but "assuming the perspective of another in their specific situation and thus sharing their real or imagined reaction to the situation" (Fritz, 2019). At first glance, this seems like a good idea, but there can be "dark sides" of empathy. Empath serves the empathizer first and foremost and there is "egoism" and "aesthetic pleasure of the empathizer", and at its darkest, one may even want the people who are being helped to remain the "inferior victim because it can sustain your feeling of being a hero" (Fritz, 2019).

Limitation of resources and "quick fixes"

Sometimes it is not misunderstandings which lead to unintended outcomes, but limitations in tangible resources or time. In times of crisis, people must act quickly to respond. Rapid localized adaptation and quick "off-the-shelf" solutions might be necessary. Innovation is not always easy or possible given the political and social environment (O'Connell et al., 2015). Radical innovation would be too complex and waste valuable time and scarce resources during a time of immediate crisis. However, short term adaptation to stresses does not always lead to resilient outcomes, and resilient systems are not always sustainable. Incremental adaptations can lead into more extended and deeper versions of a current regime and make transformation more difficult. This has immediate and lasting effects on policy and planning. For example, the extension of water distribution systems in Malawi, Africa has left a more centralized system that is sensitive to environmental conditions and shocks. The dam-powered electric pump stations are dependent on water levels and extended pipes that do not have their own water sources in the event of central well failure. Although this method of extending infrastructure is effective in the short term, it creates a highly centralized system that is vulnerable to rigidity traps and failure if the central node is disrupted. In addition to rigidity traps, some adaptations like foreign-funded deep wells, may lead to forms of poverty traps or dependence on government or foreign aid. If we are to tackle the problems surrounding our critical infrastructure, it is key that decision makers are knowledgeable about the benefits or drawbacks to certain types of development informed by innovation. This requires an understanding of possible differences between localized, short-term, iterative adaptations for survival versus long-term transformation or system-wide change. More

consideration should be given to the avoidance of quick fixes that can lead to long-term traps. Those desiring resilience must have all the tools available to us in our toolbox and are capable of making informed situational decisions. This goal is idealistic, but realistically difficult to achieve.

Bad actors

In some circumstances, technological and social innovations can be a publicly available community solutions and viewed as a common resource. Communities are composed of heterogenous members and in such situations, common dilemmas can be present in which some actors use the resource responsibly, while others abuse the system by freeriding or extract value through cheating behavior. A common example is water wells in Africa. Many wells are developed as a community resource accessible by all. Some community members use the well responsibly, taking their proportional allotment and contributing to the maintenance and well-being of the well. However, others abuse the resource and extract a disproportional amount, such as a herdsman bringing animals to the well or a business person connecting to the well and harvesting large amounts of water for industry. Still others in the community use the water proportionally, but do not contribute back in the form of maintenance or well-being.

Further breakthrough and wider diffusion depends on changes in policy and institutional frameworks. This is especially the case for transitions towards sustainability, which refers to collective goods (with associated free rider problems). Because private actors have no immediate incentive to address sustainability problems, public authorities have to change economic frame conditions and formal institutions (regulations; subsidies; incentives; taxes) (Geels, 2013).

Sources of knowledge

Traditional engineering work and research in the Global South is underpinned by the belief that engineers know the answers, that technology should shape development, that the public lacks knowledge and should be engaged and educated so that they can accept technology answers, and that the development process starts with a good design (Robbins, 2007). In other words, the scientific “experts” predict what problems will arise, design solutions to control for the predicted issues, and then share the results. “Political ecologists challenge this ‘rule of experts’ with counternarratives from indigenous communities and/or local people who have deeper and more

extensive knowledge of local conditions who may also develop innovations (Birkenholtz, 2008; Escobar, 1996, 1998; Forsyth, 1996; Zim- merer, 1997)."

Nature of reality

The disciplinary team sees this scientific as the best way to know reality, as science is seen as the source of true knowledge and scientists as the discoverers of truth (Sijbesma and Postma, 2008). Community members who expect to play a meaningful role are sometimes left out of the process, resulting in a loss of indigenous knowledge and local complacency, resentment, or feelings of exploitation (Joanne, et al., 2005; Pillow, 2003). From an ontological standpoint, the local cultural elements, water practices, superstitions, etc. are entirely missing in the water planning process when local people are not intimately involved (Kamash, 2008). As Watts (2003) summarizes: "knowledge is uneven within societies; knowledge is not necessarily right or wrong because it is local/indigenous; and local/indigenous knowledge may or may not be developed through widely representative voices". One solution might be the co-production of knowledge and collaboration between outside experts and locals. One idea which has been proposed is the formation of competency groups in which knowledgeable professionals and relevant, affected actors work alongside one another (Whatmore, 2009).

Interpretation through lens: Empathy and gaze

In order to make studies more socially responsible, a social survey is administered, but many times the surveys are reliant upon the interpretation of the individual researcher (Schutt, 2011). These "social" actions will be informed by a Eurocentric or Western perspective, not taking into account local factors such as family hierarchy, gender roles, or other socio-political boundaries (Elmhirst, 2011). This problem is exacerbated when a traditional single-practice scientist or engineer attempts to do work in the Global South under the label of "social" and interpretations of data and knowledge are viewed solely through their lens (Haig-Brown, 2003). This view is epistemologically flawed as the foreign engineering team represents only one social reality governed by laws different from that of local realities (Sijbesma and Postma, 2008). Many engineers or scientists are not well versed in reflexivity and not skilled in the art of critical self-evaluation of one's positionality or the way that position affects the research (Bradbury-Jones, 2007; Guillemin and Gillam, 2004; Stronach et al., 2007). To remediate the issue of positionality,

Smith recommends that the connections between researchers, indigenous communities, and broader decolonization efforts should continue because disconnection reinforces a divisive colonial separation of knowledge (Smith, 2007). If engineers are to continue extensively working abroad, greater social and institutional learning around the development process is needed (Miller et al., 2014).

Mixed methods approach

Development issues can be viewed from a philosophical perspective, where epistemology is heavily weighted, or from a transformative position in which it gives a voice to overlooked types of information, such indigenous knowledge or women's voices in male-dominated societies (Creswell, 2013). In situations of complexity, solving problems requires diverse groups and different research methods from a variety of disciplines (Blackstock et al. 2007; Spangenberg 2011; Talwar et al. 2011). This includes local participants, although this should be done in a way as to not overwhelm these stakeholders (Robinson et al, 2011). Indigenous communities can use counting, measuring, estimating, valuing, ranking, and scoring to create numerical data (Chambers and Mayoux, 2003). They can often provide certain types of high-resolution information and insight such as which water points are broken, used most frequently, or taste the poorest. This level of information is not available in government statistics (Sijbesma and Postma, 2008). Many researchers lack proper ethical frameworks, seemingly extracting information from indigenous groups in the absence of a long-term commitment (Chambers, 2006). Outside researchers often lie at the center of colonization of information, making use of local knowledge in an extractive and expropriating manner. They interpret the knowledge that belongs to communities and groups within communities and only send it to donor agencies (van Wijk, 2001).

Randomness of innovation

Transformation and radical innovation seem to be emergent qualities instead of inherent abilities, relying on both internal and external forces and circumstance—some of which is outside the control of the actors involved. The genesis, geography and effects of innovation are difficult to predict. From the perspective of environmental policy aiming at sustainable development, innovations are problematic because their effects are in principle uncertain. "Their environmental net effect may be either beneficial or detrimental, and frequently it cannot even be established

qualitatively before years and decades of widespread diffusion of the innovation" (Buenstorf, 2000, p.131). Transformational discoveries are difficult to predict as they appear to emerge in large social communities and geographical landscapes. Truly transformational innovation many times comes from random and scale-free patterns of innovation and growth companies and depends on individuals (Yas, 2014). Challenges in translating policy into practice, changing environmental conditions, along with the inherent emergent qualities of resilience and innovation make implementation a challenge.

2.4.2 Implications for policymaking

In pursuit of social and environmental goals, governments have "recently, become more pro-active in using deeper and new forms of policy intervention and in expanding their areas of involvement" (Borrás, 2009, p. 1). The push to impact socio-ecological outcomes is in response to the technology focus of the last 50 years, in which innovation policy has been led by a mission-led approach with an orientation to technologies viewed as crucial for coping with new societal challenges such environmental sustainability or energy/resource security (Gassler et al., 2008, p. 203; Kemp, 2011). In addition to technology-focused mission-oriented innovation, other new forms of innovation have emerged which prioritize social and environmental (Ely et al., 2017). As policymakers encourage certain desired outcomes, such as environmental or social transformation, it is crucial that they articulate their intended goals clearly to avoid misunderstandings. As stated throughout this article, when innovation is treated as a normative term, the nuances and complexity is lost and left up to interpretation. Undesired outcomes could result from misinterpreted innovation policy.

As discussed, there are many disagreements around the definition of innovation and its relationship to adaptation and transformation (Davidson, 2016; Dale et al., 2010). These have tangible implications for policy. The differences in theoretical perspectives on innovation are not purely scholarly and could manifest themselves in the form of misaligned policy-making, infrastructure that does not enable intended outcomes, social programs meant to spur innovation in incremental ways, and overlook alternative forms of innovation (e.g., radical innovation). For instance, if transformation is a goal, and incremental innovation can indeed lead to transformation, then an emphasis of research and training on diffusion of simple solutions might be best. If

transformation is a goal, but incremental innovation *cannot* lead to transformation, then decision-makers should perhaps seek more radical forms of innovation.

The primary reasons for the disconnect between resilience goals and innovation described are fundamental differences of opinions within the social-scientific community on the 1) types of outcomes produced by different types of innovation, 2) manner and scale of diffusion of different types of innovation and, 3) the relationship of innovation to adaptation and transformation. Decision-makers may benefit from a practical innovation framework which helps navigate the misunderstandings above and communicate about innovation in a meaningful and effective manner. This clarity is imperative in order to have meaningful dialogue and appropriate application of innovation in practice. Important points of clarification regarding innovation discussions are: 1) relationship of innovation to outcomes, 2) understanding on genesis and scalability of innovation and, 3) …understanding of incremental and non-incremental forms of innovation as binary or continuum,

Each disparate perspective on innovation has built-in assumptions about the role innovation plays in enabling adaptation and resilience (Davidson, 2016; Dale et al., 2010). If there are indeed different types of innovation that correlate to different scales of change, then there is a time and place for different kinds of innovation. On the other hand, if both adaptation and transformation are just two steps on a continuum, then radical innovation could help circumvent or leapfrog to transformation (Folke, 2010; O'Connell et al., 2015). In some studies, policies and approaches, innovation is equated to a product of design thinking processes. Although such design thinking practices have been found to be fundamentally conservative and incremental (Iskander, 2018), many of these articles incorporate design thinking with the word radical when referring to the outcomes they hope to achieve (Rogers, 2010; Godin, 2014; Few et al., 2017). The role of innovation in resilience is dependent upon the role that innovation plays in the nested processes of adaptation and transformation. Innovation policy impacts, and is impacted by, these various interpretations of innovation. In light of the various interpretations, it might be advantageous for policy makers to consider the many ways in which innovation is understood, practiced, and studied within the field of resilience.

The outcomes, or perceptions regarding outcomes, of different types of innovation can impact whether policy makers and practitioners prioritize between incremental innovation (Djalante et al., 2011) or radical innovation. Organizations like the United Nations might intend to

achieve sustainable and resilient outcomes and propose innovation as a mechanism by which to achieve those outcomes. However, without a working typology, it is unclear what type of innovation is proposed and if those are the appropriate mechanisms to achieve the desired outcome. As presented earlier, inappropriate innovation decisions could lead communities or populations into deeper basins or push local regimes toward negative thresholds. Policymakers, unintentionally, might recommend innovation that diffuses and leads to entrenched regimes and rigidity traps ranging from environmental to social traps. Further, without such a framework it will be difficult to judge whether or not the innovations which are implemented are appropriate. The aim of this synthesis is not to define a single typology, but to examine different perspectives, expose fundamental differences in innovation theory within resilience literature and propose ways of critical examination moving forward. In the next section, we propose a set of questions which may be employed to examine and discuss cases of innovation. Answers to such questions improve understanding and alignment among scholars, policymakers, and practitioners.

2.4.3 Proposed questions for alignment

We have shown that although innovation is treated as normative, there is misalignment and lack of clarity in the literature. Further, through a political ecology lens, we see the importance of identifying interrelated problems, of considering a broader range of actors and their knowledges, understanding power relations and their influence on human-environment relations, and the broader outcomes of decision-making processes, including their impact on power relations. Scholars, policymakers, and practitioners need a way to clearly communicate these elements in a way that exposes misalignments and allows individuals a way to express conceptualization of innovation, as well as motivation and intentions. In an effort to encourage substantive dialogue and avoid the normalization of innovation concepts, we propose the questions in Figure 11 as a starting place for investigations and discussion.

Just as (cite) suggests a resilience question of what, for whom, etc, we propose similar questions for innovation.

	Question	*Example responses*	*Framework For Reference*
WHO	Who is driving innovation? *Indigenous or autonomous *Outside forces Who is the innovation for?	*Indigenous people groups are innovating for their own local community.*	*Autonomous innovation (Bahadur and Doczi, 2016)*
WHY	What is the motivation for the innovation?	*Innovation is a response to local shock with the goal of transformation of social practices.*	*Resilience (Davidson et al., 2016)*
HOW	What is the process of innovation? What tools or practices are employed? * Design Thinking	*Innovation will emerge from an iterative process of problem identification and ideation.*	*Design Thinking (Brown and Wyatt, 2010)*
WHERE	Where does the Innovation occur?	*Outside of the community*	*Disruptive innovation (Godin, 2008).*
WHAT	What is being innovated? * tech, institution, social, meaning	*New meaning is being attributed to an existing technology.*	*Meaning-Driven Innovation, from radical innovation framework (Norman and Verganti, 2014)*
DEGREE OF NOVELTY OR CHANGE	To what degree is the innovation process, product or social system novel? * Disruption/or radical change * Incremental, stepwise * Entirely new or new to region	*Innovation happens in a stepwise and incremental fashion.*	*Panarchy, incremental innovation, and radical innovation (Holling et al. 2002).*
DEGREE OF DIFUSSION	To what degree is the innovation used and adopted? * Scale	Innovation is widely adopted across the country.	*Diffusion of innovation (Rogers, 1962)*
PRIMARY INDICATOR	What is the primary indicator of innovation in the framework: product, process, the innovator, the outcome, impact?	The outcome of the innovation is disruptive and widely adopted.	*Outcome of innovation (Christensen 1997; Dahlin and Behrens, 2005)*
VIEW ON RESILIENCE	Definition of resilience Relationship of adaptation and transformation: binary vs continuum	Adaptation and transformation are connected along a continuum and local, incremental adaptations can lead to large scale transformations.	*Continuum, panarchy (Biggs et al, 2010; Holling et al., 2002)*
FOCUS OF TRANSFORMATION	What is the focus of transformation? * Adaptation practices vs regime	Transformation of adaptation practices	*Disruptive innovation (Godin, 2008); Transformation and innovation (Few, 2017)*

Figure 2-11: Clarifying Questions to Inform Innovation Discussion

These questions provide a framework to inspect examples of innovation in the literature and dissect definitions, meanings, and nuances. The questions can help scholars reflect on assumptions and bias, and provide a basis from which to make clarifying statements about innovation within academic writing. The questioning framework can academic authors in considering aspects of innovation traditionally not conveyed within the literature, adding to the rich discussion of innovation within a given discipline.

The questioning framework might also help practitioners in the field pose clarifying questions to policymakers in an effort to clarify the intent of a given policy. In a policy context, we would encourage that the term innovation should be accompanied, at minimum, by a definition ("innovation is defined as…"), clarifying statements and/or examples, and reference to views, theories, frameworks and the like which have informed the authors view.

2.5 Conclusion

The term innovation has, in its history, been broadly conceived and defined leading to debates and disagreements. It is treated as normative, although in reality it is not conceptualized, discussed or practiced in a consistent way. The term innovation is used throughout research and policy, as well as resilience literature. This article provides a synthesis of peer-reviewed literature to better understand how innovation is interpreted and incorporated into resilience literature and how the concept of innovation has been *used* across this literature. We highlight some of the ongoing debates and disagreements that surround innovation within the resilience literature.

Innovation is a mechanism within the nested processes of adaptation and transformation. Because innovation has been posed as a solution to resilience, and innovation is operationalized as a mechanism of adaptation and/or transformation within resilience, we show that it is impossible to decouple the normative nature of innovation from that of sustainability, resilience, adaptation and transformation. We considered the ways that normative concepts of adaptation and transformation are further complicated by normative dimensions of innovation. Views on innovation, adaptation and transformation impact the way that we theorize about resilience; practice innovation; measure success of policies or of projects; educate; and how we choose to spread or diffuse innovations. We show that the misalignment of innovation goals and innovation activities could, in practice, result in negative consequences. This lack of clarity may lead to unintended outcomes and may result in poor sustainability when implementing innovation in the field.

Explicitly considering the normative dimensions of innovation enables us to better understand the applications and limitations of the concept, identify opportunities for improving interdisciplinary collaborations and to consider different approaches to minimize unintended policy and program outcomes (Johnson et al., 2018). Such synthesis can aid practitioners in identifying and building the adaptive capacity of communities.

We analyzed frameworks in the context of innovation and explored the various approaches and hypothetical impacts of each. This article reveals that while some frameworks of innovation are complementary, others are fundamentally exclusive of one another. We presented various innovation frameworks derived from the literature and demonstrated overlap in the terms and concepts within these frameworks, inconsistencies and disagreements.

We considered how analyzing contradictions can further reveal tensions between normative and descriptive dimensions of these key paradigms and analytical concepts, which often become particularly noticeable when applying them to address real-world problems. Research and scholarly discourse affect policy, which in turn drives market forces and finally impacts communities and individuals. Because each way of framing innovation has some merit, it is ultimately important for scholars, practitioners and policy makers to be explicit about the descriptive criteria and the normative assumptions involved in using specific innovation strategies for achieving adaptation and transformation. The underlying epistemological tensions must be explicitly described and addressed in order to form effective policy and innovation programs. We presented a set of questions which can help interrogate specific cases of innovation to better understand in the context of resilience, and provide example clarifying statements which can be utilized by researchers and policymakers to clarify innovation concepts.

The result of this synthesis highlights the need for scholars, practitioners and policy makers to be explicit about the normative assumptions associated with *innovation, adaptation and transformation* when proposing policy, programs and implementing new social innovations. Further studies should focus on the normative and descriptive dimensions of innovation and the way in which innovation is incorporated into policies and programs, such as Sustainable Development Goal 9. Such studies will be crucial for moving towards developing transformative adaptation interventions for promoting resilient and sustainable communities (Buenstorf, 2000; Griggs et al., 2013; Johnson et al., 2018; United Nations, 2015). Alignment among scholars when using the term innovation would lead to meaningful scientific discourse. Clarifying the intent of policymakers will help practitioners evaluate, interpret and operationalize policies. Furthermore, it can guide further research studies on the role of innovation in resilience (Armitage, 2003).

More cases and field data are needed to better understand the pragmatic application of innovation concepts on the ground. Future field studies might include retrospective analysis of shock, resilience objectives, innovation type and their relationship to resilience outcome. The field

of resilience may benefit from a better understanding of innovation's relationship to traps and cycles of dependency. This area of research will likely involve the study of social institutions. From a social science perspective, studies could be conducted to contrast scientific and local opinion on change and innovation.

Together, these endeavors will allow the scholarly and policy communities to move beyond theoretical discussions about which analytical concepts can be better operationalized within which key paradigms, and to address epistemological tensions between normative and descriptive dimensions of these paradigms and concepts. With such endeavors, the scholarly and policy communities will be able to ask questions with high policy relevance—namely how innovation, adaptation, or transformation at different scales contribute to achieving resilience goals.

3. INNOVATION IN ADAPTATION TO WATER STRESS: LESSONS LEARNED FROM CENTRAL AND SOUTHERN MALAWI

3.1 Introduction

In response to global water challenges, the United Nations' Millennium Development Goals (MDGs) included a specific goal of reducing water scarcity in hard hit areas such as Africa (UN, 2019), but fell short of that goal, particularly in the poorest areas of Africa (Rigaud et al., 2018) such as Malawi (UNDP-WSP, 2006). Failure to meet the goal was due, in part, to the approach. The MDGs were focused on addressing access to water, but not necessarily on the resilience or sustainability of those systems. As a result, new water systems were created but the new systems had very low sustainability rates (UNDP-WSP, 2006; Adanke et al., 2012; Costanza et al., 2007).

In response to these failures and the shortcomings of the original MDG approach, the UN developed the Sustainable Development Goals (SDGs). The SDGs were created to build upon the existing MDGs by leveraging innovation (Griggs et al., 2013) to address sustainability and resilience (UN 2018, Brown and Wyatt, 2010; United Nations, 2015). In the literature, we find that innovation can enable adaptation and transformation (Few, 2017) which are, in turn, nested within resilience (Walker et al., 2004). However, although innovation has been mentioned to some extent in the resilience literature and to a larger extent in the development conversation (Bahadur et al., 2015; Burnharm and Ma, 2016; Mitchell, 2013; Winderl, 2014) it is sometimes treated as normative (Young, unpublished). In fact, the vagueness of SDGs and contributing factors, such as the normative treatment of innovation, interfered with locals in poor countries, like Malawi, in meeting the SDGs. Malawi, like other UN member nations, proposed ideas ranging from implementing new technology to changing governance structures (UN, 2015). Although Malawi has made great effort toward the SDGs (Citizens Unite interview, Oct. 15 2014), many water solutions are failing (MWB, 2014). In the face of ambiguity, locals are left making choices based more on intuition, subjective values, and social norms than on rational use of scientific data. As a result, local people might not make the choices intended by the SDGs and therefore, fail to achieve the results proposed by the SDGs. Without additional clarity and working framework for innovation, operationalization of the SDGs will continue to prove challenging.

Previous studies have documented the implementation of innovations and their outcomes. Still other studies have reflected on the normative treatment of innovation in the resilience

literature in light of the SDGs. However, no empirical studies could be found that classify the innovations based on the SDGs. This research aims to add empirical insights into the way innovation is implemented at the community level as an adaptation strategy. The research is important, because when innovation is poorly executed as an adaption strategy, it lead to failure to achieve resilience (Few, 2017). We are concerned with examining real cases of adaptive strategies in Malawi and the role of innovation in adaption to increased water scarcity. We consider practices, activities and decision-making processes which might enhance resilience outcomes at scale. The results of SDG efforts have been poor in Malawi, and little is known about how SDGs are translated into practice. By comparing adaptation strategies in the field within a common innovation framework, we aim to gain insight into how policy becomes operationalized in Malawi.

In this paper, we focus on how innovation is being operationalized for adaptation, and how well the outcomes align with the goals of the SDGs. Using Rogers' (2003) definition, innovation can be defined as undertaking a new practice or incorporating a new technology, to compare views of innovation across local, governmental, and NGO perspective. We view adaptive innovations through this lens and seek to understand what this says about local interpretations and understandings of innovation in Malawi. We use data we collect on adaptations to apply a working framework to evaluate actual innovations which have been implemented in Africa. By understanding the role of innovation and how it is operationalized in practice, decision-makers will be able to better communicate needs, goals and desired outcomes and to analyze and select innovations among alternative choices. Understanding innovations will help communities leverage innovation to nudge or shift themselves into more desirable regime states, avoiding ramifications that accompany shocks or disturbances to the system. Ultimately, community-level decision-makers will have the knowledge to be able to take action to make their communities more adaptive to shocks and disturbances to their water systems.

3.2 Literature Review

The concept of innovation has been treated in a normative fashion in policy documents calling for innovation as a solution to resilience (UN, 2019). However, within the resilience literature, authors have documented dozens of types of innovation (Edquist, 2004; Godin, 2008; Young, unpublished). Most research on innovation within resilience literature stems from other literature which focuses on technology-based innovation (Rogers, 1962; Rogers, 2003; Rogers,

2010) and product or business innovation (Christensen, 1997; Keeley et al., 2013). Additionally, other scholars have focused primarily on technology, incremental innovation (Godin, 2008) and innovations which originate in a top-down manner (Batterbury & Forsyth, 1999; Carr, 2008; Droogers, 2004) without considering local social norms or indigenous knowledge (Bahadur and Doczi, 2016) which could lead to better adaptation and innovation (Ostrom, 2010). For example Rogers (2003) focuses on technical innovation, and Christensen (2008) has inspired many in the resilience literature (Leach et al., 2012; Biggs et al., 2010; Moore and Westley, 2011; Westley et al., 2011) with his disruptive innovation framework which concentrates on business and product. Contrasting the technology approach, some scholars including Ely et al., (2017) and Biggs et al., (2010) focus on social innovations. Some studies have shown that the Millennium Development Goals have failed in Africa due to a focus on technology and access while overlooking social factors (Onda et al., 2012; World Health Organization, 2010). The focus on technological innovation underestimates the importance of social factors and places an overemphasis on technical solutions which alone do not have the capacity to serve as foundations for societal transformations (Few 2017; Leach et al., 2012; Ely et al., 2017). There are fundamental disagreements between the technology an social approaches regarding the outcomes which these varying innovation types might achieve, and the relationship of small incremental innovation to large scale change, radical innovation and transformation (Holling 2001, Gunderson and Holling 2002); Young, unpublished). This issue of cross scale innovations is a rift in the literature between those which believe grassroots local and frugal innovations can scale up to lead to large scale and radical transformation and those which hold a view that it cannot (Norman and Verganti, 2014). Some scholars have found that failure to consider social forms of innovation can lead to lack of novelty, poor adoption and top-down approaches which ultimately lead to failure to achieve the desired outcome of adaptation and transformation (Bahadur and Doczi, 2016).

In Malawi, a number of constraints limit the effectiveness of adaptation to water stress and wide adoption of innovations, including top-down decision-making, various forms of inequality, government corruption and reliance on foreign solutions and resources (UNDP, 2013; Mwamsamali and Mayo, 2014; Kayuni, et al., 2014; Dulani and Dionne, 2014; Transparency International, 2016). Adaptation strategies are based on technology systems which, in large part, have been centralized and centered on the largest cities, utilize expensive materials and are designed by people outside the community (Bowyer, 2017). This “neo-colonial” form of aid and

adaptation has not led to transformation (Storey, 2017). Adaptation decisions are made top-down and favor urban affluent populations and communities with existing ties to government or they have special ties to NGO resources and resources to fix and maintain the expensive systems. Further, they do not scale well because they are complex, resource intensive and require special knowledge (Campbell, 2017). As Storey states (2017, p.5), "Instead of growth, the $1 trillion spent on global aid to Africa by Western nations since the 1950s has created crippling dependency and abject poverty."

Communities are adapting, but these adaptions are incremental at best, and many times not novel or broadly adopted, therefore are not considered innovation by some scholars. The inequality is pronounced across the urban to rural gradient as wealthier urban and peri-urban populations have greater access to resources and support, whereas urban slums are the first to lose water access in times of drought because the government directs water to the wealthy areas (BWB, 2014). The inequality present in the solutions, which have been implemented across Africa, point to a lack of indigenous voice and socioeconomic inequality in decision-making and are also challenges to equitable decision-making (Kayuni, 2014; Ensor, 2014; Forsyth, 2013; Granderson, 2014; Walker et al., 2014; Pauwelussen, 2016; Ingalls and Stedman, 2016). Scholars pose that more participatory decision making is needed, which takes into account local preferences, social norms, and views of adaption which is needed for transformation to occur (UNDP, 2016; UN, 2019). Further, the success of innovation projects "depends upon the recognition that local, practical knowledge is as important as formal, epistemic knowledge." (Storey, 2017, p.16)

Many researchers have studied the social, financial, mechanical and hydrogeological factors of water system decisions and system outcomes in African nations, including Malawi (Fisher et al, 2015; Foster, 2013; Boakye-Ansah, 2016; Anscombe, 2011; Liddle, 2017). In central and southern Malawi, near Blantyre, floods destroy expensive wells largely subsidized by NGOs, leaving communities without water and without the means to repair or rebuild (WFP, 2016; Guardian, 2015; NOAA, 2016). Foreign and technical solutions which intend to solve this challenge can lead to low sustainability and dependency traps (WFP, 2016). In order to achieve quotas or reach timelines, these foreign workers often ignore the governmental laws, traditions (van der Leeuw et al., 2012) and indigenous methods of water management. Prescribing specific technologies or practices is risky if its treatment of social action is flawed, and can have severe and widespread impacts (Walker et al., 2006).

Additional studies observe how centralized piped systems create urban to rural gradient inequality (Graham et al., 2015; Jaglin 2008; 2014; Alda-Vidal, 2018). However, no studies address the beliefs about innovation and adaptation which inform decision making which are the underlying causes of misalignment between adaptation choices and adaptation goals, such as views about where innovation should originate.

Some scholars have presented frameworks for considering the social factors related to innovation. Bahadur and Doczi (2016) and Ostrom (2010) have found local and indigenous input to be critical to the innovation process. Iskander (2018) found that mainstream innovation processes can be conservative and further the existing entrench gender roles in a community, which should be considered in the innovation processes. Rogers (1962; 2005; 2010) described in detail the importance of social factors, such as compatibility of the innovation in one's life, in the scaling and adoption of innovation. By addressing technology choices and social processes separately and differently, we are not able to combine these conversations into new forms of innovation like autonomous frugal innovation or radical innovation (Bahadur and Doczi, 2016; Ely et al., 2017; Ling and Newman, 2010). As long as they are separate, we cannot expect to achieve different results than that of the current paradigm. However, when innovations are able to emerge from local, indigenous and diverse groups, and are designed in consideration of social norms, meanings and resources, they have higher success rates because local communities understand them, adopt them to their way of life and can maintain them and improve them over time (Bahadur and Doczi, 2016; Kshetri, 2016; Thorn et al, 2015). Few studies within the resilience literature examine the types of innovation to understand how local and social understanding of scalability, technology, and meaning inform innovation decision and subsequent adoption. Empirical studies on innovation for resilience are limited and mostly originate from a technical paradigm and a continuum view of the adaptive cycle, a view which assumes that incremental innovation can scale up into radical (Resilience Alliance, 2019). These studies, which are informed by Christensen (1997), (Rogers (2005), Holling (2001), and others, stand in contrast to social innovation and binary innovation views held by other scholars like Norman and Verganti.

The SDGs promote innovation, and Malawi has committed to working toward them. As such, we would expect to see innovations implemented in the field. In this paper we add to the resilience literature by examining the social context, local understandings of adaptation and innovation and cultural norms associated with adoption of innovation in Malawi, which

collectively affect the innovation decision making process. In this study, adaptation is context by which we observe and understand innovation. We focus on three specific questions: 1) What types of water stresses do Malawians face? 2) What type of innovation(s), if any, have Malawians applied in response to stresses, and how do communities make decisions around innovation? 3) In what ways, if any, can the innovations implemented be replicated in order to fulfill or achieve their adaptation needs?

We provide an analysis of adaptations in ten (10) villages and examine them through an innovation lens. We provide a discussion of local perspectives on adaption, innovation and resilience. We argue that adaptations will be more effective, more innovative, and will diffuse with fewer unintended consequences if local, indigenous and diverse perspectives are included in the origination and decision-making process. In this way, we can better understand why they choose to innovate, what goals they perceive as important and how relationships can be drawn between these perspectives and those which have been proposed at the global, national and regional level. Ultimately, more autonomous, frugal and emergent innovations can be considered.

3.3 Methods and Site Description

This research focuses on the use of innovation as an adaptive strategy to water scarcity, using Malawi as a case study, by framing adaptation choices within an innovation framework (Norman and Verganti, 2014). The research method follows a qualitative interview approach guided by Neuman (2013) and Schutt (2011), in which semi-structured interviews were conducted with individuals and groups of individuals, in order to consider both breadth and depth of information (Schutt, 2011). By conducting semi-structured interviews, we provided a mechanism for eliciting information not likely to surface through a blanket survey approach (Schutt, 2011). We analyzed our work through a critical social science lens (Neuman, 2013) seeking to address problems that we had identified during our research in the field, such as inequality in water access, cycles of dependency in the water sector and gender inequality in water decisions. The nature of the problems involved a mix of inductive and deductive approaches, so we chose a pragmatic approach (referred to as abductive) so that we could 1) explain, develop or change the theoretical framework before, during or after the research process and 2) switch between inductive and deductive approaches (Dubois and Gadde, 2002).

3.3.1 Site Description

Malawi is a small country located in Sub-Saharan Africa. Since its decolonization in 1965, Malawi's population has increased from 3.6 million to almost 17 million in a square area of 118,000 km2, giving a population density of 177 people/km2 (World Bank, 2016). The growth rate has varied from 2.2% in 1960 to 3.6% in 1990. At 3.33%, Malawi has the sixth highest population growth rate in the world (World Atlas, 2015). Fertility rates are decreasing gradually, but even if the total fertility rate declines from the current level of 5.2 to 4.6 by 2020, the population is still projected to reach 26 million by 2030 (Population Reference Bureau, 2012). The population is distributed unevenly amongst the Northern (69 people/km2,13% of the country's population), Central (194 people/km2, containing 42% of the nation's population) and Southern regions with a high population density of 258 people/km2, equivalent to approximately 45% of the nation's population (Ricker-Gilbert, Jumbe, and Chamberlin, 2014). The target cities of Blantyre and Lilongwe lie in the Southern and Central regions respectively. Over 85% of the population lives in rural areas (United Nations, 2015).

Since 2012, economic shocks such as devaluation of the Kwacha by 49 percent and inflation of above 20 percent have contributed to high living costs, ranking Malawi as the 13th worst performing economy in the 2014/15 Global Competitiveness report produced by the World Economic Forum (Schwab, 2015). Malawi's gross domestic product per capita in 2013 was $314.50 (US dollars) (United Nations, 2015). Approximately 50% of Malawians live below the national poverty level with a gross national income per capita in 2013 of $307.90 (US dollars) (United Nations, 2015). Longer term residual issues have create ongoing challenges, such as colonialism, environmental degradation, vital but contested international waters of Lake Malawi, and racial strife with Indian and Chinese immigrants.

Malawi's economy has largely been agricultural-based. Most people live in rural areas and derive their livelihood from agriculture (World Bank, 2016). Only 31% of the land available is suitable for rain-fed agriculture. An additional 18% of the country's marginal land is also used for agriculture. Banerjee & Duflo (2007) report that food accounts for 56 to 78 percent of total consumption. The agricultural sector contributes over one-third of Gross Domestic Product and 90% of export revenues (UNDP, 2013). According to the 2013 Human Development Report, Malawi's Human Development Index (HDI) is 0.418 which places it among the 20 lowest countries in the world (Malik, 2013). Development is clearly needed, but there is also a call for

cultural preservation, curation and restoration that can be at odds with development, sustainability, resilience and progress (UNESCO, 2005).

Malawians rely on a range of rainfall, surface water and groundwater sources including Lake Malawi, Lake Malombe, Lake Chilwa and numerous rivers including Shire, Songwe, North Rukuru, South Rukuru, Dwangwa, Bua, Linthipe, Ruo, Phalombe and Mwanza Rivers (SDNP, 2016). Malawi's climate has two distinct seasons, 700 to 1800mm of rain from November to April and a dry season from May to October. Rainfall patterns are influenced by the country's proximity to Lake Malawi that covers almost two-thirds of its length (SDNP, 2016). Malawi has been hit by both devastating droughts and floods that are part of global climate changes, resulting in hundreds of thousands of displaced people and failed water systems (Guardian, 2015; NOAA, 2016). Throughout these areas, various water systems can be seen across an urban to rural gradient, utilizing everything from buckets of water to simple irrigation, progressing to complicated networks of dams, pipes, and treatment centers (Adanke et al., 2012; Costanza et al., 2007). These engineered and natural water systems are related and embedded within and/or connected to other built infrastructure, governance systems and social networks of stakeholders (Showers, 2002). In Malawi, various stakeholders rely on the water systems, including domestic households, commercial or industrial companies, government and agriculture (Mpande and Tawanda, 2013).

Groundwater resources are very important to Malawi's water strategy and are comprised of three major aquifers: 1) an extensive, low-yielding aquifer that produces one to two liters per second, 2) a weathered basement aquifer of the plateau area, and 3) a high yielding aquifer in the south that produces up to 15 liters per second (SDNP, 2016). Most urban water systems are government owned-and-operated centralized piped networks controlled and regulated by the Malawi Water Board and regional boards.

Experts say that a maximum of 61% of land could be used under strict management (SDNP, 2016). Cultivable land and human population are not evenly distributed, resulting in an increase in the cultivation of marginal land (Ricker-Gilbert, Jumbe, and Chamberlin, 2014). As many farmers do not follow soil conservation practices, expansion of agriculture into marginal and unsuitable areas poses many problems for the country's sustainable agricultural development (SDNP, 2016). Due to allocation practices, rights issues and degradation of land, agricultural production must intensify in order to produce enough food for the growing population (Ricker-Gilbert, Jumbe, and Chamberlin, 2014). In the past two decades, Malawi has diversified their

economy to include other sectors such as mining, tourism and service sectors. As a result, the share of agriculture declined from approximately 38 percent in 1994 to 27 percent in 2010.

Figures from the United Nations'(UN) World Food Program report that 40 million people in rural areas and 9 million in urban centers who live in the drought-affected parts of Zimbabwe, Mozambique, South Africa, Zambia, Malawi and Swaziland needed food assistance in the last few years (WFP, 2016). At least 2.8 million people, of whom 1.5 million are children, are facing a food shortage in southern Malawi, one of the country's worst affected areas by a severe drought exacerbated by the El Nino phenomenon caused by warm water in the Pacific Ocean (WFP, 2016). Such droughts also affect the millions of water users in Blantyre and Lilongwe who rely upon the water systems, including domestic households, commercial or industrial companies, government and agriculture (Mpande and Tawanda, 2013).

3.3.2 Participants

Our research was conducted throughout a total of ten purposely selected communities across central and southern Malawi. To select villages for our interviews, we held a number of discussions with the central and local Water Board, members of parliament and Head Chief in the region to identify an initial three to five communities where water stresses were acute. Communities were specifically chosen so that a variety of water issues and distances to the local population center were represented. Once these initial communities were chosen, snowball sampling was used to identify the remaining interviewees. In snowball sampling, respondents introduce researchers to other potential informants who are then interviewed, thus building the interviewed sample in an accumulative fashion (Noy, 2008). While snowball sampling is effective for identifying respondents in a target community and building rapport and trust between the researcher and informants, it has several notable limitations. Snowball sampling is non-random and individuals are selected for their involvement from within a particular social network. This may lead to a homogenous sample in which all respondents belong to the same socioeconomic categories (Browne 2005). To minimize this potential effect, we asked our interviewees to recommend particular types of water leaders and individuals, specifically woman-led water committees, refugee camps or slums for additional interviews.

The data in this study is derived from thirteen (13) semi-structured, face-to-face qualitative interviews with individual key informants, five (5) face-to-face qualitative group interviews with

a total of 27 individual participants and two public forums totaling about 80 individuals. Key informants included tribal leaders and elders, community government officials, agencies/NGOs, and academia in ten select communities across an urban/rural transect. A total of 120 individuals participated in the interviews and public discussions.

3.3.3 Interviews

We first designed broad interview questions and sub-questions derived from the resilience and adaptation literature. Our interview questions were designed to draw out the types of water stress; their response to water-related issues; community members' past and present collaboration with organizations to address water issues; community adaptation to stresses and at what scales; and how communities implement technologies to improve resilience (Howard and Bartram, 2010). We explored their experience with climate issues and how it has impacted their access to clean water; systems they have implemented and changes they have made to their practices to bring clean water to their communities, management challenges, sustainability challenges and socio-economic information.

While an interview protocol was used, participants were allowed to deviate from the question to explain their responses in detail facilitating a more in-depth understanding of the research topic. All interviews were recorded on audio, together with written notes and sketches when appropriate. To better ensure accuracy, interviews were transcribed by PhD student Landon Young, two undergraduate research assistants and two native Malawians in order to cross reference transcriptions for errors, consistency and accuracy (Schutt, 2011).

Additional data was collected ad hoc via direct observations (the decision-making process, planning and implementation) and participant-observation. We participated in water meetings as observers; actively worked with a borehole drilling team to drill a new Water4 borehole by hand; observed water collection at a variety of water point sources; observed brick making and agricultural uses of irrigation water; and observed water sample evaluation and well maintenance.

The interview transcripts were analyzed using semi-open coding of direct content analysis of interviews, research questions and guided initial code families. Additional codes were added as themes emerged from the data (Burnard, 2016). Coding occurred in three passes. First, we read through the transcripts and conducted open coding. In order to allow for the unexpected directions of conversations and to explore a wide range of shocks and adaptions, we 1) identified relevant

information in data, 2) assigned a word or phrase that best represents the relevant concepts that were consistent with research questions, and 3) documented why the information was important through notes and memos (Bazeley and Jackson, 2013). Since codes can be attached to segments of varying size words, phrases, sentences, or whole paragraphs connected to a specific setting (Miles and Huberman, 1994), we analyzed the transcripts and segmented them into words or blocks of text that we determined to be representative of the concept being coded. Next, axial coding was completed by Landon Young and a post-doctoral researcher from Dr. Zhao Ma's lab for intercoder reliability check (Campbell et al., 2013). During axial coding, we identified relationships and connections among the open codes. Next, during a selective coding phase, the coders identified the core variable that included all of the data for each set of axial codes. Finally, the coders reread the transcripts and selectively coded any data that related to the core variable identified (Strauss, 1987). A systematic codebook was developed, and each code given a label, definition, qualifications and an example (Neuman, 2013). After initial coding of the first transcript, the coders met to review codes and discuss discrepancies. Coding innovation proved more challenging. As discussed in the chapter on innovation, scholars disagree on what constitutes innovation and what constitutes particular types of innovation such as incremental versus radical. For consistency, clear inclusion and exclusion criteria were developed for type of innovation based on the definitions used, examples from literature, and finally, intercoder agreement upon discussion. The coding frame was updated, and transcripts were recoded and compared a second time.

After the second round of coding, we determined additional codes were needed to differentiate existing management of systems from planning of future adaptations. These additions were added under the broader adaptation code as current management and future planning. We also agreed that systems code required an additional code to differentiate social institutions and their relationship in the broader systems narrative. Accordingly, we added formal social institutions codes under the broader systems code. A second and third transcript were coded, and memos were recorded to document our reasoning for selecting certain codes, remaining questions, or points of clarification that were left outstanding. Next, the coder from Dr. Ma's lab and Landon Young met to discuss discrepancies. During this meeting, final inclusion and exclusion criteria were agreed upon and additional examples were added for clarity. Final refinements and corrections were made to the coding frame. The original transcript was then recoded, and we were

found to be in agreement. Finally, the remaining transcripts were coded in NVivo according to its code book. For analysis, a combination of contrast context and path dependency were used (Neuman, 2013) to describe the decision-making, implementation and outcomes of innovations as adaptation. This data was triangulated with information shared with us during the interviews, including records and maps of water systems and cities, offered by the Lilongwe and Blantyre water boards.

We anticipated that different communities might have different adaptive capacities and face different water issues. Communities were intentionally chosen that had both positive and negative adaptive outcomes and a range of water systems. Our first level analysis revealed many themes including relationships; communication; networks; types of water systems and resources; water quality and quantity; water uses; water stresses; water strategy failures; and adaptation strategies.

To identify an innovation within the adaptation strategies, we first separated adaptations into those that were selected for either short-term survival or long-term outcome(s) categories. We then used Dahlin and Behrens' (2005) framework to separate innovation types. Dahlin and Behrens (2005) suggest three criteria for identifying an innovation: *Criterion 1:* The invention must be novel: It needs to be dissimilar from prior inventions. *Criterion 2:* The invention must be unique: It needs to be dissimilar from current inventions. *Criterion 3:* The invention must be adopted: It needs to influence the content of future inventions. Finally, in order to frame adaptation choices within an innovation framework, we placed each strategy reported into the framework by Norman and Verganti (2014), which includes the following categories: Market-Pull, Technology-Push, Meaning-Driven, and Technology-Epiphany. A full description of our definitions and categories used in the coding process can be found in the Appendix.

3.4 Results

3.4.1 Profile of interviewees

Organizational affiliations and types of entities represented by interviewees are summarized in Table 2.

Table 3-1 Interviewees

ORGANIZATION / LOCATION	ENTITY TYPENTITY TYPE		# INTERVIEWEES
Citizen for Justice (Lilongwe)	NGO	Individual	1
Malawi Central Water Board (Lilongwe)	GOV	Individual	1
Ministry of Agriculture (irrigation)(Lilongwe)	GOV	Individual	1
Water Zone Founder (Blantyre)	Local company	Individual	1
Kusamala Institute of Agriculture(Lilongwe)	NGO	Individual	3
Village (Madisi)	Village	Individual	1
Business owner with well (Madisi)	Local company	Individual	1
World Vision (Blantyre)	NGO	Individual	1
Member of Parliament (Lilongwe)	GOV	Individual	1
Ministry of Agriculture (agronomy & irrigation) (Blantyre)	GOV	Individual	1
Chief and Traditional Authority (Chiwasanje Village)	Village	Individual	1
Refugee camp (Dzaleka)	NGO/GOV	Group	3
Water Technician (Blantyre)	GOV	Group	4
Group of chiefs (Zomba)	Village	Group	5
Water Zone Drillers (Blantyre)	Local company	Group	7
Village chief (woman) (Madisi)	Village	Group	8
Duku Village (Lilongwe)	Village	Public Forum	40
Pamphira village (Salima)	Village	Public Forum	40
		TOTAL	**120**

3.4.2 Water stresses in Malawi

Interviewees consistently reported that there is an overall shortage of potable water. In conversations with people in the city of Blantyre, the consensus was that only about 40% of people have access to water that meets government standards. Interviewees frequently addressed the interrelated nature of quantity and quality with one interviewee stating: *"If the quantity is not sufficient, then the quality is not sufficient because quantity affects quality."* The relationship of quality to quantity proved common in nearly every village, slum or refugee camp visited. Safety (clean water) and proximity play key roles in quality and quantity.

Interviewees across Malawi reported that natural and manmade water systems are relied upon for household consumption, irrigation and small-scale industry such as brickmaking. Many

hospitals and schools use off-grid sources of water—typically deep boreholes and wells. During site visits throughout the Chikwawa and Balaka districts, we witnessed hand-dug wells which, in addition to surface water, many people relied upon to provide drinking water. When water stops appearing in hand-dug pits or stops flowing from taps, people turn to alternative sources of water; rivers, swamps, etc., but report the surface water is not safe. One interviewee reported that "*there is not a river or other source of water available in the area with the exception of "zithaphwi*" (dirty water or mud from a hand dug well). In the villages, people are suffering from water-borne diseases because they do not have clean water. One person stated, "…*we drink water from unreliable sources which causes diseases. The majority of these people you see here were suffering from diarrhea."*

Shocks and Stresses influencing access to water

Interviewees reported a number of disturbances and shocks to water supply that affect their quality of water—population growth; floods and droughts; groundwater conditions; funding and climate change. A categorical list of stresses is provided in Figure 1.

Affecting short term survival
Drought
Flood
Water point physical failure (ex. well pump broken)
Water point quality failure (ex. increased turbidity; Cholera)
Pipes shut off
Affecting long-term planning
Population growth
Climate change
Political landscape
National water rights (ex. Lake Malawi shared with other nations)
Aquifer depletion

Figure 3-1: Shocks and Stresses

Population growth and urbanization

The government officials reported to us that the quantity of water is insufficient due to high population rates. Many people are moving to urban areas such as Blantyre, Mzuzu, Zomba and Lilongwe. The age distribution is skewed young, with around 60% of the population below the age of 18 and either "…*at school, unemployed, or affected by HIV/AIDS and that's a challenge for planners*." One Chief, during an interview, reported that the population in his village has not been counted, but if it were, it would be found that the population has increased in the last twenty

years from fifty community members to over 600 people. When referencing the larger cities, he said, *"There are two million plus people in Blantyre for a water system which was planned for 600,000 people. Now its capacity cannot sustain the current population. If nothing is done, there will be more water shortages not only because of droughts but because of population growth."* Water planners confirm that they did not plan for a growing population and the influx of people:

The population boom is felt at all levels of communities—from urban to rural. One Chief noted that the change was obvious: *"... one community in Salima called Chisomo doesn't have enough water, not because the water is bad, but because the community is too big. If you go by the borehole in the morning, you will find over 50 buckets on the queue."* Population growth, population density and groundwater conditions appear to be interrelated. A villager made the connection by saying, *"The quantity is not sufficient because the population is high, but water sources are low and as a result we face challenges in having clean water and water for domestic purposes. Machines have not been upgraded to support the influx of people. A borehole would serve 250 villagers, but now it has to serve over 500 people."*

With the urbanization and population growth, pollution is also of concern. Pollution intensifies the effects of the flooding during the rainy season. Interviewees reported that during emergencies there are numerous problems of water borne diseases, especially during flooding. Health issues, caused by pollution, affect the local population. Human excrement, rubbish and dead livestock are thrown into the waterways which severely limits the use of the water for domestic purposes. A program called "Beautify Malawi" was pioneered by Malawi's first lady and involved cleaning cities, but ironically it was reported that the program itself dumps waste into places close to the villages.

Creative solutions were shared by several interviewees for providing sufficient water supply. A director at an agricultural NGO said he advocated for a holistic approach, *"If every city/village were able to harvest water starting from the household level, there would be no flood problems. As long as the water is fully treated, there will be enough water."* An agronomist who practices permaculture at a national NGO acknowledged the relationship between drinking water, livelihood and food when she said, *"More people; more mouths to feed. But, they can be rotating their crops or grow crops that do not need a lot of water. Irrigation is practiced on a small scale so if there is a large population we will not be able to feed them all."* Several interviewees want to grow trees and gardens, but there is not enough water to water the plants. One interview said,

"Water meant for irrigation is also used for other domestic purposes…". Many did not see the situation improving in the future, and one could sense the desperation in responses. One villager said, *"Again, we can't dig a well hence there is so much pressure on the borehole that we have. We can't see the future of our kids if we parents are suffering now. The problem will be worse in the future when the population grows. People are moving from villages to town in search of opportunities."*

Droughts and floods

In a country which has two distinct seasons, rainy and dry, people are familiar with extreme swings in water supply. When asked what types of shocks they expect to occur in the next five to ten years, they responded, "droughts or floods." There are districts, such as Chikwawa and Nsanje, where droughts would be severe. Although they are familiar with extreme water conditions, the conditions are getting worse. Droughts and floods are reported as changing in frequency, duration and intensity. One interviewee said, "*The drought situation is getting worse. The water table has moved further deep and the population has increased, so the water is not meeting the needs for the population."* Another said, "*Because of climate change and deforestation, we are experiencing more droughts, because areas where we used to have heavy rain falls like Nkhatabay or Nsanje the rainfall pattern has changed in these areas*." Reflecting on the change, one interviewee posed that, *"Droughts do not last long, but in recent years they are frequent and they do not affect the whole country. Our greatest problem is to harvest water and use it during the dry season."*

When asked about the intensity of the drought, one interviewee responded that the drought is not bad, as measured by *"…how much maize we have because we depend on rain for agriculture*." However, other interviewees consistently told us that the weather is changing and droughts are getting worse. These changes have affected their ability to utilize indigenous methods of predicting weather patterns. One person discussed how indigenous methods are not utilized any longer, saying, "*We used to predict weather long time ago but now we can't.*" Some attributed the major causes of changes in weather patterns to deforestation. Whatever the reason for the changes, it has a significant impact on a country that depends upon agriculture to exist. Discussing the devastating effect on agriculture, one person noted that, "*Last year the rain did not start when it was expected to start. If the rain doesn't come in time then there will be no maize or low maize production. The recent happened in April last year where about two thousand people died*." The consensus in the

communities we visited was that the dry seasons have worsened, although the exact cause was not agreed upon.

Interdependencies

Malawi relies on a complex system of large dams, pumping stations and piped water distribution in major cities like Lilongwe and Blantyre. Sometimes these centralized pumped systems fail, cause far-reaching effects. When asked whether there is anything they could imagine that would be such a big external shock that it could shut down the system, Interviewees responded that they had one last year when the pumps could not pump.

> *"It happened because we had a low power voltage which caused our pumps to fail, but the problem was caused by the electricity water supply of Malawi. The water board does not provide water to ESCOM (Electricity Supply Corporation of Malawi) to generate water. The water used by ESCOM comes from the Shire River. Most of the time, we just use it directly because boiling requires firewood which is in limited supply. Furthermore, the government prohibits villagers from cutting down trees for firewood. If we do not do anything; there will be a scramble for water. There will be a water war. I have heard that electricity is a problem sometimes and so the pumping sessions do not work because there is no electricity. The problem is severe in Blantyre because the district pumps water from Shire River using with electricity from ESCOM."*

There are complex interactions among various elements of the socio-ecological and socio-technical systems, including population growth, pumped systems, and inequality. During discussions with the Water Board and others, we discovered that those in the villages and the slums were the first to have their water shut off in the event of a drought. As we heard many times, population is one of the big drivers of system failure. As noted by an interviewee, *"There will be more water shortages, not only because of droughts, but because of population growth if nothing is done."* When discussing the risks associated with these interactions, another person said, "*It's basically droughts, floods and electricity which is used to pump water. Floods don't occur frequently, but when they do it affects the pump stations by causing an influx of sediment*." One interviewee said that *"... we had an incident last year which affected our [pump] system.*" They have had floods "*causing a lot of damage to houses. The rain would come late and stop early affecting levels of water. Last year a lot of rain came for a short period of time and "a river in*

Zomba filled up. During rainy seasons dambo/wet areas get flooded. Water has destroyed crops. What we have seen in the southern region is that buildings were swept. There was a lot of water that it became uncontrollable." In the villages of Blantyre or Lilongwe, drought is felt strongest due to their dependency on tap water from the pumped systems.

3.4.3 Adaptive innovation in Malawi

Upon analyzing the adaptation strategies employed in the water sector in Malawi, five overarching categories emerged: 1) man-made systems, 2) utilizing natural resources, 3) accessing outside resources, 4) reducing water use, and 5) stealing. Rogers definition for innovation includes any new technology or practice, including those new to certain people or locations (2003), and using this lens we used adaptation and innovation interchangeably. We observed that the types of adaptation strategies varied in type and scale, from very simple adaptations at the household or village level, such as open pits, to multi-community water solutions such as extending the centralized water distribution pipes from the city to the villages. The decision-making process varied based on where the adaption occurred and the resources available, including outside advice from professionals. During analysis, it became apparent that many strategies can easily be broken into either short-term survival strategies based on urgent need or longer-term planning or strategic activities. An exception was the concept of boreholes, which proved to be more challenging to categorize due to the highly contextual situations and normative used of the word "borehole." In some instances, an interviewee used the term "borehole" to describe a deep well, while another interviewee used the term to describe a shallow well, but still another was using the term to describe an intermediate solution. These three types of boreholes differed in design, cost, function and effectiveness. Distinguishing among these turned out to be extremely important and led us to discover the unique and beneficial differences of one intermediate level system called Water4 which is discussed in more detail in Section 4.

Short term strategies

Short-term survival strategies are based on an urgent need for a solution, therefore sustainability is sometimes sacrificed for speed. Examples of short-term strategies include constructing quick and low-cost man-made solutions such as hand-dug pits, replacement of boreholes after a failure, treatment of contaminated water by boiling, sieving, or using chemicals

for purification. At times, unimproved and potentially dangerous natural sources such as rivers, swamps or springs are utilized as a survival strategy. A third strategy is soliciting outside sources such as sending a budget and list of items needed to an NGO, relying on the government to intervene during droughts or floods, or relying on an outside advocate to request help from various sources like NGOs, government, or companies. While most strategies involve procuring additional water, some strategies rely on reducing water consumption, such as water conservation practices in agriculture, light industry such as brickmaking, or reducing domestic uses such as bathing. Finally, faced with desperate situations some turn to stealing water by illegally tapping into water sources.

In reality, most adaptation scenarios involve multiple strategies. Communities with a diverse set of adaptation strategies (redundancy) and access to natural resources are less vulnerable. We found examples of urban and peri-urban communities which had a diverse set of government provided piped systems, deep and shallow boreholes and surface water. Both urban slums and remote villages on the other hand had few water options leaving them extremely vulnerable to disruptions in water provision. Slums were found to be most vulnerable, depending entirely on very polluted surface water and unreliable government kiosks. Furthermore, interviews with a government agency and a large water NGO confirmed that water is shut off in slum areas first, in favor of reserving water for wealthier areas. Residents in slum areas therefore resort to desperate tactics including stealing. A shortlist of water sources across the urban to rural gradient is provided in Table 3.

Table 3-2: Water Sources

	Slum	**Urban**	**Peri-Urban**	**Rural**
Unimproved Sources	Polluted surface water Hand-dug pit	Polluted surface water Hand-dug pit	Surface water Hand-dug pit	Hand-dug pits
Improved Sources	Kiosk Limited piped water	Piped water Boreholes Deep wells Trucks Bottled water	Limited piped water Boreholes Wells	Boreholes Some wells

Longer-term Management and Planning

Management and planning are characterized as the ongoing activities in the water sectors that are not in response to immediate needs or impending hazards. To illustrate, the Malawi Water Board stated during an interview that, *"Over the next ten years, the shocks will still pose a challenge but the [organization] is developing some strategies to curb the situation. The strategies are upgrading of pipes, constructing new sources of water and the possibility of drawing water from Lake Malawi, but that is a long-term strategy."* Long-term strategies include constructing robust, expensive, or extensive man-made solutions to include boreholes, reservoirs and water treatment options. Examples of long-term built infrastructure includes deep wells, mechanical pumps, boreholes constructed or replaced often as a result of existing boreholes breaking down and reservoirs which serve as a way to reserve water in times of emergency. Natural resources are also utilized at the larger scale, by building engineered systems to deliver water from large lakes such as Lake Malawi. Another strategy is relying on significant outside sources for capital and other resources, such as the president requesting aid, loans, or investment for the country. Water conservation and water use efficiency solutions considered on a long-term scale include population control, government subsidies for conservations practices—like irrigation—and a payment-based national kiosk network.

3.4.4 Categorizing innovations as adaptations using radical innovation framework

The strategies were categorized using Norman and Verganti's radical innovation framework which includes the following categories: Market-Pull, Technology-Push, Meaning-Driven and Technology-Epiphany. We considered specific examples for each strategy, documented the intended adaptation goals, and observed whether the strategy was effective at achieving the goals. A full list of strategies according to their respective innovation types can be found in Table 4.

Table 3-3 Adaptation strategies

SURVIVAL			
Market-Pull	**Tech-Push**	**Meaning-Driven**	**Tech-Epiphany**
• River water • Shallow pits • Water bowsers • Boiling • Chlorine drops • Natural spring • Rainwater harvest at home • Water guard (chemical) • Use hospital/school water • Water harvesting tanks • Boreholes*	Boreholes*	• Waste water – bricks • Water4 boreholes* • Rainwater harvest at home • Mosquito net sieve* • Drink irrigation water	• Water4 borehole* • Pit planting • Manure planting
LONG-TERM PLANNING			
Market-Pull	**Tech-Push**	**Meaning-Driven**	**Tech-Epiphany**
• To learn more about the water issues; develop a strategy to tackle the problem • One large tank • Use a solar powered pump • Have different demonstrations • Use solar power • Increase the number of boreholes and use solar power	• Deep wells • Agro-forestry • Solar-pump • Bottled water from NGO • Water kiosks • Drawing water from Lake Malawi • New farming technologies • Conservation agriculture • Organic manure promotion • Swales	• Environmental conservation • Fee-based water kiosks • Mandatory prepaid water meters • Communal water points (water kiosks) • Catchment areas • Integrated water resources management	• Water kiosks with a partnership with Water-Aid • Conduct a needs assessment involving the people • Prepaid water meters • Water kiosks • Structures like water harvesting wells;

Table 3-3 continued

- Borehole Drilled two boreholes
- Deep well
- Bought a pump
- Large open reservoirs
- Increase number of reservoirs
- Enlarging the treatment plant
- Enlarging dams and the water treatment plant
- Enlarging the dams and constructing a new treatment plant
- Upgrading of pipes; constructing new sources of water and possibilities of drawing water from Lake Malawi as a longer-term strategy
- Operating on water shedding
- No-till
- Water detection devices
- Demonstration farm
- Helping design a system water harvesting systems
- Permaculture demonstration
- Basins
- Using manure to modify the clay
- Public network supply system, e.g., Pipe / Tap water system
- Manure planting
- Organic manure
- Contour ridges and swales
- Agro-forestry; farmers plant trees
- Communal taps
- Cultivation throughout the year; learned cultivation methods
- Permaculture demonstrations throughout Malawi in collaboration with schools/colleges
- Permaculture in hospital
- Water harvesting swells
- Basins
- Dams
- Weirs to divert water
- Terraces
- basins, dams, weres; also use net and pan collecting water from roofs, making a lot of basins each basin will be harvesting close to a thousand liters of Water; using manure on the farm and modifying the clay to absorb water.

Market pull

Market-pull innovation "starts from an analysis of user needs and then develops solutions to satisfy them (Norman and Verganti, 2014)." The most common type of innovation witnessed firsthand and described in our interviews is market pull. Market pull is characterized as a solution based upon a determined need or desire of a particular group of people. For example, one camp we visited determined there were "*not enough boreholes to supply water to the entire camp. Water for Life, an NGO, was hired to drill two boreholes."* The boreholes were working producing high

water quality, therefore meeting their expectations. This example of digging shallow holes in the ground to access water was very common. The holes, or "pits", ranged from a *"few feet to over twenty feet deep and were dug by hand".* Other household examples we witnessed in Malawi included: 1) individuals and communities using a product they can buy at stores called WaterGaurd in an effort to kill micro-organisms; and 2) boiling water, which is a very common and inexpensive demand-driven water treatment in Malawi. Community-level examples include a tap system which was not working in the refugee camp, so *"the internal water team decided to purchase and install a pump and drill a well instead."* Regionally, the system of large-scale dams in central and southern Malawi was created due to increased demand. One interviewee was confident that increasing the number of government-built dams would be successful, saying, "*Currently engineers are enlarging damns and the water treatment plant is being increased to accommodate more water*." However, when asked about past system failure, he responded, *"...when the pumps [at the dams] are not pumping or when water is not reaching the required tanks and reservoirs. Rate of population growth is greater than the water supply. Water consumed per person must decrease. Water is not reaching the required tanks and reservoirs because the pumps are not pumping.*" A former Vice President at the largest water NGO in Malawi reported several problems with enlarging dams, one being that the *"water treatment plant causes less water downstream and disruption to villages downstream. In addition, because dams are highly centralized systems, when flood pumps stop working, all piped water shuts down for up to a month."*

Tech Push

Technology-push innovation is a result of "radical changes in technology without any change in the meaning of product." Technology push innovation does not come from users. There were many examples of Technology Push innovation reported. Technology push is characterized by one organization or person recommending, suggesting or forcing a given technology onto others. We witnessed that deep wells are a common Tech push solution throughout Malawi. Deep wells are "*constructed by using expensive and specialized machinery to drill a deep borehole into the water table below the natural filter of the earth*." We were told that deep well systems are seen as the safest and most reliable option and provide the heaviest throughput of water. Unfortunately, locals said that when a break occurs, the well is not easily repaired as expertise is needed and expensive parts are required. Other examples of solutions being pushed on locals include 1)

"During times of drought, the government ships chlorine tablets to communities for treating their water", and 2) During times of extreme drought, outside countries and NGOs bring in bottled water. Larger scale examples include 1) *"the Water Board chose to extend the existing piped infrastructure into communities"* instead of distributing systems; 2) In response to drought and flooding events, *"the Ministry of Agriculture advised farmers to adopt soil conservation practices, such as pit planting, swales, organic manures and agroforestry"*.

Although technology push was seen by some as a negative, we saw that one example was successful and generally positive for the communities we visited. We heard from an interviewee in the agriculture sector that "*schools/colleges in Malawi are establishing permaculture demonstrations in the whole of Malawi. We work with UNC and are establishing permaculture in hospitals at the maternity waiting home so that we can help them produce enough food to feed pregnant women when they come for labor*."

Meaning driven

Meaning-driven innovation "starts from the comprehension of subtle and unspoken dynamics in socio-cultural models and results in radically new meanings and languages, often implying a change in socio-cultural regimes (Norman and Verganti, 2016, p.17)." In Malawi, water provides the means to grow crops, make bricks and provides water for livestock. We walked through fields with Malawian farmers and visited irrigation projects funded by the government. The crops were larger as compared to the small and stunted appearance of crops of nearby villagers. We met farmers who had been trained by a permaculture NGO on radical and experimental techniques to store and conserve water, such as shallow pits that hold rainwater to grow banana trees, and the intense use of groundcovers. Other examples of water technologies changed the meaning or norms. Examples included 1) *"During times of extreme drought, some experimented by using waste water for brickmaking"*, and 2) vulnerable and "*poor urban areas, such as slums, were provided a new type of water system called a water kiosk that, unlike expensive piped systems to homes, can be provided at a lower cost*." A particular example of a meaning-driven strategy stood out for its resourcefulness and effectiveness. One interviewee stated that during times of low water, some "*people use waste water to mold bricks and this has eased pressure on the boreholes.*" One strategy that seemed to fall under both market-driven and meaning driven was the stealing of water from piped resources. Illegal water connections are on

the rise and are likely stemming from the desperate situations in the areas with kiosks—particularly the slums.

Tech epiphany

At the most innovative end of the spectrum is the technology epiphany. Technology epiphanies "bring a radical change in meaning, enabled by the emergence of new technologies or the use of existing technologies in totally new contexts" (Norman and Vergant, 2016, p. 90). There were very few examples in the field of technologies, practices, or social institutions that the coding team placed into this category. However, one such innovation applied met the technology epiphany criteria—the implementation of the Water4 hand dug borehole and pump. This system is *"co*

nstructed by locally trained experts and gives agency to local people, teaching them how to dig, test and repair their own wells by hand using equipment produced nearby for a fraction of the cost of machine drilling." Other technology epiphany examples include: 1) During times of floods and high turbidity of the water, people were observed repurposing the mosquito nets donated by an NGO to sieve the dirty water for drinking. Long-term examples include an NGO that invented a machine that hand-drills an intermediate level borehole that local people can operate and repeat in their community instead of relying on outsiders. In another creative example, an interviewee reported that their village was collecting water from roofs and creating reservoirs. Their goal was that "*during the dry season we will be having enough water to take us through the dry season even if we had a drought.*" They reported that the effort is considered a success and now *"...we are making a lot of basins each basin will be harvesting close to a thousand liters of Water.*"

Recently Prepaid water meters have been added to many slums. Although this was classified as a technology epiphany due to change in both technology and the meaning of accessing and purchasing water, the social meaning change was not necessarily positive. Many people are impoverished and cannot afford the meters or cannot to pay in advance. Some people thought that this was in due, in part, to the governments' failure to conduct a needs assessment involving the people. As a result, two interviewees reported that:

> *"...people did not have a voice when the decision was made to use prepaid meters. The government made it mandatory for everyone to own a prepaid water meter instead of a postpaid water meter. It is considered a failure, because "They had not done any due diligence in terms of how the VAT (Value Added Tax) was going to affect people in town and local communities that depended on kiosks for water. Shops were not open every time*

to buy credit for water throughout the day. They also put the same system in public institutions like primary schools and hospitals. Primary school teachers take a long time to receive salary from the government hence they will not have enough money to pay for water bills all the time."

"The guarantee that credit vouchers would always be available in shops would not be guaranteed. It stands against the rights that Malawi has committed to; the right to water at international level, access to clean water and sanitation. The government did not involve people in decision making. They thought that prepaid water meters would be the easiest way to collect money and reduce their own operational cost".

3.4.5 Innovation and adaptation decision-making process

Multi-level Decision-Making

Adaptation strategies in Malawi are selected in a multi-level fashion—from households to the nation's Parliament. Strategy selection occurs at a basic level, such as a woman within a household choosing a water source for domestic water uses or choosing a treatment option such as boiling or chlorinating water. At the village level, selection occurs within a complex process and includes many stakeholders including informal local chiefs, village elders, community water boards and official government. For illustration, we witnessed that deciding to install a well in a community involves, at minimum, the chief and elders, the Malawi Water Board and water testing agency. The decision, many times, involves an outside funding agency, technical NGO, well drilling team and villagers. Individual households in the community select adaptation strategies they believe are most advantageous, then other individuals replicate those strategies. At the community level, some individual strategies are observed to be advantageous for many people and are officially or informally encouraged. At the community level, the chief and water board make most decisions concerning water, if either should exist. Interviewees state they recognize the importance of approval by the government for borehole projects so, therefore, boreholes are in the government's record of boreholes that require maintenance. The government will also provide pre-approved borehole designs in areas where there is not tap water. According to an interviewee, *"Parliament approved the government to borrow money to drill boreholes in districts, such as Nkhotakota, with critical water problems."* However, the programs are underfunded and rely on local help in which few poor communities can deliver. One example from a remote village illustrates the point. A well driller said,

> *"They have been reporting to the district commission for many years, but have received no help. They feel the community should contribute money toward the project and learn how to repair boreholes and have an account with funds and connection with the government to get help in times of need."* To fill the gap in funding, contractors usually tell people to mold bricks and gather sand and encourage villagers to contribute in-kind help: *"…when there is no water, we talk to the community to volunteer in drilling a well."*

Local and indigenous knowledge

Many interviewees referenced local and indigenous knowledge and believe it to be important. One water expert stated, "*The best thing to do is to conduct a needs assessment in the community and have a full understanding of what the community needs. Include women, children, men, youths, chiefs and everyone in the process. A needs assessment helps to provide projects that tailor to their needs*." A borehole driller commented on the importance of enlisting local advisors when selecting optimal drilling locations by saying, *"…when I go to a village, I talk to the chiefs and old people. Sometimes they can tell you where water used to be, and that information would help in finding a suitable site to drill a borehole*." In a warning against not including the local communities in decision-making, a water professional said, "*When you take communities for granted, and they know that they are being taken for granted, that becomes a problem for both the government and organizations. There is no transparency. Taking people for granted means not involving them in decision making or undermining their wisdom*." One person told us that locals see indigenous knowledge as a positive asset in decision-making. Several examples included the ways in which elders would watch certain indicators in the natural world. For example, one person said "*Years back people living in remote areas would tell that rain was about to come if they saw animals relocating to a certain area or when birds were migrating."* Another example involved a water sector worker relying on indigenous knowledge for locating water, "*I was the first coordinator to hire a contractor to drill boreholes. The contractor was Greek, and he was using indigenous knowledge to detect where water was and then geologist would confirm his findings*." Another engineer said, "*We love talking to people before we start drilling. That's how best we get information from the community member. We get the history of the community and what they do in times of shocks. The primary source of information is the people on the ground. We interact with them because we do not have machines which detect droughts*." Another said, "*Locating sites to drill a borehole requires involving people in the community. They can tell places with water and rocks. Community members drill boreholes and wells so they have an idea of how it's like*

beneath." When asked if a certain community could still use nature to predict weather, they said "*No we can't predict now. The weather pattern has changed. We used to predict more than five years ago.*" When asked where a certain village gets water information for decision-making, they say, "*Nowhere. The majority of those who had the information died a long time ago*." One interviewee tied the loss of traditional knowledge to a change in process with negative consequences, "*It has changed because in the past our parents were using fire as a tool to facilitate the decomposition process of grass into manure. But the way we are using fire now is like a destructive tool to the environment, burning everything without a cause leaving a large percentage of our land bare. That's why we are anticipating severe floods and drought in the next five years*". One government worker said that,

> *"Understanding water trends requires a series of data collected over the past years. The problem is that we do not have a good system to manage our data system hence we can't analyze the situation. The department has accumulated a lot of data over the years but has not analyzed it to determine the trends of water quality in Malawi.*

Some government policies prevent active solicitation of information from local communities. A government water tester said that, "*For example, we can only test Madisi water if Kelly approaches us to test a borehole in Madisi, but Kelly may not be drilling boreholes every year and this would imply that the department will have to wait until Kelly comes back with a request. This in return affects our data collection process and analysis*." Further he said that, "*…most organizations do not request a water test from our department. Had it been that all organizations were coming, we would have collected enough information from all parts of the country*." This becomes a major issue when local people lose their voice because they do not go through the proper channels. One example shared by a government worker was that *"Poor people get their water cut off first because they do not have a voice and a platform to speak out while the rich will take it to the social network or make a call to the water board."* Further discussing challenges of the government, a person suggests that,

> *"Our history from the first president to the multiparty system of governance shows that development in this country is not need based. We spend a lot of time trying to achieve the Millennium Development Goals. We want to be seen on an international level that we are doing something, but practically on the ground there is nothing. Why? Because we do not have resources to do much on the ground. The state is supposed to provide social structures for people to benefit but it appears that NGO's are doing the work of the state."*

Being able to solicit local information is crucial for understanding patterns of water changes and climate changes that may lead to devastating events such as droughts or floods. A government official said,

> "*Malawi does not have an early warning system. We do not have the capacity to understand weather patterns because we are not good at keeping records. We are behind technology, so we do not have the technical know-how to understand weather patterns. There are no mechanisms to take people away from vulnerable/crisis prone areas. We are always taken by surprise when a disaster strikes. For example, People living in the Nsanje District (in the southern part of Malawi) live two separate lives; they live uphill during the rainy season and near the shire river during the dry season. During the dry season they live by the river side to grow crops and in most cases, they over stay into the rain season when floods usually occur. There is no proper mechanism to stop people from living near the river during the rainy seasons hence they are always victims of floods every year.*"

3.5 Discussion

In response to water stresses, communities in Malawi have adapted in a number of ways which differ drastically from recommendations by the SDGs. While the Malawians we interviewed want to address the challenges they face in securing water, they have not yet achieved their goals at either the local or national level. We observed that the types of innovation that are being chosen as adaptation strategies are largely incremental, small scale, localized and marginally advance technical aspects of procuring water. Many were conceptualized, designed and funded from outside the community and were too complex and expensive to scale or maintain. In addition, we were told by village chiefs and the water boards that the manner in which communities select adaptation strategies has shifted over time away from localized decisions to decision-making occurring at the government level or decisions-making by international NGOs. We witnessed that decision-making has shifted from including many local and diverse stakeholders to decision-making by a very few outside the community who are predominantly male. These types of systems and manner of decision-making stands in contrast with the scalable innovations and participatory decision-making process outlined by the SDGs.

In contrast to the above, we noted several factors which led to successful adaptation strategy and scalability, including local knowledge from a diverse group of people in the design phase, local implementation and training for replication and long-term relationships encouraging feedback loops and ongoing innovation. A select few radical technology innovations emerged

which changed the meaning and use of the system in entirely new ways, resulting in improved resilience and adaptive capacity.

3.5.1 Analyzing innovation as adaptation strategy in Malawi

Current strategies and SDGs

Interventions and adaptations by Malawians in response to water stresses are effective and considered innovative by locals, but are not entirely novel. An analysis of the qualitative interview work revealed that in Malawi innovation does not have to be something entirely new and that adaptations don't (which are behaviors in response to some change) do not have to be new to be effective. The types of innovation chosen as adaptation strategies are largely incremental, small scale, localized and marginally advance technical aspects of procuring water. We categorized these types of adaptations as market-pull or technology-push depending on the entities driving the adoption.

In addition to a lack of novelty was a clear dependency on outside resources. Many adaptationsadaptations were conceptualized, designed and funded from outside the community. Examples included replications of systems built elsewhere in the country, such as water storage tanks or extensions of existing centralized water systems like the piped water system of Blantyre. Of these, some were very complex and expensive, and although desirable to the community, not feasible for scaling or sustainable over time without outside help. Given that the ability to scale is crucial for success of SDGs, and the majority of solutions are expensive and foreign, then we must assume that long-term sustainability is being overlooked for the sake of access. Such access-based development goals do not align with the SDGs and could create problems similar to those found with the previous MDGs. These systems have failed at a high rate, and our findings validate the literature that states government water provision numbers are considered to be inflated. Some reports indicate that, in reality, almost half of the water produced is lost due to leakages, illegal connections and vandalism (EWB, 2009; BWB, 2011).

Communities do not have enough water, although they expressed a deep desire to increase total water supply and water quality. We were told that water shortages were not evenly distributed, with urban slum and poor rural areas suffering the most. This aligns with the literature which finds that water supply shortages are more prevalent in high-density, unplanned and poor residential

areas (Maoulidi, 2012). The Blantyre Water Board (BWB) has failed to provide regular water supply due to the rapid population growth and poor planning (BWB, 2011). We witnessed this in Blantyre, where the city chooses the wealthier areas to deliver water to first during frequent water shortages due to system failure. A representative said, "*Slums are the first to experience water shut off in times of need"*. As a result, in low-income areas, unreliable water supply is leading some residents to rely on unimproved (and risky) sources of water such as shallow wells, streams and drainage ditches. (Maoulidi, 2012). We can assume from this disparity that they lack agency or capacity to accomplish their goals. This is likely due to the complexity and expense of many systems built by NGOS or because the systems built by the government are increasingly centralized and robust. Institutions and engineering solutions drive communities into greater poverty and dependence. These outcomes do not align with the goals of the SDGs which seek to end poverty, improve health and clean water access and build sustainable infrastructure. The results or outcomes presented above align with literature, showing a high number of incremental innovations, but do not align with the goals of transformation at scale as stated by NGOs and the government of Malawi.

Alternatively, some innovations we witnessed were what Bahadur and Doczi (2016) and Godin (2008) call "frugal innovation" which are based on local capacity and are inexpensive and feasible to scale up, but are not necessarily desirable because they do not fit into the local culture. Still others offered a hybrid option, leveraging local knowledge in the creation, and training local teams to replicate, scale and repair over time. These we labeled as meaning-driven or technology-epiphany innovations, depending on the degree of new technology and change in meaning-based on other local solutions.

If we believe that the intention of the SDGs and other policymakers' calls for innovation is in regard to something "more significant" than small incremental innovations, then we need to understand how the SDGs and other policymakers define "more significant". The qualitative data suggest that we might extend the definition of innovation to define it as something which is new to a people or location, though not entirely novel. In fact, one of Rogers definitions for innovation includes any new technology or practice, including those new to certain people or locations (2003), and applying this definition we used adaptation and innovation interchangeably at a basic level. However, the motivation of innovation might dictate whether it is an adaptation. For instance, not all innovation is adaptation. Innovation can also be a change for the sake of improvement and not

in response to an external challenge. The degree of change might also dictate whether something is merely an adaptation or something more.

At the most innovative end of the spectrum is the technology epiphany. Technology epiphanies "bring a radical change in meaning, enabled by the emergence of new technologies or the use of existing technologies in totally new contexts" (Norman and Vergant, 2016, p. 90).). As stated before, Dahlin and Behrens (2005) offer three criteria for radical innovation: *Criterion 1:* The invention must be novel: It needs to be dissimilar from prior inventions; *Criterion 2:* The invention must be unique: It needs to be dissimilar from current inventions; *Criterion 3:* The invention must be adopted: It needs to influence the content of future inventions. Using this definition, many of the adaptations are considered innovations even though they are not radical innovations. More research is needed to differentiate these radical definitions.

Challenges of placing adaptations within innovation framework

Approaching adaptation within an innovation framework provides more clarity and makes innovation more broadly applicable in practice. Descriptively categorizing innovation helps decision-makers and stakeholders discuss the nuances of adaptation strategies and hopefully lead to better adaptation outcomes. However, when placing strategies within the framework, we quickly experienced several challenges. While some categories, like Technology Push, were easy to identify, others were quite difficult. Technology Push could easily be identified by asking ourselves "Is this community driven, or outside driven? Did this strategy originate locally or by someone outside the community? Who is driving the adoption?" However, categorizing certain innovations like those that might fit within meaning-driven or technology epiphany, require a great deal of subjectivity and expert knowledge. For example, when considering the first and second radical innovation criterion, one must determine the "novelty and uniqueness" of a strategy (Norman and Verganti, 2016). This determination begs the question: "How do we objectively determine if something is "dissimilar" from other technology? How unique or different must something be?

Adaptation as innovation: differing views

We observed adaptations which seemed to contradict Few (2017), who states that adaptation is just another word for innovation. We observed that some of the adaptation strategies

were not new, novel, unique or adopted—for example, water collecting from a roof or filtering water from a river using cloth. Some household and grassroots methods were unique to their village or community, and some scholars have found these types of adaptations to be important (Campbell, 2017). We also witnessed that many adaptation practices are not new but are effective at adapting. In addition, Rogers (1962) states that technology is another word for innovation. However, we observed adaptations which were not technology-based nor in line with definitions of innovation. It is here where we depart with Few and Rogers' generalizations and argue that at least, in certain circumstances, some adaptations and technologies are not innovations, and that some innovations are not adaptations. If we use the definition that innovation is anything new, including simply neutral location, and if we build off of the assumption that adaptation and innovation are one of the same, then we identified many innovations. Further, we found Dahlin and Behrens' third criterion involving adoption and scale to be extremely difficult to define (Dahlin and Behrens, 2005). We found ourselves feeling forced to choose an arbitrary threshold of adoption. Answers might be found in diffusion and network theories, such as Rogers product adoption curves or Moore's s-curve which is typically used in a business context (Christensen 1997).

3.5.2 Innovation decision-making and the role of institutions

Decisions are made in the context of unique stresses, environmental, social and political circumstances, and each scenario requires a nuanced approach. When communities have diverse approaches to choose from and diverse perspectives informing decisions, they are better equipped to select an adaptation strategy.

The manner in which communities select adaptation strategies has shifted over time away from localized decisions using indigenous knowledge to western engineering solutions brought in from outside the community, either from the government or international NGOs. Although indigenous knowledge once played a central role in water provision, its use has been reduced with the advent of new technologies and innovations.

Participatory methods such as those that incorporate local knowledge and ideas, are seen as very important in the decision-making process in Malawi, but such activities are under-funded. Collecting and making use of the data can be challenging. Water4 and well drilling teams were observed using mobile applications on cell phones for collecting local knowledge and ground truth from communities to inform where water systems would be installed, but they expressed many

challenges in the participation. “Ensuring that diverse opinions and values (within and across scales) are represented and respected is necessary to ensure the knowledge, values and perceptions of communities are integrated into planning, to mitigate the potential for elite capture of adaptation resources and to avoid perpetuating inequitable development outcomes” (Ensor, 2018, p.145). Although participatory methods were used in some situations, such systems have not been widely successful.

Foreign aid is heavily relied upon, which contradicts the literature on autonomous, grassroots and asset-based innovation. It also goes against the SDGs call for more local and participatory knowledge generation and design. Grassroots and autonomous innovation relies upon such indigenous and local knowledge, and if this type of innovation is important, then policymakers and scholars should focus on explicitly encouraging such activities. Communities can utilize participatory methods to solicit local and indigenous knowledge, sense local conditions and create a system for reporting innovative ideas. The SDGs place an emphasis on participatory methods placed at the center of decision-making *across* various geographical levels (UN 2015). Areas of progress include increased access of citizens to information and increased participation in decision-making, human rights, indigenous peoples and gender equality (UN 2015). To meet the SDGs, goals we believe that local communities’ empowerment to make decisions should be increased and that the creation and monitoring of water sources is needed.

Emergent quality of radical innovation

Radical innovations are many times the result of highly local and autonomous innovation and remains largely unknown to other communities. These type of radical, emergent and autonomous forms of innovation are not only hard to find, but at times impossible to predict or anticipate. One opportunity might be to leverage the vast number of people with mobile phones to report ideas and innovations. We believe that participatory methods can be leveraged to identify and study additional radical innovations in the field and share findings broadly with others. Crowdsourcing and participatory reporting has been used before in U.S. corporations for suggestion programs. Crowdsourcing has been used in Africa for technology development and data collection. As mobile phones expand across the developing world, research on mobile innovations and their role in the water sector are needed.

Another challenge affecting decision-making at the governmental and local levels is gender equality. Although major efforts have gone toward gender equality and the empowerment of women (UNDP, 2013), only 11% of technical decision-makers in Malawi are female. (Mwamsamali and Mayo, 2014). At the national level, the proportion of seats held by women in Parliament fluctuates around 15-20% (Kayuni, et al., 2014; Dulani and Dionne, 2014). Although the decision roles are predominantly male, it is well documented that the participation of women in decision making and implementation of water and sanitation projects is important and leads to system sustainability (Mwamsamali, 2007). Women maintain and use water systems, yet many times have little say in the design of the implementation of the systems. This leads to disruptions in the sensing networks that provide feedback loops to decision-makers. The ability to successfully communicate with local people is critical for participatory work and for ensuring that local opinions and indigenous knowledge is accounted for.

Ecological limitations of innovation

Development, adaptation and novelty or innovation is not de-facto beneficial for communities, nor is it always beneficial for the surrounding ecological context. We must consider the ecological limitations to innovation. By viewing innovation through an environmental innovation framework, we can see limitations and boundaries of the innovation concept. In Malawi, we see the effects of hydrological innovations such as the massive dams which power the major cities of Blantyre and Lilongwe. These dams have affected the surrounding landscape and extensively reshaped watersheds. In contrast, the reforestation of trees which were harvested for charcoal can restore hydrological processes which affect Lake Malawi. Deforestation has decreased the rain in the area and even the Lake levels (MWB, 2016). The innovations which are implemented can have profound effects on the environment, and the examples such as the dams, piped water system, and kiosks show that newness is not always a force for good but can in fact be harmful.

3.5.3 Innovation success factors and future opportunities

There were several key factors which led to successful strategy selection and scalability of innovation including local knowledge from a diverse set of constituents in the design phase, local implementation and training for replication, and long-term relationships encouraging feedback

loops and continual innovation. We observed that together these factors led to radical technology innovation in multiple contexts. The resulting innovations transformed the local meaning and social norms surrounding the procurement of water from foreign-dependent to local empowerment and lowered the cost for implementation. Moore and Westley (2011) discuss such disruptive social innovations, saying, "In the context of complex adaptive systems, we refer to such transformations as social innovations—that is, any initiatives, products, processes, or programs that change basic routines, resource and authority flows, or beliefs of any social system." Two examples of such innovation were the replication of agricultural irrigation pits from other areas and the Water4 borehole system developed hand-in-hand with communities in Sub-Saharan Africa. The Water4 system is a novel process and set of physical implements which allows local people to find water, drill a borehole by hand and maintain it over time. Such systems have started to explosively spread in Africa (Danert, 2015). The pit agriculture system was an enlarged pit roughly a meter wide and a meter deep into which a banana tree and other plants with high water requirements were planted. The irrigation water and rainwater were conserved deep in the hole out of the sun under the shade of the banana tree. These pit-based systems have spread across Africa (Fandika, 2014). These two systems fundamentally changed the physical systems, social institutions and adaptation and innovation activities in communities across Malawi. Such innovations are radical according to Norman and Verganti and disruptive according to Christiansen's definition. Such innovations are essential to achieve the adaptive capacity at scale that is desired in the SDGs, and "…have profound implications on the capacity of a linked social ecological system to both adapt and transform, and is an essential component of its "general" social and ecological resilience" (Moore and Westley 2011). A particularly surprising finding was that while these systems actually had lower sustainability than other systems, the local community could replicate or fix the system within an extremely short time period and actually enhance the resilience of communities. In addition, communities had agency, access and ongoing adaptive capacity through innovation.

A particular example of a meaning-driven strategy stood out for its resourcefulness and effectiveness. One interviewee stated that during times of low water, some "*people use waste water to mold bricks and this has eased pressure on the boreholes.*" This would appear as a practice that could easily be adopted and scaled, but could undergo negative selection pressure due to social perceptions of the handling of wastewater.

Implications for radical innovation frameworks

The examples of radical innovation highlight opportunities to redefine the way we look at radical innovation: 1) innovation does not need to be a radical change in technology to be considered radical innovation, 2) the concepts of social innovation and meaning-driven innovation overlap and can complement one another, 3) partnerships can achieve equal or better social results than grassroots efforts alone.

The example of agricultural pits highlights that innovation does not need to be a radical change in technology to be considered radical innovation. Strong change in meaning and slight change in social practices led to a dramatic change in impact and adoption of the innovation. A practical modification to the radical innovation categories might add language around radical social institutions, and broader our definition of social to include the concept of Norman and Verganti's Meaning-Driven innovation category. Such additions would better describe the empirical range of social phenomenon that has been found to impact innovation novelty and adoption.

Another framework consideration is reconciling the belief that some scholars have that adaptation and transformation are on a continuum. If we believe this, and we also hold the belief that innovation is defined by degree of impact, then we might consider an alternative to Norman and Verganti's binary classification system. Other frameworks like that offered by O'Connell et al., (2015) may better align with a continuum view of adaptation and transformation. Still others focus on the product of innovation instead of the process. It might also be advantageous to combine the descriptive qualities of Norman and Verganti's framework with the categorization strengths of O'Connell's framework.

3.6 Conclusion

Our results demonstrate that local opinions about innovation adaptation goals and innovation contradicted the goals of the SDG by focusing on small scale and incremental changes, such as extending existing systems or making systems more robust, instead of radical new innovations which may have led to transformation. Our results also highlight important factors that lead to resilience beyond technology adoption, system optimization and asset-based water systems, as discussed in the literature. We identified four key factors which play a role in determining the

way in which innovations are selected, designed and implemented in Malawi: 1) stakeholder views about adaptation and scalability of innovations, 2) stakeholder regard for local and indigenous knowledge, 3) epistemological position of policymakers and practitioners in Malawi regarding the importance of technology versus social factors in innovation, and 4) the resilience objectives.

We observed a disconnect between the adaptation goals desired by many Malawian communities and the ways in which communities actually responded to water stress. This disconnect led to lack of sufficient water, reduced autonomy and low community capacity for innovation. Such understanding is crucial for reframing the disconnect between desired adaptation outcomes and goals and innovation practices in a way that empowers local communities, achieves the SDG's, and creates resilient socio-ecological regimes. We also learned that outside NGOs are responsible for building many of the water systems in Malawi and that many NGOs fail to cooperate with local communities or the government water board to ensure quality, quantity and the alignment of systems to local needs and goals. This reflects a much larger conflict of interest of access-based incentives that the NGOs have for project completion versus long-term design, maintenance and innovation relationship. Finally, we found that radical innovation can start at either the grassroots level or in partnership between locals and NGOs, and that innovations can be radical even if the degree of novelty and uniqueness is lower, as long as adoption and societal impact is high. It should also be noted that although transformative and radical innovation can happen at the grassroots level, it is more likely emergent and random rather than planned.

The “who” of innovation is important. Local and grassroots efforts can lead to transformation, but resources are not always available. For transformations or adaptations which inherently require resources, partnerships with outside entities is necessary, but not at the sacrifice of local voice. A nested approach is needed. New policy should be written in such a way as to shed light on the many facets of innovation and provide a frame of reference to define both the intended innovation outcomes and localized implementation options. Policymakers should supplement local practitioners and decisionmakers in the field with resources for distinguishing, discussing and promoting specific types of innovation.

Although challenging, planners must decide what the goal of innovation, adaptation and transformation is to accomplish and the reason for increasing resilience. For example, if it is important that water provision (the amount of work that fulfills the needs of a specific population) is to be provided, then to accomplish this, communities need to know what water provision means,

what works realistically, and at what scale. Water provision is considered by some to be subjective based on the individual and to others objective and scientifically ascertainable. Consideration must be given to questions such as, “Innovation, adaptation and transformation for increasing the resilience of what? Are values shared across communities? What does community mean in the context of Malawi? What are the implications of villages in rural locations versus neighborhoods in urban locations?” The heterogeneity that we find across scales is very important as actions at one scale may translate to other scales. The questions provided in this article help a person to answer “innovation for whom, where, and to what end?”

Future research should include studies which further our understanding of the way in which localized innovation knowledge and norms affect innovation selection. In addition, scholars should also look at mechanisms which can be used to effectively source local knowledge from local stakeholders. Awareness of local knowledge, practices and norms are critical to the success of innovation decision-making processes. Community-based and participatory methods have been found to be effective in obtaining such information, but few of these have been widely successful in Africa (Kshetri, 2016). In order to build sustainable, participatory, and equitable water systems, further research is needed to understand how communities at various scales envision their future and implement both technical and social change (Miller et al., 2014). More research on successful cases and best practices are is needed to enable appropriate innovation development toward the SDGs and most importantly help build adaptable and resilient communities capable of meeting the water sector challenges brought on by climate changes and other stressors.

4. EFFECT OF REWARD, PRIVACY, AND REPUTATION ON EVOLUTION OF BEHAVIORAL NORMS IN COMMUNITY-LEVEL PARTICIPATORY SENSING

4.1 Introduction

Addressing large-scale environmental challenges, such as climate change, requires collective action (Ostrom, 2010; Rockstrom et al., 2009; Dickinson, 2013; Holderness and Turpin, 2015). Participatory sensing is one such collective action activity in which a large number of individuals, acting as human sensors, actively collect and report data (Silva, 2016). Since this sensing data is free to the public and can be used by anyone for individual benefit (Khan, 2013), the sensing data collected can be considered public good.

Participatory sensing has the potential to improve our understanding of climate change in places such as Africa, where data is most needed (Chan et al., 2014). Africa is likely to be the continent most vulnerable to climate change, increased water stress and increased exposure to disease and other health risks (Parry et al., 2007). Although participatory sensing has been tried in African countries like Malawi, more research is needed to understand the lack of success due, in part, to low participation (Animal Demography Unit 201; Essoungou, 2010; FEWS NET, 2011; Meier, 2011; Sylla, 2003). Participation rates affect the quality and quantity of the public good. Low participation can occur at the beginning or launch of a participator sensing application. Low cooperation may be caused by "cold start" at the beginning or launch of a participatory sensing application. "Cold start" refers to the initial stage in participatory sensing during which service adoption remains sparse and, hence, the collected data does not offer adequate coverage." (Saremi and Abdelzaher, 2016). Alternatively, participation can be very high at the beginning, especially if many initial participants have been recruited. However, participation can trail off if motivation decreases or if the quality of the data becomes unattractive, such as when many cheaters contribute false data, or if motivation crowding occurs. The cold start problem can also be caused by detracting factors such as cost of sensing activities. Solving these types of participation challenges is critical to addressing the grand challenges facing our world (UN, 2015).

Human sensors incur some cost when they sense (Hsu, 2014; Kollock, 1998; Ganti, 2011), and since each individual receives benefit, regardless of participation in the sensing, the individual faces a choice to receive benefit without sensing ("free-riding") or to participate, referred to as

"cooperation" (Traulsen and Nowak, 2006; Nowak, 2012). This choice of free-riding versus cooperation can be framed as a public good dilemma (Kollock, 1998). Some people participate due to pure altruism, while others are motivated by social imaging through recognition by peers (Ariely et al., 2009), reciprocity (Nowak, 2012), or impure altruism such as the “warm glow” feeling of doing good things (Frey, 1999; Meier, 2007; Silvia, 2016).

In some situations, influencing participation requires extrinsic motivation, such as monetary rewards. Some scholars have found that that such monetary rewards can cause people who are altruistic to become selfish and work only for rewards, causing the "crowding out" of altruistic behavior (Ogie, 2016). Prior research suggests that individuals do not use cost–benefit mindsets for social decisions, but do so once a monetary incentive is integrated into the decision (Ariely, 2004). Marketing research suggests that a “calculative” mindset will lead to more selfish and less socially oriented decision-making (Wang et al, 2014). Therefore, any shift toward a cost–benefit mindset would have led to further decreases in the weight placed on intrinsic motives, thus increasing the possibility of crowding out. However, crowding out is not complete because some intrinsic motivation may remain. In fact, one study found that “higher donations may correspond to higher intrinsic motives such as altruism” (DellaVigna et al, 2012; Chao, 2017). In this, scholars disagree regarding the direction of the effect of reward on altruism, with some believing that rewards increase altruism and others finding it diminishes altruism. Specifically, several studies have shown that the use of monetary incentives may encourage crowding out by destroying pre-existing intrinsic motivations (Ogie, 2016; Wang et al., 2015). “Participants are more likely to deceive or cheat the system to increase financial gain (Guo et al., 2015, 1:22).” Sometimes the amount of the reward attached to a crowdsensing task cannot sufficiently motivate some participants, particularly if they are driven by intrinsic motivations and not necessarily financial gains. An alternative scenario can exist in which individuals are given monetary incentives for some time and become accustomed to those incentives only to have them removed. Upon removal of monetary incentives, a reverse crowding out effect can occur in which extrinsically motivated individuals are no longer motivated and cease to participate (Ogie, 2016).

Some scholars have found that such motivation crowding can be minimized by hybrid incentive mechanisms that combine both monetary and non-monetary reward models. (Jaimes et al., 2014). Combining more than one incentive mechanism simultaneously may achieve better results (Kershaw et al., 2014; Kostakos et al., 2017; Reddy et al, 2010; Silva et al., 2016) and could

lead to large-scale participation (D'Hondt et al., 2013). However, "The majority of the proposals to encourage cooperation in participatory sensing focuses on only one strategy (Silva et al, 2016) with very few studying the dynamic relationship between intrinsic and extrinsic motivations over time (Kostakos et al., 2017). It is unclear how reward level or other factors, such as reputation and privacy, influence long-term motivation crowding.

Appropriating intrinsic and extrinsic motivation typically takes the human sensor's reputation into consideration. Reputation can be tracked and leveraged to sanction cheating by using reputation-based rewards. Assigning and maintaining reputation scores for agents requires some level of decreased privacy. Although low privacy leads to lower cheating, it discourages participation due to risk of personal information exposure (Krontiris and Maisonneuve, 2007; Krontiris and Freiling, 2010). In a high privacy situation, the potential to assign reputation is low, allowing cheating to go unchecked and preventing motivation from affecting positive reputation. Although existing studies mention human behavior, many have emphasized the technical aspects of managing anonymity, reputation and rewards (Frohlich and Oppenheimer, 1998; Krontiris and Maisonneuve, 2007; Krontiris and Freiling, 2010; Silva, 2016) and of optimizing payment mechanisms such as the use of auction-based pricing (Xie et al., 2009; Lee and Hoh, 2010; Yang et al., 2012). Few studies exist on the long-term dynamics or evolution of human behavioral norms toward participatory sensing. There is a need for more evolutionary studies of behavioral dynamics (Gao et al., 2015). Finding and deciding a reward value that "minimizes costs of program and, at the same time, motivates users requires further investigation" (Gao et al, 2015; Silva et al, 2016, p. 40)."

For situations in which incentives transition from monetary to intrinsic or vis versa, under what conditions of reputation, privacy and reward will the crowding out effect occur? We can identify more effective strategies for motivating participation in large-scale sensing by exploring how such conditions combine to shape outcomes and which combination of extrinsic, intrinsic and social imaging lead to cooperation. The specific research questions are: 1) "Under what conditions of extrinsic, intrinsic and social image motivations is cooperation sustained over time?", 2) "Does privacy affect evolution of behavior strategies, and if so, in what ways?", and 3) "What combination of extrinsic, intrinsic, and social image leads to motivation crowding?" The current study tackles these questions by modeling a participatory sensing scenario inspired by qualitative research data from Malawi. By analyzing the effects of motivation and privacy on cooperation,

our model represents a dynamic population of agents interacting indirectly and reporting data about physical phenomenon in their environment. This research seeks to: a) understand the relationship between motivation strategy and behavioral dynamics, b) identify thresholds for reward that lead to adequate participation while maintaining quality of data, and c) investigate the role of privacy and reputation for sustaining quality and participation.

The model described in this research is based on a wealth of empirical studies (Rode et al., 2015) and modeling experiments (Levy et al, 2018; Chattoe-Brown, 2012; Kirakozian and Charlier, 2016; Silvia and Krause, 2016) of the relationship of monetary reward and extrinsic motivation, privacy and cooperation, and reputation and intrinsic motivation. In this model, which is designed to study how human sensors behave under certain conditions of reward, privacy, and reputation tracking, agents are given a starting behavioral strategy and then adopt subsequent behavioral strategies through evolutionary replication dynamics. This research builds on the many previous modeling and laboratory experiments which study motivation and incentives by adding emergent and unexpected evolutionary phenomenon which is particularly useful in studying large scale sensing scenarios. According to Ogie (2016) the area of research studying how to predict quality of data from agents in high privacy environments is "still grossly under-investigated and only a few studies exist." In essence, our approach reflects the challenge raised by Ogie (2016), D'Hondt (2013), Silva (2016) and Kostakos (2017) to study hybrid incentive structures in participatory sensing. Our modeling approach addresses calls by Guo (2015) for long-term evolutionary studies to complement other studies.

We examined the evolution of behavioral strategies in response to reward level, privacy level and reputation tracking in terms of the following conditions: number of false data reported, the quality of publicly available data (considered a public good) and the proportion of cooperators in the population. The proportion of cooperators in our model varied over time in response to the conditions studied and cooperation was found to be a path dependent under certain circumstances. This paper adds to previous studies on participatory sensing by considering the evolutionary dynamics of a social system in which heterogeneous agents report on the condition of physical phenomenon and in which agents replicate social behaviors based on the payoff of neighbors.

This paper first provides a theoretical background on motivation in the context of participatory sensing, then explains why our model likely offers clues to understanding the role of reward, reputation and privacy on the effectiveness of incentive structures. In Section 2, we provided a

brief overview of the design of the model, the indicators used to measure outcomes and the analysis of the model. Our findings suggest that certain thresholds exist for reward, below and above which little additional value is achieved and cooperation is not changed, that initial reputation value assigned to agents has a large effect on the evolution of strategies, and that privacy causes certain incentive thresholds to shift and become more prominent. We hypothesize that a hybrid incentive approach is best achieved with low initial reward to compensate for the cost incurred while sensing, but prevent crowding out of altruism, medium privacy levels and reputation tracking to encourage social image motivation.

4.2 Background

Three broad categories of pro-social motivation have been identified: intrinsic, extrinsic and social Image Motivations (Ariely et al., 2009). Intrinsic motivations are based on a personal preference for contributing to the social good. They can be driven by an altruistic concern for others, by the "warm glow" that engaging in pro-social behavior provides the doer, or by a need to support a positive self-identity" (Frey, 1999; Meier, 2007; Fischbacher, Gächter, and Fehr, 2001; Batson & Powell, 2003; Andreoni, 1990; Levy et al, 2018). Altruism can be viewed as benefiting others at a cost to oneself (Tooby & Cosmides, 1996; Batson, 1998; Sober & Wilson, 1998). Extrinsic incentives are material rewards or benefits received for engaging in pro-social behavior; can come in a variety of forms, including tax credits, rebates, and additional conveniences" (Silivia and Krause, 2016). Social Imaging or image scoring is when engaging in pro-social or altruistic behavior helps create that individual's positive social image (Ariely et al., 2009; Chattoe-Brown, 2012). One's concern for how others perceive them, or social approval, leads to a conscious effort to display traits considered "good" by their reference group. Some authors find that different incentives (i.e. altruism or reward) do not have an effect on one another (Fiorillo, 2011), but others find that different motivation categories are separate but do interact with one another (Silvia and Krause, 2016). For example, intrinsic and extrinsic motivations can interact either positively or negatively (Carpenter and Myers, 2007). Narloch et al. (2012) found that the positive or negative effect varies depending on if the rewards are administered at the individual or group level (Narloch et al. 2012).

4.2.1 Cooperation based on rewards and reputation

The information collected through community-level participatory sensing often exhibits the characteristics of a "threshold public good", especially in scenarios where the value of the data produced increases with the number of quality sensing participants, such as mapping changing flood waters. (Ogie, 2016; Ogie, 2018). Scholars point out that "getting people to participate and contribute" to the sensing task is one of the most important challenges of participatory sensing (Guo et al, 2015). Silva argues that understanding social and behavioral factors that impact community-level participation in the production of public goods is crucial for improving sustainability of environmental innovations (Silva, 2016). Solving the participation challenge involves finding ways to overcome self-interest by encouraging many people to participate and contribute though intrinsic or extrinsic motivation (Hsu, 2014; Kollock, 1998; Silva, 2016). More research is required to better understand what factors affect human behavioral norms (contribution, freeriding, cheating, etc.) and how human behavioral norms change over time under the influence of these factors (Kollock, 1998; Nowak, 2012; Silva, 2016). Our focus is on the evolution of behavioral norms over time in the context of community-level participatory sensing for the production of public good.

Cooperation in collective action activities for the production of public goods can be influenced by several factors: 1) financial reward for extrinsic motivation; 2) reputation; 3) privacy; 4) intrinsic motivation; and 5) the nature of the public good (linear public good vs. threshold public good) (Ganti, 2011; Hsu, 2014; Silva, 2016; Kollock, 1998; Nowak, 2012). Although some have found intrinsic and altruistic motivations lasting and sustainable motivators for participatory sensing (Holderness and Turpin, 2015; Pouryazdan et al., 2016), some scholars disagree about the impact of intrinsic motivations on accuracy and productivity. Also, some scholars believe that simple altruism is not enough (Sheng et al., 2013) and that some people require compensation such as monetary payment (Pouryazdan et al., 2017; Sheng et al., 2013) that is not "trivially small" (Kollock, 1998) but in proportion to the task at hand (Ganti et al., 2011; Silva et al., 2015; Silva, 2016). Such payments may clash with intrinsic motivations (Kostakos et al., 2017)) and have been linked to decreased voluntary participation as a form of "crowding out" volunteerism (Deci, 1975. Payment also creates an opportunity for some people to act selfishly and "game" or cheat the system by entering false data resulting in lower quality data (Cardone et al., 2013; Silva, 2016). It is not clear if rewards even lead to better results (Kostakos et al., 2017).

This said, there is still disagreement about whether or not payment affects quality at all (Ogie, 2016). More research is required to understand the right balance between giving financial reward to induce participation and reducing financial reward to prevent erroneous data entered by cheaters (Cardone et al., 2014; Dickinson et al., 2010; Guo et al., 2014; Talasila et al., 2016, p.78).

4.2.2 Tracking of behavior and privacy

Tracking of past behavior in the form of public reputation can increase cooperation ((Dickinson, 2013; Chaudhuri and Paichayontvijit, 2006; de Oleveira et al., 2009; Page et al., 2005; Croson et al., 2006). Reputation reflects the previous good or bad behavior of a participant, creating a sense of efficacy and self-realization that can lead to higher cooperation and quality of participation (Kollock, 1998). In a digital environment and private environment, is is less likely that direct interactions will take place among individuals. The phrase "I'll scratch your back if you scratch mine" would not apply because, due to privacy, one cannot identify others (Nowak and Sigmund, 2005). However, if some form of behavior tracking is available as a the form of reputation scoring, then that reputation allows one to see anothers past good or bad behavior. This reputation can enable a greater likelihood of "third party altruism" or "indirect reciprocity" in which I help others and a third individuals sees that behavior and helps me (Kollock, 1998; Krontiris and Maisonneuve, 2007; Nowak, 2012). Belief about the nature of humans and motivation informs views on starting values for reputation. For example, if one believes that people are inherently good then the starting value for an agent's reputation might be high. If one believes that people are inherently bad or selfish, then the reputation score might initially be set low. Different starting values could have an effect on replication and agent's payoff.

Tracking reputation requires a lower privacy level, but the level of privacy can have an adverse effect on participation if tracking behavior violates a user's sense of privacy (Guo et al., 2016; Xu et al., 2009). Several studies have found that anonymity lowers the rate of participation (Fox & Guyer, 1978; Jerdee & Rosen, 1974; Kahan, 1973). One example of a privacy dilemma is with location privacy in which data collection using mobile devices involves sharing GPS data which can be used to infer personal activities, political views, health status, and launch unsolicited advertising, physical attacks or harassment including the user's identity (Krontiris and Maisonneuve, 2007).

4.2.3 Image score as reputation

Because participatory sensing occurs in digital environments using personal mobile devices, and participants want to minimize privacy risk, participant identities often remain anonymous. When anonymous, direct interactions between participants is unlikely or impossible based on system design: Indirect reciprocity in place of direct reciprocity. Participants are given a score within the application which "reflects an individual's reputation and status, which is constantly assessed and reassessed by others and which may be taken into account in future social interactions (Wedekind and Milinski, 2000, p.851)." Such image scoring can lead to indirect reciprocity when direct reciprocity is not likely (Wedekind and Milinski, 2000). In fact, public good contributions are increased when contributions are publicized and contributers given more status and prestige than other group members (Hardy & Van Vugt, 2005). Computer simulations also show that if reputational information is available, altruism becomes an evolutionary stable strategy (Van Vugt et al., 2007). Therefore, image score can be leveraged to scale up cooperative behavior and may play a key role in the evolution of cooperation in larger groups (Wedekind and Milinski, 2000).

Image score calculation

When calculating image score, researchers have used various score ranges and strategies. A prominent image score calculation method is that proposed by Nowak and Sigmund (1998). The authors use an image score range from −5 to +5, although many real life applications, such as the traffic mapping app Waze, use stars, points, or other scoring systems based on alternative ranges such as 0-5 (Waze, 2019) and 1-5 (Uber, 2019). Applications on Ushahidi, a data collection software, use a hybrid approach. There are other types of reputation strategies, such as the "good standing-strategy" (Sugden, 1986) which take into account the partner's previous behavior. The good-standing method has been shown to be superior to image scoring (Leimar & Hammerstein, 2001). There are other kinds of reputation systems that could give an edge to altruists, but still await further investigation (Nowak & Sigmund, 2005; Panchanathan & Boyd, 2004). The range of image score values and method of calculation can affect perception of reputation and cause misleading perceptions, such as negative and positive ratings averaging as a positive value.

The value of image score is important because it affects how agents interact with one another and image score can affect reward. In Nyborg et al., (2006), the social dimension is introduced

based on a reward associated with self-image which considers the external benefits of the individual decision. Referring to the social norm introduces the social benefit of the individual decision in the utility function. This necessarily enhances the incentive to contribute to the public good (Kirakozian and Charlier, 2016).

While many scholars base scoring models on the work of (Nowak and Sigmund, 1998) and calculate the image score in a linear way (adding 1 to the image score value for cooperative behavior and subtracting 1 for cheating) other scholars have reported improved cooperation when calculating image scoring systems in a non-linear manner (Schlosser et al., 2004; (Tomasic et al, 2014). Methods for calculating image score in a non-linear way include Bayesian models (Schlosser et al., 2004; Ganeriwal, 2008), summation (Schlosser et al., 2004), average (Yang, 2011; eBay, 2019), and discrete trust (Jøsang, et al., 2007); SlashDot, 2019).

A number of frameworks or systems are available to score reputation. Bayesian frameworks or systems (Schlosser et al., 2004; Ganeriwal et al., 2008) are one of the more complex forms of reputation management. Bayesian systems use probability distributions to arrive at a participant reputation score. Such systems can further be adjusted by added features such as aging out older ratings by using a weight factor when updating reputation (Ganeriwal et al., 2008). Summation-based calculation ratings systems are aggregated by summing to create a single reputation score (Schlosser et al., 2004). One such system is that used by eBay in which the ratings of -1, 0, or 1 are added together (Ebay, 2019). Alternatively, an example of averaging is Amazon, which relies on an average star rating system that ranges from 1-5 (Amazon, 2019).

An alternative scheme to having reputations being a numerical value is to use discrete labels. An example might be the use of categorical tiers for participants that include terrible, bad, neutral, positive, good and excellent. This method, like summation and average, is easy to understand. Discrete labels are not mathematical in nature and therefore it is difficult to determine reputation confidence (Jøsang et al., 2007).

Other practical considerations when calculating reputation scores are the treatment of cheating behavior. While averaging and summation models are common because they are easy to understand, they are primitive in nature and can cover up negative ratings if many positive ratings exist in proportion (Jøsang et al, 2007). One way to deal with this is to penalize or remove users from the sensing application. For example, within Waze, there is a graduated process by which Waze penalizes those users who are caught cheating. Administrators have the ability to eliminate

those Users who frequently cheat (Road and Track, 2019). This is effective at ensuring that participation remains high and cheating participants are gradually removed from the system to improve data quality.

4.2.4 Motivational crowding

One is said to be “intrinsically motivated to perform an activity when one receives no apparent reward except the activity itself (Deci, 1971, p.106).” When money is used as an external reward, there can be an undermining of social values (Titmuss, 1970) and decrease in intrinsic motivation (Deci 1971), whereas verbal reinforcement and positive feedback increases intrinsic motivation (Deci, Koestner, and Ryan 1999; Deci and Ryan 1985; Houston 2006; Ryan and Deci 2000; Georgellis et al., 2010). The term "crowding out" was coined by Bruno Frey (Frey, 1997, p.746) to describe the observation that “providing extrinsic incentives for certain kinds of behavior can sometimes undermine intrinsic motivation for doing that behavior.” Lowered motivation can lead to a decrease in desired social behaviors. Therefore, previous motivation, such as that through altruism, can be crowded-out by monetary reward. The concept of motivational crowding was expanded by others in psychological and economic exploration supporting the basic phenomenon of crowding out (Andreoni 2017; Frey, 1997; Titmuss 1970; Mellstrom, 2008). Frey found that intrinsic motivation is potentially affected by all kinds of intervention coming from outside the person considered and that intrinsic motivation may be reduced or raised. Opposite of crowding-out, is “crowding-in” when intrinsic motivation is increased as a result of increased extrinsic incentives especially where pro-social norms exist (Vollan, 2008). Thus, there may not only be hidden 'costs' but also hidden 'gains' (Frey, 2012; Frey and Jegen, 2001). This is especially true for tasks which “unobservable and unverifiable (such as anonymous participatory sensing) and high extrinsic rewards are likely to result in lower intrinsic motivation” (Georgellis et al, 2010, p.477). However, evidence also shows that “extrinsic rewards do not necessarily reduce intrinsic motivation, since the effect of rewards is determined by the nature of the task being performed and other determinants of behavior such as self-efficacy and the nature of the motives themselves” (Bandura 1977; Bartol and Locke 2000; Frese and Fay 2001; Locke and Henne 1986; Locke and Latham 1990; Thierry 1990). Fiorillo (2011, p.160) asserts that “monetary rewards increase the amount of time that Italian individuals dedicate to volunteering and that these incentives do not affect intrinsic motivation.” In examining volunteers, Carpenter and Myers (2007) present data

revealing that monetary incentives have a positive relationship with the time donated by volunteer firefighters in Vermont. Narloch et al., (2012) arrives at more nuanced conclusions. This paper conducts experiments with Bolivian and Peruvian farmers in which the subjects choose how much land to allocate to conservation. The study finds that collective rewards for conservation behavior is associated with an increase in free riding, while individual rewards are associated with cooperation and conservation. The authors hypothesize that by increasing individual payoff and one decreases the incentive to freeride (Rodriguez-Sickert et al., 2008). They also hypothesize that "introducing collective reward systems might raise expectations among individual farmers that others in their community will bear the burden of conservation and thus the provision of the local public benefits would occur without their share of conservation effort, thereby weakening pro-social behavior" (Narloch, Pascual, and Drucker, 2012, p. 2104).

Image-Motivation

In addition to extrinsic and intrinsic, social image and reputation also influence motivation (Ariely, 2009; Georgellis et al., 2010). Individuals derive positive utility from both intrinsic (prosocial) and extrinsic job aspects, as well as from their reputation for being prosocial (Georgellis et al, 2010). Carpenter and Myers (2007) find that altruism and reputational concerns are positively related to individuals' volunteerism. "In fact, the positive effect of monetary incentives on volunteering may decline with reputational concerns (Carpenter and Myers, 2007, p.20)." Reward procedures requiring specific task performance that signal personal or social significance result in increased intrinsic motivation (Eisenburger, Pierce, and Cameron, 1999; Wiersma 1992). Because of the digital nature of many participatory sensing applications, social imaging is accomplished through image scoring. Ariely (2009) found that increasing visibility increases the level of prosocial activity and that visibility may influence the effectiveness of material rewards. The image score within an application represents the participants reputation. Ariely (2009) found that introducing or increasing extrinsic incentives affects prosocial behavior in two ways: by increasing the extrinsic rewards, and through image motivation. Image motivation refers to "an individual's tendency to be motivated partly by others' perceptions. Image motivation therefore captures the rule of opinion in utility, i.e., the desire to be liked and respected by others and by one's self (Ariely, Bracha, and Meier, 2009, p. 1). "On the one hand, the relative price effect will increase prosocial activity. On the other hand, higher personal benefits associated with

a prosocial activity tends to decrease its image value. The intuition is that if an individual receives greater extrinsic rewards for the activity, s/he is suspected to be acting in prosocial ways for the extrinsic rewards rather than out of intrinsic motivation (Ariely, 2009, p.546).” In other words, “people want to be seen by others as doing good. But with extrinsic incentives, the signal of a prosocial act gets diluted, as one might behave in prosocial ways mainly to do well for oneself. If no one is watching (i.e., private contribution), the incentive to also do well for oneself cannot dilute any signal to others, and consequently extrinsic incentives are very likely to increase prosocial behavior. (Ariely, 2009, p.554)”

Sustainable cooperation in participatory sensing has been challenging due to low motivation for some undesirable tasks, mismatched incentives resulting in low extrinsic motivation, and cold-start issues including the difficulty of implementing image-based solutions for indirect reciprocity. Scholars disagree about the ability of intrinsic motivations to produce sustained cooperation (Holderness and Turpin, 2015; Pouryazdan et al, 2016; Pouryazdan et al., 2017; Sheng et al., 2013). Rewards are required in some circumstances, but there is no framework for selecting an appropriate reward (Ganti et al., 2011; Kollock, 1998; Silva et al., 2015; Silva, 2016) given other factors like intrinsic motivation (Pouryazdan et al., 2017; Sheng et al., 2013). In digital applications, social imaging is used to facilitate indirect reciprocity (Nowak and Sigmund, 1998), but image scores can suffer from “cold-start” problem at low participation rates (Franks and Griffiths, 2015), and contribute to the cold start problem by discouraging participation or encouraging poor behavior (Nowak and Sigmund, 1998). These interdependent motivation challenges are roadblocks to successful participatory sensing applications and require exploration.

4.3 The Behavioral Models

4.3.1 Model description

Participatory sensing data for public good can be considered as analytically equivalent to N-player public good games, in which the group size is a known barrier for reciprocal cooperation due to anonymity and lack of responsibility, which negatively affect cooperation.” (Boyd and Richerson, 1988, Olson, 2009). The purpose of our model is to investigate, in an evolutionary setting, a series of questions pertaining to cooperation for the production of public goods. Inspired by the participatory sensing models of other scholars and calls to explore evolutionary dynamics, this

model explores the evolutionary dynamics within participatory sensing (e.g. Levy et al., 2010; Levy et al., 2018; Silvia and Krause, 2016). To investigate the impact of motivation strategies on participation and data quality, we use an agent-based modeling (ABM) approach. ABM is a suitable tool to study complex systems—systems characterized by many interacting entities and non-linear interactions among them (Wilensky 1999).

Simulation offers an opportunity to study evolutionary processes. Although mathematical models exist, these "typically require unreasonably strong simplifying assumptions for solubility. Here, an evolutionary process based on reasonable assumptions can be observed directly." Chattoe-Brown, 2012, p.348). ABM has been "used extensively to simulate complex behavior in attempts to predict the effect of changes on agent or system (e.g., infrastructure) attributes, thereby revealing possible optimal solutions (Levy et al, 2018, p.49)." There are two fundamentally different ways of modeling in ABM, phenomenon-based modeling and exploratory modeling. When conducting phenomena-based modeling (Wilensky, 1995; 1996) you design strategies for individual parts of a system in an effort to achieve a particular goal for the overall system. With exploratory modeling, you start with rules for the individual parts of a system, and you observe the group-wide patterns that arise from the interactions (Wilensky, 2012). Our aim is to understand system behavior in a generalized way. We do not intend to replicate any single situation or locale in a realistic way for prediction. The outcomes of the simulations resemble reality in a qualitative manner; however, they do not provide a firm foundation for quantitative forecasts (Gilbert, 2008). Moreover, as with all empirical models, the "quality of ABM results is tied directly to their inputs, in this case parameter assumptions, environmental set-up and the information on which both are based" (Silvia and Krause, 2016, p.108). Using exploratory agent based modeling, I create a set of agents, define their individual behavior, and explore the patterns that emerge.

This research applies participatory sensing as a case for studying the production of a public good, in this case publicly available environmental data that is reporting by distributed agents. The model is used to explore (1) the effects of reward on participation and data quality, (2) the degree to which privacy can influence participation, and (3) the impact of initial reputation assignment on evolution of behavioral strategies. An appendix with the model code and model documentation using the ODD (overview, design concepts and details) protocol for describing individual- and agent-based models (Grimm et al., 2006; Grimm and Railsback 2005; Grimm et al., 2010) can be found at the end of this document. The model is implemented in NetLogo 5.0, which has been used

for modeling participatory sensing and prosocial behavior evolution (Levy et al., 2018; Chattoe-Brown, 2012; Kirakozian and Charlier, 2016; Silvia and Krause, 2016). (Wilensky 1999; http://ccl.northwestern.edu/netlogo/).

4.3.2 Parameters and consideration

The agent behavioral model is hypothesized based on commonly held theories of crowding out and warm-glow. Parameterization is informed by Malawi case (Table 8). It is important to be clear about the limitations of the model and what this model is not intended to show. ABM which represent artificial environments provide "simplified representations of context and are commonly used when the focus is on behavioral rules rather than the dynamics of a particular ecosystem (McLane et al., 2011, p.1548)." The model is inspired by real Malawian community structure (BWB, 2016) and informed by existing participatory sensing applications (Waze, 2019; Levy et al, 2018) (Silva et al, 2012) (Lee and Hoh, 2010), but is not an exact replication. Although the model is not a precise replication of the real world, it can be used to "illustrate the value of evolutionary simulation without building a detailed simulation of a real city" and understand system behavior in qualitative way (Chattoe-Brown, 2012, p.349).

The computation of this simulation comprises four components: environment initialization; agent initialization; agent behavior simulation; and evolutionary behavior replication. The model comprises a landscape consisting of cells and agents which do not interact directly, but rather interact indirectly in a similar way to that within a private digital environment. Agents discover other agent through random pairing to represent an anonymous but local participatory sensing application in which people might observe another person soley through their posted data associated with a pseudonym. We simulated a 151 × 151 cell environment, which was populated in every generation by sensing agents which represent a Malawian community. Assuming an average Malawian community size of ~1000 individuals in which each household consists of ~4.5 individuals, half of which have a cell phone (MDHS, 2017), we assume 100 agents representing households in a community (N = 100) (Levy et al., 2018; Nowak and Sigmund, 1998). No agents are added during simulation, but agents can be removed based on conditional logic associated with behavior types and cheating behavior, which resembles existing participatory sensing applications (Waze, 2019). Conditional logic for removal is addressed in the model description.

Within the model, there are three behavioral strategies: cooperation, freeriding, and cheating (Table 6). When agents hold a cooperative strategy, they participate by contributing correct data and enjoy the benefit of the public good. Those acting as a freerider do not contribute any data but still enjoy the benefit of the public good (i.e. free-riding). Those who are acting as cheaters participate by providing data, but that data is a guess and carries with it a 50% chance of being incorrect. If caught, they are removed from the system so that the sum of the three behavior types plus the agents removed equals 100, or 100%. Each behavioral strategy carries with it costs and benefits which are used to calculate a payoff (Table 7). The agents' primary behaviors are to 1) choose behavioral strategies based on (a) individual peers following a competition-based decision-making process (Figure 4-2) and 2) behave according to the chosen behavior strategy. At the start, the model starts with an initial random assignment of behavioral strategies to agents according to empirical distributions of 5% cheat, 20% cheat, 80% coop (Nowak and Sigmund, 1998; Kirakozian and Charlier, 2016). Instead of treating strategies as fixed for the lifetime of the agent, the agents "change their strategies within a lifetime by processes of learning that are themselves reasonable if not formally rational. (If someone is doing better than I am with a different strategy then I should probably change my strategy to the one they use.) (Chattoe-Brown, 2012). The model assumes that agents choose their strategies but implies that they do so 'rationally' (in other words as a best response to the strategies of other agents). (Gezelius, 2007: 204). According to Gezelius (2007), the model assumes that payoff of each agent is available when privacy is low, and that agents can see and compare payoff with others. The model parameters and parameter values reflect that found in experimental, empirical, and other models which can be seen in the parameter table (Table 4-3). Some values, such as reward amount, were calibrated to represent empirical data on real participatory sensing applications. We aimed for a neutral setting with behavioral breakdown of ~20% cooperation after 100 time steps (Adar and Huberman, 2000; Hughes, et al., 2005; Tomasic et al., 2014).

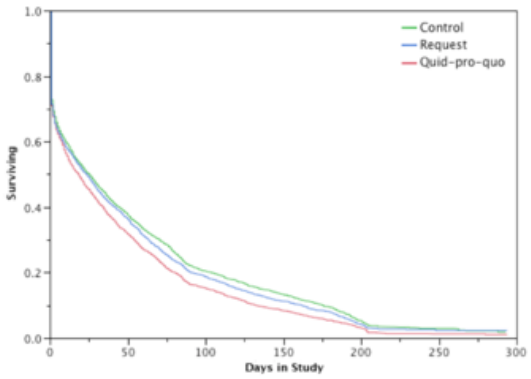

Figure 4-1: Average Participation At 100 Days Around 20%, assuming that 80% have left or been removed at time 100 (Tomasic et al., 2014)

A given agent's cheating behavior negatively impacts the likelihood of others to imitate that given agent's behavior. Based on existing participatory sensing applications, lying about data, or cheating, results in a lower image score. Lower image score can reduce the reward received and reduce total payoff. Lower payoff could make other agents less likely to replicate that agent's behavior. Repeated cheatings result in an agent being placed completely outside the group and eliminates the public good benefit received by that agent.

Agents may display (and will monitor) certain behaviors that the group regards as normatively unacceptable, such as lying about data. The punishment for getting caught is a lowered image score, lower economic rewards, eventually disconnected from the network connections (losing access to the public good), and social status diminished through the image score (Chattoe-Brown, 2012). However, not all agents are caught initially. It is not possible for all agent actions to be monitored in the real world, and the agents in the model have a chance of not being caught. A full list of motivation strategies can be found in Table 5.

Individual agent behavior

To study individual agent behavior simulation, we implemented a participatory sensing scenario in which each agent operates according to the agent's current behavioral strategy at each timestep. The set of behavioral strategies represent a mixed altruistic and selfish behavioral type (Levy et al., 2018). Specifically, the three types of behaviors are cooperation, cheating, and freeriding. Agent action process is illustrated in Figure 15. The figure describes the process that an agent cycles through at each timestep, comprised of an agent's basic action of social learning and immitation. The agent's given behavioral strategy prompts actions (e.g. cheating, cooperating,

or freeriding). Depending on the privacy level within the simulations, an agent's actions are used to calculate image score, and actions impact level of external rewards and social pressure. Rewards and costs are then calculated for each agent, resulting in a utility payoff (positive integer) for the given timestep (e.g. cooperation means the participant pays a cost and receives some benefit) (Nowak and Sigmund, 1998)(Table 7). This timestep payoff is added to the agent's total lifetime payoff. An agent is then randomly paired with another agent, for payoff results comparison.

Table 4-1 Motivation strategies

Motivation	Example	Possibly explanation
Extrinsic	Rewards, sanctions	Material rewards or benefits received for engaging in pro-social behavior; can come in a variety of forms, including tax credits, rebates, and additional conveniences" (Silivia and Krause, 2016)
Intrinsic	Altruism	"Intrinsic motivations are based on a personal preference for contributing to the social good. They can be driven by an altruistic concern for others, by the "warm glow" that engaging in pro-social behavior provides the doer, or by a need to support a positive self-identity" (Frey, 1999; Meier, 2007; Fischbacher, Gächter, and Fehr, 2001; (Batson & Powell, 2003; Andreoni, 1990; Levy et al, 2018). Can be viewed as benefiting others at a cost to oneself (Tooby & Cosmides, 1996; Batson, 1998; Sober & Wilson, 1998).
Social Imaging	Image scoring	Engaging in pro-social or altruistic behavior helps create that individual's positive social image. (Ariely et al., 2009; Chattoe-Brown, 2012). One's concern for how others perceive them, or social approval, leads to conscious effort to display traits considered "good" by their reference group.

Modeling is useful for exploring long-term dynamics of such behavioral strategies under a range of conditions (Matthews et al., 2007; Clifford, 2008; Polasky et al., 2011).

% Cooperator + % Free-rider + % Cheater = 100%

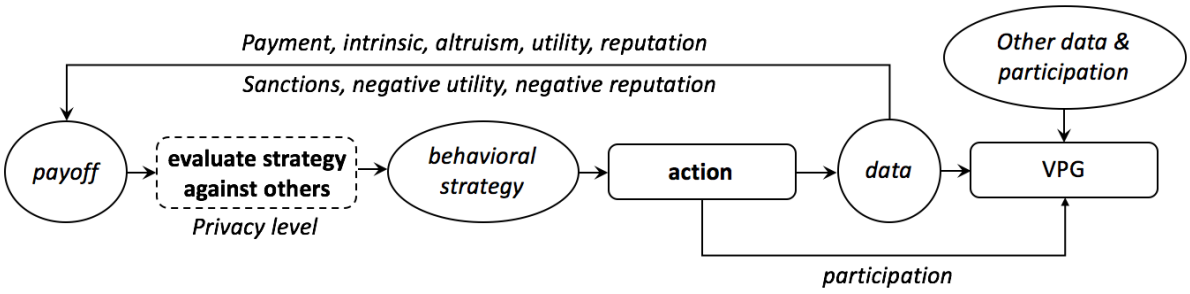

Figure 4-2 Agent behavior model. *Behavioral cycle which agents go through during each time interval.*

Model Overview

The behavioral model structure follows a cycle and according to the following: the model starts with a set of *N* agents whose objective is to seek a behavior strategy which yields the highest payoff. At time t_0 they are assigned a behavior strategy randomly, at time interval t_i, they earn payoff π_{xi}, and at time t_i, are presented with the payoff of one random other, *n* randomly and compare payoff. They maximize payoff by changing their behavior to the behavior strategy of the other agent with the other payoff is higher. This is repeat T times.

Table 4-2. Three behavior strategies

Strategy	Description	Benefit	Cost
Cooperator	- Participate/contribute and enjoy the benefit of public good	- From public good - From reward - Positive utility from reputation	- From contributing to public good - Negative utility from privacy concern
Free-rider	- Do no participate but still enjoy the benefit of public good (i.e., free-riding)	- From public good - No reward	- None from contributing to public good - Social pressure not participating
Cheater	- Participate but enter wrong data to get reward (i.e., cheating)	- From public good - From reward	- Some cost from contributing, but lower - Negative utility from privacy concern - Social pressure not participating

Based on empirical studies of social games, in each round two individuals are chosen at random (Nowak and Sigmund, 1998), and in the replication step, agents evaluate their payoff against another agent and if the payoff is less than the other agent, adopts the behavioral strategy of that agent.

Table 4-3 Utility functions for each behavior strategy

Payoff of behavioral strategy	Benefit from Public Good	Extrinsic reward	Intrinsic benefit	Cost of participation
COOPERATOR π_C =	VPG	$+ R(i(v))$	$+ \sigma(R,R_t)$	- c
CHEATER, π_X =	VPG	$+ R(i(v))$		$-(\delta * c)$
FREERIDER, π_O =	VPG			- X(i(v))
E =	*data about water well on cell phone*	*+ money earned*	*+ altruistic benefit*	*- cost of cell data*

VPG: Average benefit from public good per person
$R(i(v))$: Reward as function of image score (i) and privacy (v)
$\sigma(R,R_t)$: intrinsic benefit as function of reward (R) and reward threshold (R_t)
c: cost-from-contributing
$\delta * c$: cost from contributing to public good, where δ is less than 1.
$(i(v)X)$: reputation-adjusted reward

To capture the social expectations and beliefs about how their society values prosocial behavior, and the associated social pressure that cheaters feel, we add a social pressure mechanism in the utility equation inspired by Kirakozian and Charlier (2016). In our model, we represent the accumulation of reputation as an image score calculation. Computed reputation ratings may be a binary value (trusted or untrusted), a scaled integer (e.g. 1 to 10), or on a continuous scale (e.g. [0,1]) (Resnick et al, 2000). Based on Resnick et al, (2000) and other existing participatory sensing applications, we chose a scaled integer system from 1-5 because a binary value would likely be insufficient in a P2P environment where all peers are untrusted, but we want to rank peers based

on how reliable they are likely to be. Other studies have utilized a similar scale and assumed a neutral starting value (neither positive or negative (Nowak and Sigmund, 1998). In this model with a range of 1-5, a value of 3 is neutral, with 1 being worst and 5 being best image score. The model uses a common method of summation-based image scoring in which the image score is added to for positive behavior (cooperation) and reduced for negative behavior (cheating) (Nowak and Sigmund, 1998). The summation process is weighted and changes in a non-linear fashion, in which negative behavior results in a reduction of image score reduction of 1 and cooperation results in an image score addition of 0.1 (Tomasic et al., 2014). Each behavioral strategy is associated with a unique function, equation 1. We apply this approach and add a third calculation for freeriding which introduces a reduction in image score for inactivity. This represents a system administrator in Malawi penalizing freeriding and incentivizing participation. We assume that agents cannot see another agent's given strategy, but only see other agents' image scores. Visible and continuous image scoring is commonplace in mobile and web applications, allowing agents to associate trust with others in an indirect way. In our model, image score accumulates and continuous, meaning that image score is visible and accumulates even as agents change strategies. This means that if an agent first cheats, and then switches to cooperating behavior, their image score will be negatively affected even though they are behaving as cooperator currently. The agent must "earn" back higher image score. The calculation for image score is shown:

Image scoring: i(v) (1)

- Agents can see another agents' image score and strategy
- Image score in continuous, meaning that image score is visible and accumulates even as agents change strategies
- Image score is calculated using a weighted summation model (Reddy et al., 2010):
    - Image score Cooperator = previous image score + a, where a is positive but less than b;
    - Image score Cheater = previous image score – b; Image score
    - Freerider = previous image score
- This means that if an agent first cheats, and then switches to cooperating behavior, their image score will be negatively affected even though they are currently behaving as cooperator. The agent must "earn" back higher image score.

In pilot sensing applications in Malawi, participants receive rewards based on their behavior. In the model, image score acts as the measurement of behavior by which reward is calculated. To reflect the non-linear relationship between an agent's reputation and the rewards payed to that agent, we rely on the logarithmic function with base 5. The curve of the function, shown below in Figure 4-3, is representative of the non-linear attribution of award based on the agent's image score on a scale of 1-5. Therefore, the result x of the logarithmic function is 0 > x > 1, which is then multiplied by the reward to give an adjusted award value. The reward function is as follows:

$$\boldsymbol{R(i(v))}$$
$$\textbf{= reward * } \boldsymbol{log_5} \textbf{ (image score)}$$

Value of public good

The nominal total benefit from public good (VPG) is sum of people's total contributions:$P_N = F(\sum_1^N c)$, where c is contribution made by an individual. However, because cheaters enter wrong information, their contributions lower the quality of the public good. Only truthful participants' contributions increase VPG. So, the actual total benefit from public good is:

$$VPG = \frac{(F * Nx) + (C * Nc)}{N}$$

Further, because anyone can access and enjoy the benefit for public good, we assume that the total value of public good is equally distributed to people regardless of their contribution levels, i.e., each person receives the benefit of P/N.

Social pressure for not cooperating

$= p * ((i(v)X * (1 - v))$
$= p * (\frac{1}{image\ score}) * (\frac{number\ cooperators}{N}) * (1 - v)$

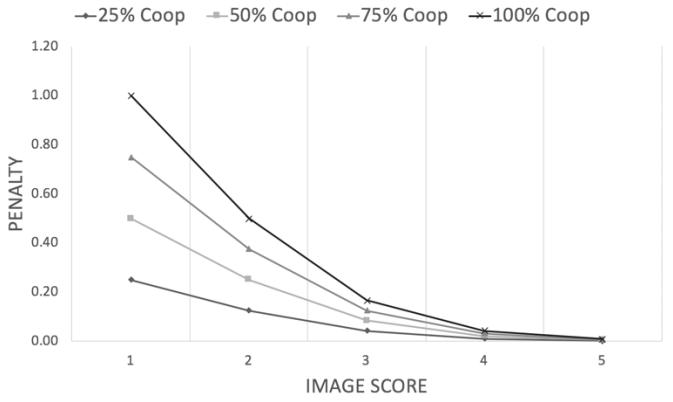

Figure 4-3 Pressure for not cooperating

If in a low privacy environment, agents are capable of viewing others' image scores and individual payoffs for comparing and selecting the highest payoff;

If high privacy, agents compare payoff to the average of all agent payoffs, provided by administrator:

- If privacy = 100%, then compare to some third party average payoff
- If payoff is lower than average, then agent randomly selects one of two alternative strategies
- If payoff is equal or greater, keep current strategy

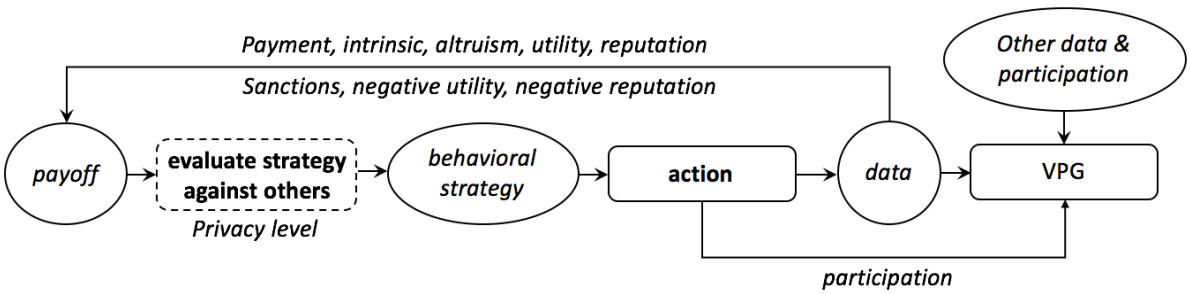

Figure 4-4. Agent behavior cycle

Table 4-4. Model parameters

Parameter	Meaning	Notation	Value or Range	Citations and Alternatives
privacy		**v**	**Binary: 0,1 Alternative: 1-7 scale in citation**	**Xie, En, Hock-Hai Teo, and Wen Wan. "Volunteering personal information on the internet: Effects of reputation, privacy notices, and rewards on online consumer behavior." Marketing letters 17.1 (2006): 61-74. Huang, Kuan Lun, Salil S. Kanhere, and Wen Hu. "A privacy-preserving reputation system for participatory sensing." *Local Computer Networks (LCN), 2012 IEEE 37th Conference on*. IEEE, 2012.**
reward		**r**	**Binary: 0,1 Value range: 0 - 100 (20 ideal)**	**Xie, En, Hock-Hai Teo, and Wen Wan. "Volunteering personal information on the internet: Effects of reputation, privacy notices, and rewards on online consumer behavior." Marketing letters 17.1 (2006): 61-74. Huang, Kuan Lun, Salil S. Kanhere, and Wen Hu. "A privacy-preserving reputation system for participatory sensing." *Local Computer Networks (LCN), 2012 IEEE 37th Conference on*. IEEE, 2012.**
altruism				**Bester, Helmut, and Werner Güth. "Is altruism evolutionarily stable?." Journal of Economic Behavior & Organization 34.2 (1998): 193-209. Boyd, Robert, et al., "The evolution of altruistic punishment." Proceedings of the National Academy of Sciences 100.6 (2003): 3531-3535.**
# runs				
Cost			**0-50; Cost of 1/3 of payment (Edmund chattoe-Brown)**	**Feng, Z.; Zhu, Y.; Zhang, Q.; Ni, L.M.; Vasilakos, A.V. TRAC: Truthful auction for location-aware collaborative sensing in mobile crowdsourcing. In Proceedings of the 2014 INFOCOM, Toronto, ON, Canada, 27 April–2 May 2014; pp. 1231–1239. Chattoe-Brown, Edmund. "Combining Ethnography and Game Theory Using Simulation: A Critique and Development of 'Can Norms Account for Strategic Interaction?' by S. Gezelius." Sociology 46.2 (2012): 339-353.**

4.3.3 Experimental design

Because it is difficult to know what the aggregate pattern with be, I explore the aggregate patterns that emerge from the interactions of cooperators, cheaters, and defectors under different experimental conditions. To answer the research questions, several analyses were conducted. To understand what conditions of extrinsic, intrinsic, and social image motivations can sustain cooperation, the independent variables which were manipulated were monetary reward (extrinsic), the level of warm-glow utility (intrinsic), and social image score. Next, to explore the affect, if any, of privacy on the evolution of behavior strategies, the independent variable which was manipulated was the level of privacy. Finally, to observe the effect of reward and image score on motivation crowding, the level of monetary reward (extrinsic) and social image score were varied.

The dependent variable measured for each analysis was the resulting percentage of different behavioral types in the population.

Experimental variables

Experimental variables which are manipulated in the experiment are reward, initial image score which is assigned to agents, and privacy level of the environment. Reward *(r)* is varied within the range of (0 - 50) and controls the payment components to the agent's motivation. Reward can be treated as continuous or discretized (e.g. 3 payment levels of 0, 20, and 50). Image score *(i)* is initial reputation assignment given to agents on a scale of 1-5. Privacy *(v)* is binary (0 or 1) and controls the privacy level. A privacy level of 0 represents a scenario in which agents can view other individual's characteristics including total payoff, behavioral strategy and image score. A privacy level of 1 represents a scenario in which agents cannot view other individual's characteristics but can see some averages within the application (e.g. average payoff of all users).

To understand the boundaries of effects, we investigated the entire parameter space of the model ranging from r = 0 to r = 100 and witnessed cooperation leveled out and found no statistical difference above r = 50 (Levy et al, 2018). A list of the parameter space for each experiment in the results section.

Response variables

Response variables measured in the experiments include percent of cooperators remaining at time t, total value of public good at time t, and crowding coefficient. Total crowding coefficients are calculated as follows:

$$\text{Crowding effect} = \Delta\, C/X,$$

$where\Delta$ C is (cooperative due to Y) – (baseline cooperative) and X is the baseline cooperative. Where cooperation is the measure cooperation at r1 and baseline is based on a baseline cooperation of 20% cooperation at t = 100 (Tomasic et al., 2014)

A coefficient measuring the rate of crowding per change in units of experimental variable is calculated as follows:

$$\text{Crowding effect} = \Delta\, C/\Delta\, X,$$

$where\Delta$ C is (cooperative due to Y) – (baseline cooperative) and Δ X is the change in experimental variable X. Where cooperation is the measure cooperation at r1 and baseline is based on a baseline cooperation of 20% cooperation at t = 100 (Tomasic et al., 2014; Khoi, et al., 2018).

Cost-benefit and Altruistic Scenarios

Prior research suggests that individuals do not use cost–benefit mindsets for social decisions but do so once a monetary incentive is mixed into the decision (Ariely, 2004). Similar marketing research suggests that a "calculative" mindset will lead to more selfish and less socially oriented decision-making (Wang et al, 2014). Therefore, any shift toward a cost–benefit mindset would have led to further decreases in the weight placed on intrinsic motives, thus increasing the possibility of crowding out. Similar research in marketing suggests that a "calculative" mindset will lead to more selfish and less socially oriented decision-making (Wang et al., 2014). Therefore, any shift toward a cost–benefit mindset would have led to further decreases in the weight placed on intrinsic motives, thus increasing the possibility of crowding out. Due to this phenomenon, each of the analyses were conducted across three scenarios of intrinsic motivation which reflect real world situations. The first scenario is "no altruism" (cost-benefit regime), which represents a scenario in which a task is undesirable or not associated with "warm glow" (Noor and Ren, 2011; Tompkins and Eakin, 2012). An example of such a task might be collecting sewage samples, or data which carries some risk like reporting domestic disputes. The second scenario is "altruism" (altruistic regime), which represents tasks associated with altruism or "warm glow" (Andreoni, 1998). The third scenario is threshold altruism (hybrid) in which the task is associated with altruism, but motivation crowding can reduce or eliminate altruism (e.g. reward crowds out altruism, or reputation concerns) (Ariely, 2004; Andreoni, 2017).

Relationship of Strategy, Scenarios, and Payoff

Agents have one of three behavioral strategies at any given point (Table 4-2), and switch strategies over time by adopting others' strategies if they observe a higher payoff. The three types of behavioral strategies which agents may have each carry a unique payoff equation (Table 4-3) by which they calculate payoff and then compare payoffs to others. Some parameters in the equation are fixed based on the behavioral strategy, while other parameter values like altruism change based on assumptions which are unique to the sensing scenario (see caption for Table 4-3). The altruism

parameter $\sigma(R,R_t)$ is impacted by the level of reward and the threshold of reward at which agents switch from intrinsic (altruism) to extrinsic (reward) motivation:

$\sigma(R,R_t)$: intrinsic benefit as function of reward (R) and reward threshold (R_t)

Therefore, the behavioral strategy of the agent, the payoff equation for that strategy, and the scenario being modeled are inextricably linked to produce a payoff value for each agent. To give an example of this relationship of strategy, payoff equation, and scenario, consider a real-life situation in which a sensing task is particularly unattractive. Such a situation is modeled as cost-benefit decision-making since the task does not also carry an intrinsic motivation. Reward level and reward threshold do not come into play and regardless, there is no baseline altruism value derived from the task. For example, an agent with cooperative behavioral strategy has a payoff with an altruism value σ of zero (0):

$$Cooperator\ payoff: \pi c = VPG + R\big(i(v)\big) + 0 - c$$

Payoff therefore is directly related to the reward amount, and altruism does not play a role. Agents with cheater and free-rider strategies do not factor altruism into payoff and therefore their payoff equations remain the same.

Now consider a scenario in which the task is highly desirable and perceived as good in a community. A person who is cooperating has an altruism value σ of greater than zero (> 0) and a payoff as follows:

$$Cooperator\ payoff: \pi c = VPG + R\big(i(v)\big) + (\sigma > 0) - c$$

Here, altruism is present as opposed to the previous scenario in which altruism was 0. The presence of an altruism value ($\sigma > 0$) results in a payoff which is higher than cost-benefit alone which is based solely on reward value. An example could be an a nominally reimbursed and desirable task or even an unpaid sensing task, such as voluntarily monitoring air quality near a playground for child safety.

Finally, consider an alternative situation in which a sensing agent may have the ability to earn a reward or monetary payment. That reward or payment might be nominal or could be significant, even exceeding the cost that an agent incurs while sensing. In such a situation, the original altruism might be crowded out by the monetary incentive. For instance, a person might

cooperate and receive an altruistic or warm-glow feeling from a sensing task, only to lose the feeling once rewards exceed some threshold and profit is earned. This is modeled by the hybrid scenario. The agent no longer feels the warm-glow because she is getting paid high wages for the task as actually starts doing the task solely out of monetary gain. For such a scenario, the payoff equation of a cooperator starts at and altruism value greater than zero ($\sigma 1 > 0$) but transitions to ($\sigma 1 > \sigma 2$) in which the value of altruism is lower. For simplicity, in the model the parameter σ is changes from $\sigma 1$ to zero (0) when reward exceeds the threshold R_t set. In the model, the threshold is set to be equal to the cost incurred by the sensing agent ($R_t = c$). So, when modeling within the hybrid scenario, any time the monetary reward exceeds the cost of sensing ($R > c$), then an agent earns a profit and the altruism derived from sensing goes to zero ($\sigma 2 = 0$). Essentially, this shifts the decision-making of the agent from altruistic to cost-benefit.

Therefore, we see that the payoff which an agent receives depends upon a number of factors, including the behavioral strategy utilize by an agent at a given time and the scenario being modeled. The three scenarios each come with assumptions and generalizations which allow for a general and exploratory set of findings. Future research could utilize other parameter values, thresholds, and transitions from altruistic to cost-benefit scenarios.

4.3.4 Effect size and number of runs

Two common issues exist when running statistics on ABM: (i) *Statistical issues related to defining the number of appropriate runs and hypothesis testing*, (ii) *Solution space exploration and sensitivity analysis* (Lee et al., 2015). Standard statistical models that assume independence of observations or unidirectional causality inappropriate for analyzing ABM. Because "feedback also often implies a non-linear relationship between individual behavior and its macro consequences, models that seek to explain the social consequences of interdependent behavior must explicitly represent feedback between individuals' actions and their decision-making environments (Bruch and Atwell, 2015, p.189)." It is difficult to efficiently parameterize realistic nonlinear, multi-process spatio-temporal dynamical processes from a statistical perspective (e.g., Wikle and Hooten, 2010). In general, much more could be learned from ABMs if they were embedded in a rigorous framework for designing simulation experiments (Oh, Sanchez, Lucas, Wan, and Nissen 2009). Researchers using ABM strive to expose important and relevant elements in their models'

outputs. Such compelling statements about model behavior may be drawn from descriptive statistics, comparative statistics, predictive statistics, or other analysis. However, "given the stochastic nature of most ABMs, these analytical exercises require an outcome pool drawn from a sufficient number of samples (i.e., simulation runs) (Lee et al., 2015: 18 (4) 4)."

An initial sensitivity analysis was performed to understand the relationship between variables and boundaries. We initially ran 50 iterations for each experiment and each simulation runs for a period of 1000 timesteps. Once trends were observed, additional experiments were run with fewer time steps, when appropriate. Early exploration of our model revealed that around 50 simulations are necessary to reduce the variability of our statistics to an acceptable level. In addition, for the experimental variables of interest, behavior regimes stabilized between 20 and 100 ticks (Kirakozian and Charlier, 2016). Based on empirical studies which found ideal % cooperation to be within a range of 15-25%, and one of the few large empirical studies (N > 8,000) which found % cooperation of 20% at t = 100 (Tomasic et al., 2014), we chose to measure total number of agents with each behavioral strategy at t = 100.

Generally, statistical methods need to be tempered (e.g., a more critical pp-value) or an acceptable ceiling placed on the number samples (or runs) should be enforced by: predetermination of test sensitivity (e.g., effect size) and empirical estimation of the power level (Lee et al., 2015: 18 (4) 4)." Effect size should be tailored to individual ABM based on the model and resolution of results desired. Effect size varies from large down to super-micro (Seri and Secchi, 2017), depending on the number of parameters, population size and desired resolution of results. We selected a more rigorous ultra-micro effect size so that nuanced differences in the data could be observed if desired. We anticipated a low r2 due to emergence of the model and given the following set of parameter levels (Table 9):

Table 4-5. Number of unique parameter values

Parameter	Levels (range of variables)
Reward	51
Image score	5
Privacy	2
Cost	5

Using function:

$$f(G, ES) = 14.091 * G^{-0.64} * ES^{-1.986}$$

resulted in a required run number of 56 runs with power = 0.95, alpha of 0.01, and affect size of 0.05* (Seri and Secchi, 2017). For comparison, an effect size of 0.1 would have required only 15 runs, which would not have yielded the detail needed for this study. Experiments were conducted using Netlogo's built in tool, BehaviorSpace, and data was exported in csv format. The csv was imported and analyzed using R (Thiele, 2014).

4.4 Results

Descriptive statistics and regression results are presented below. Two runs were conducted of the full parameter space under both 1) cost-benefit and 2) altruistic regimes, and given 56 repetitions per combination. The number of runs of the model totaled 584,000. Unless otherwise stated, the parameter values for each chart are listed in Table 10. Based on Andreoni's theory of "warm glow", we would assume that when r > c, crowding out of cooperation will occur (Ariely, 2004; Wang, 2014). We would also expect to see cooperation maximized at neutral value of image score (based on Nowak) and cheaters will rule in private environment where they cannot be monitored. Based on Andreoni's theory of "warm glow", we would assume that when r > c, crowding out of cooperation will occur (Ariely, 2004; Wang, 2014). Finally, one might expect that cheaters will rule in private environment where they cannot be monitored

Table 4-6. Experiment parameter values

Parameter	Value or Range
Starting reputation	3
Privacy	0
Reputation Increment	0.1
Cost from Contributing	10

Our results reveal several novel interactions of extrinsic, intrinsic, and social image motivations which result in unexpected group-wide patterns of cooperation. The model also showed that image score can cause crowding in or crowding out of group-level cooperation depending upon conditions of extrinsic and intrinsic motivation. Our finding that increases in reward can actually increase cooperation when regime shifts from altruistic to cost-benefit supports other findings by Ariely (2004) and Wang (2014).

4.4.1 Descriptive statistics

Effect of reward on cooperation

To answer the question "Under what conditions of extrinsic, intrinsic, and social image motivations is cooperation sustained over time?", we first studied the relationship of reward and cooperation by varying the reward amount from 0 - 50 across the three scenarios of altruism, cost-benefit and hybrid regimes. Based on Andreoni's theory of "warm glow", we would assume that when $r > c$, crowding out of cooperation will occur (Ariely, 2004; Wang, 2014). Under the cost-benefit regime, cooperation is positively related to reward ($p > 0.05$) and increased in rate above $r = 24$. This coincides with Ariely (2004) and Wang (2014), who found that increases in reward can actually increase cooperation. This result represents a real life scenario in which altruism is low and participation is dependent entirely on payment, such as is required with an undesirable task like collecting sewage samples. The cost-benefit data is represented by the solid blue line in Figure 4-5).

Under the altruistic regime, cooperation positively related to reward between $0 > r > 10$ ($p > 0.05$) at a level above the cost-benefit regime. This represents a scenario in which the sensing task is desirable and according to altruism and/or "warm glow" motivation, such as sensing air quality around a playground to help children. This result supports the altruism hypothesis of DellaVigna et al. (2012) and Chao (2017) (shown as the dotted blue line in Figure 4-5).

Under the hybrid regime, when the reward value eclipses the cost of contributing to the public good ($r = 10$), the model resembles a cost-benefit regime. This result supports the warm glow hypothesis proposed by Andreoni (1998), which predicts a crowding out of cooperation based on reward level, and also supports Ariely (2004) in that agents switch to a cost-benefit regime once monetary incentive is mixed into the decision. Therefore, when $r > c$, crowding out of cooperation will occur (Ariely, 2004; Andreoni, 2017) in the hybrid regime, as seen with the solid black line in figure 4-5.

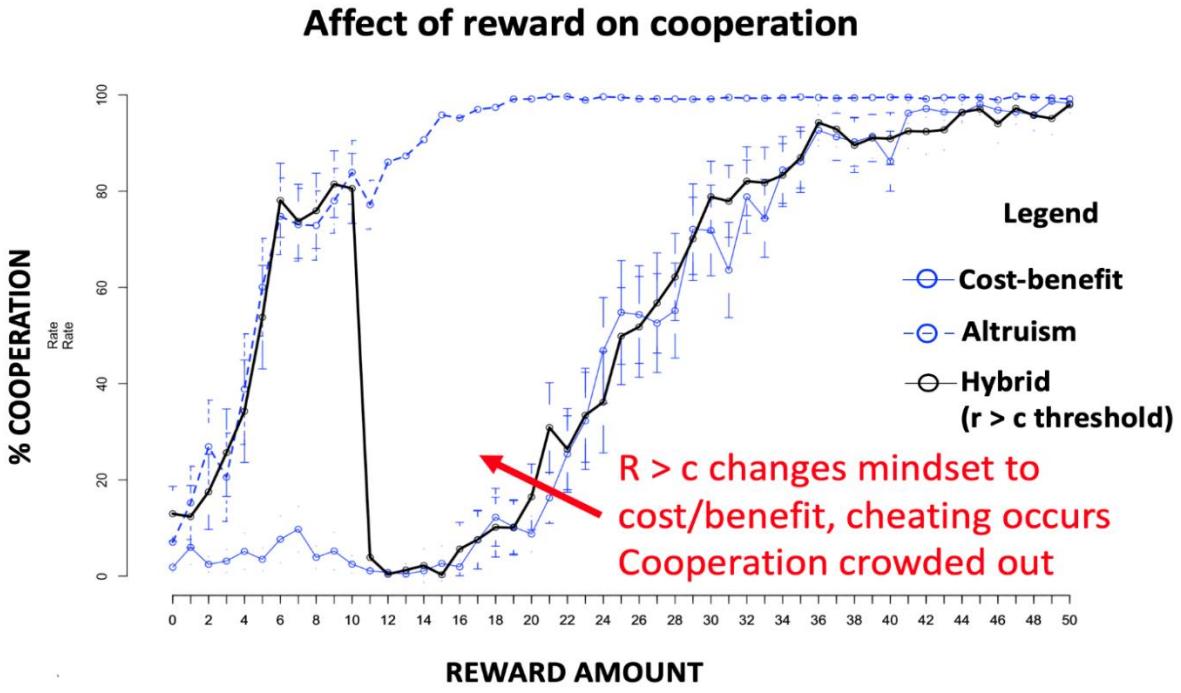

Figure 4-5 Affect of reward on cooperation. Under the cost-benefit regime, cooperation is positively related to reward ($p > 0.05$) and increased in rate above $r = 24$. The data from the cost-benefit regime is differentiated from the conventional warm-glow behavioral models, but the altruistic regime supported the "warm glow" model. When we compare cooperation across the three scenarios of intrinsic motivation, we see that when $r > c$ we see a shift to cost/benefit decision-makig, cheating occurs, and cooperation crowded out.

The crowding coefficient was measured relative to the baseline of r = 20 (Table 11), representing a medium reward. At r = 0 the crowding coefficient is -0.71 meaning a decrease in 0.71 percent cooperation per unit reward relative to medium reward. At r = 50 the crowding coefficient is 4.5, meaning a 4.5% greater cooperation per unit reward. This means that rate of cooperation per unit reward is increasing as reward increases. From this we conclude that reward "crowds in" cooperation in the cost-benefit regime.

Table 4-7: Crowding coefficients by reward level.

Crowding of cooperation by Reward

TESTING: affect of reward on cooperation

		Mean % Cooperation	
Treatment	Reward	Mean	Crowding coefficient
Baseline	20	17	
Low	0	5	-0.70588
Medium	20	17	0
High	50	95	4.588235

Effect of image on cooperation

Next, to answer the social image component to the question, "Under what conditions of extrinsic, intrinsic and social image motivations is cooperation sustained over time?", we observe the effect of image score under low (r = 0), medium (r = 20), and high (r = 50) reward levels in both cost-benefit and altruistic regimes. We also varied the starting image score from 1 - 5 across the three altruism scenarios. Based on studies using Nowak and Sigmund (1998) image score values and Georgellis et al., (2010), which found that image score can crowd other motivations, we assume that cooperation is maximized at neutral value of image score. The data show that image impacts cooperation and leads to motivation crowding in unanticipated ways. First, we see that image and reward interact to produce crowding affects as compared to the baseline image value of 3 ($p>0.05$). Specifically, crowding-in occurs at image 2 and r = 0, as well as image score 2 and r = 20. Crowding-out occurs at image 1, 4, and 5 under r = 20, and 5. Cooperation within the hybrid regime is captured in Figure 4-8 below showing the results across the range of starting image score values (1 – 5). Based on known mechanisms put in place by existing participatory sensing applications to protect against cheaters and free-riders, with the Waze app as a case. We assume that cooperation crowding will occur at i = 1 and i = 5 resulting in cooperation below 20%

threshold (Waze, 2019). The data support this assumption in cost-benefit regime but this view is rejected in altruistic regime at r < 10 (Figure 4-9). Crowding out does not occur in the altruistic regime at r < 10.

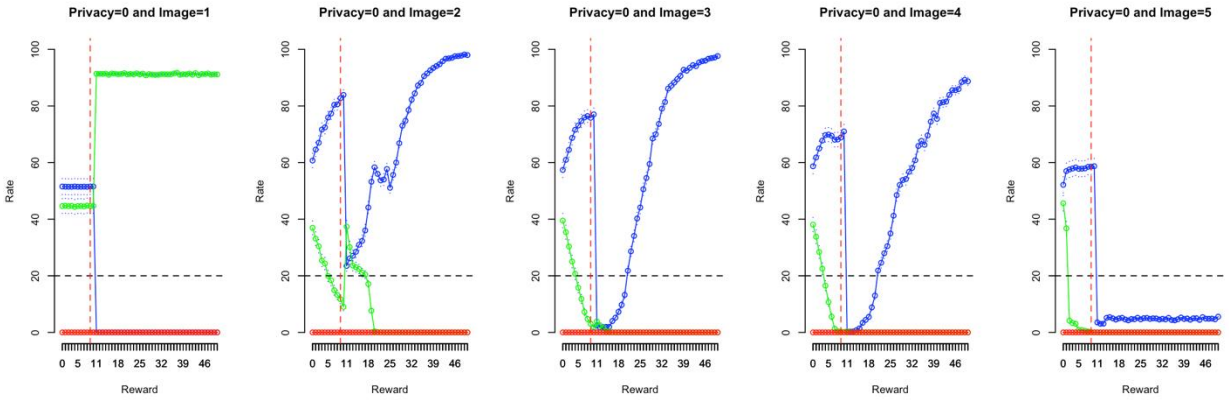

Figure 4-6 Affect of low priacy on behavior in hybrid scenario

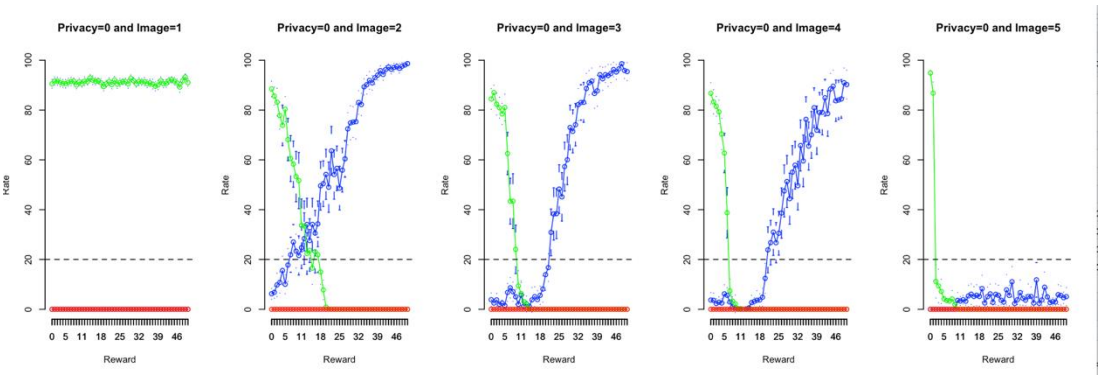

Figure 4-7. Affect of low priacy on behavior in cost-benefit scenario

In summary, when reward and intrinsic are left constant, and starting image score is varied from 1-5, the starting image score impacts cooperation and leads to motivation crowding in unanticipated ways, specifically an optimum at I = 2 for both cost-benefit and hybrid regimes. This suggests that future studies might consider starting image score values other than baseline or neutral values. Crowding-out is incomplete across image score and reward values in the altruistic regime.

Effect of privacy on cooperation

To answer the question “Does privacy affect evolution of behavior strategies, and if so in what ways?” we varied the privacy from low privacy (0) to high privacy (1) in both cost-benefit

and altruistic regimes. These were then compared across three common starting image score values found in the literature and existing applications of 1, 3, and 5 (Table 4-8). The results are in Figure 4-8.

Table 4-8. Experiment parameter values

Parameter	Value or Range
Starting reputation	1, 3, 5
Privacy	0, 1
Reputation Increment	0.1
Cost from Contributing	10

Privacy level had a dramatic effect on the cheating behavior, as we would expect, but what was new finding was the interacting effect of privacy and reward level on cooperation. When reward was held constant at 20, but privacy was low, cheaters increased, were identified and removed resulting in 80% of the agents being removed over time. The remaining fraction of participants were free-riders. In other words, the reward was high enough to motivate cheaters but was not high enough to motivate cooperators, and the low privacy allow for removal of cheaters. However, when privacy was changed to high privacy, cheaters were not able to be caught and dominated the system at around 75% of all agents. Finally, when reward was set to 0 and privacy set to high, cooperators dominated at about 60% of participants. In other words, even though cheaters cannot get caught, the extrinsic incentive is not high enough to sufficiently motivate them. This means that for tasks which carry inherent altruism association, monetary rewards may not be necessary and privacy can be ensured without risking cheating and poor data submission.

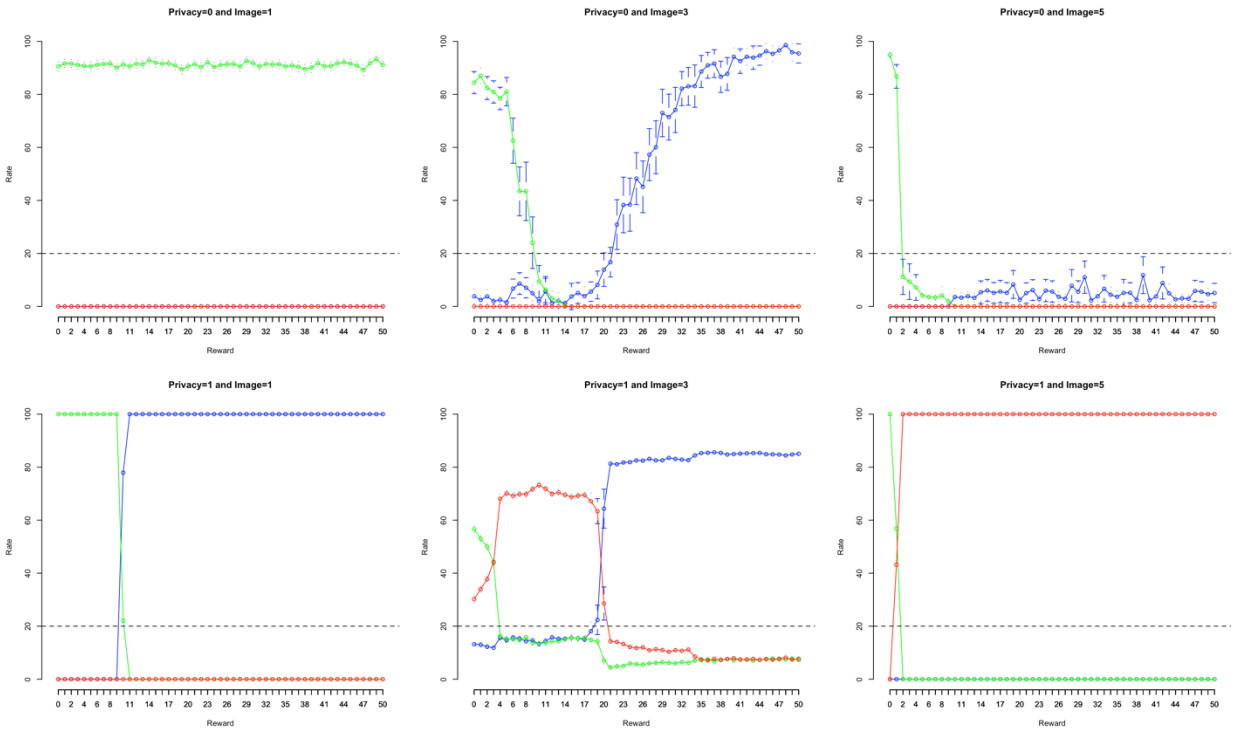

Figure 4-8 Effect of privacy on cooperative outcomes

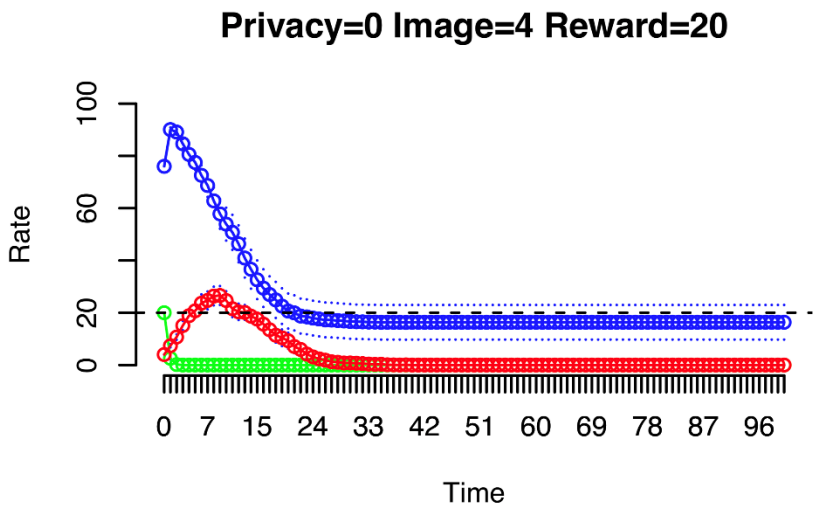

Figure 4-9. Change in percentage of behavior types over time

Based on common understanding about the vulnerability of private environments to cheating behavior, we assume that cooperation will be crowded out in private environment, the following are found:

This is supported at p = 0 and i = 1 in which cooperation is completely crowded out.
This is partially crowded at p = 0 and i = 3as evidenced by a shift to the right in the graph.
This is partially crowded at p = 0 and i = 5 in which cheaters are able to persist longer in the system due to starting with a high image score.

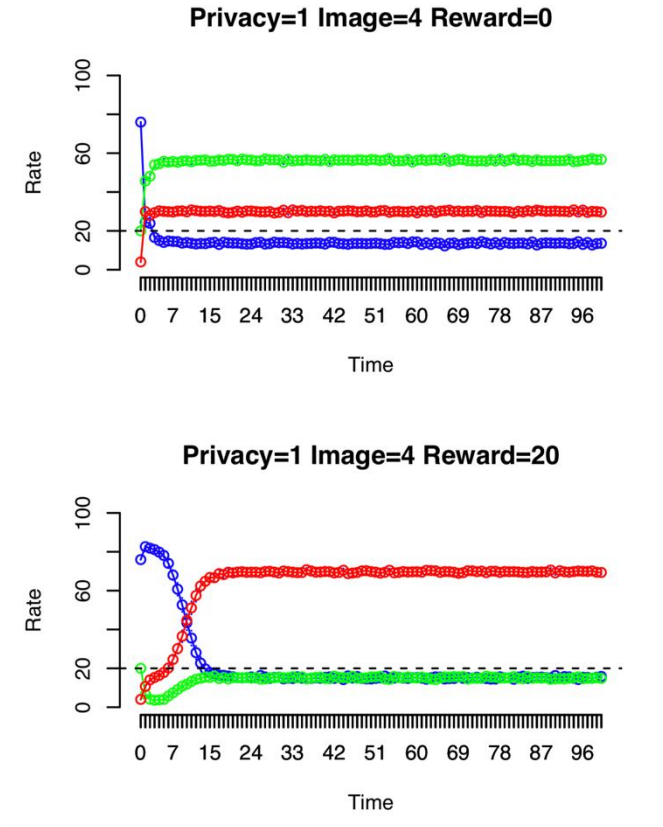

Figure 4-10. Effect of reward on behavior over time

At p = 1, i = 3 the number of cooperators is higher, the number of cheaters is also much higher, resulting in a decrease in value of public good compared to low privacy. This is shown in Figure 4-11.

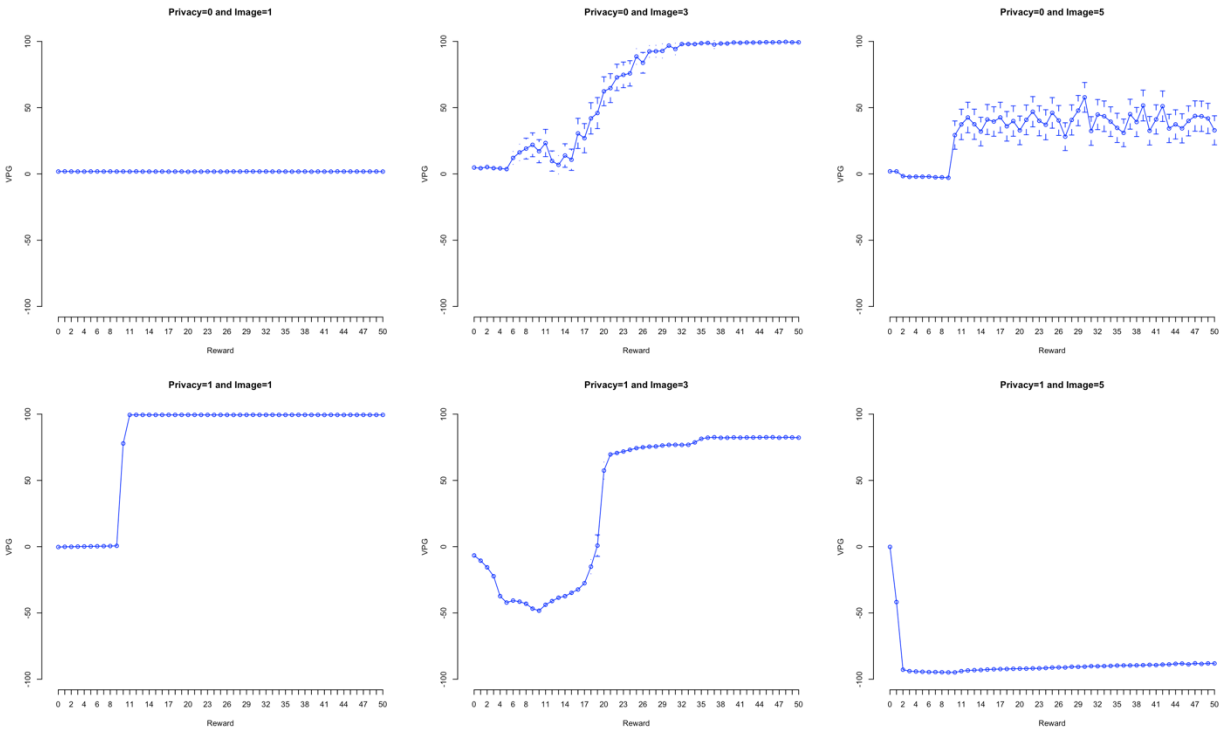

Figure 4-11. Effect of privacy on VPG across reward values

4.4.2 Regression statistics

To address the question "What combination of extrinsic, intrinsic, and social image leads to motivation crowding?", regression analyses were run on the effect of reward on cooperation across image score types. Analysis were run for both cost-benefit and altruistic regimes to explore the role of intrinsic motivation (Table 4-9). The regression for the cost-benefit regime is shown in Figure 4-12.

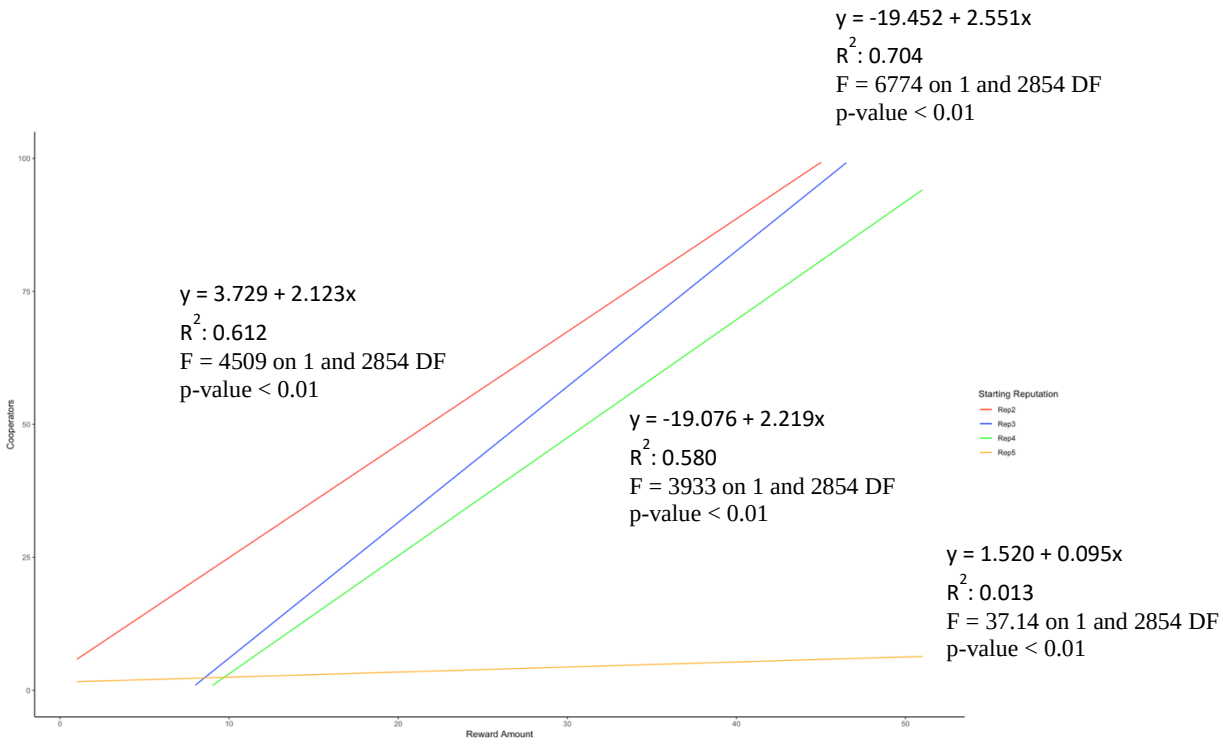

Figure 4-12 Regression for cost-benefit regime

Table 4-9. Experiment parameter range

Parameter	Value or Range
Starting reputation	1-5
Privacy	0
Reputation Increment	0.1
Cost from Contributing	10

*Significant at 0.01
* Reward treated as continuous.

In the cost-benefit regime, an image score i = 2 yields the highest cooperation with some small cooperation at r = 0 (% cooperation 3.7%). Image score i = 3 follows a very similar slope but does not yield cooperation until r > 10. From this, we see that a neutral or middle value of 3 results in a crowding out of potential cooperation, or rather than by using an alternative starting

images score of i = 2, one might achieve higher levels of cooperation as compare to a value of three. At i = 4, the slope is greater and cooperation begins at r = 8. However, the line approaches intersection with that of i = 2 for reward > 45. The slope of i = 5 is low (.095) and results in very low cooperation (<5%). Note that for i = 1, no line is present as image score has crowded out participation due to decrease reward from low earned reputation as well as high levels of punishment for cheaters (Wedekind and Milinski, 2000).

The regression for the altruistic regime is shown in Figure 4-13.

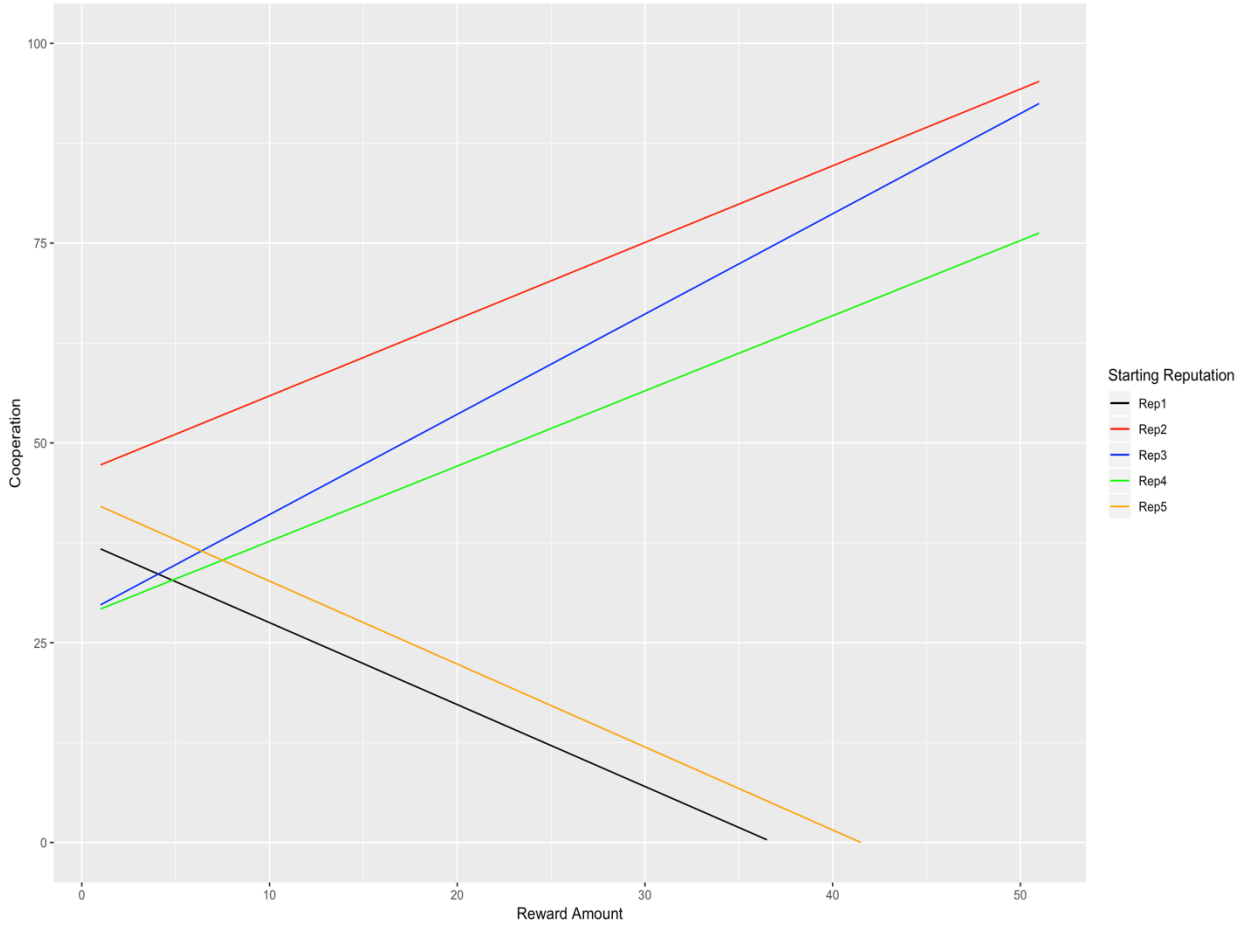

Figure 4-13. Regression of image score value and reward within altruistic regime

Here we see a shift of the graph upward and decrease in slope from the cost-benefit regime to the altruistic regime, signifying increased cooperation at lower reward amounts due to increased intrinsic motivation. We can also observe the presence of i = 1, meaning that cooperation is incompletely crowded due to altruism. In the altruistic regime, an image score i = 2 again yields

the highest cooperation and i = 3 follows a very similar slope in parallel but lower than i = 2. From this, we see that a neutral or middle value of 3 results in a crowding out of potential cooperation. Again, at i = 4, the slope is greater and cooperation and presents cooperation even at r = 0 (Wedekind and Milinski, 2000).

By categorizing reward amounts, ANOVA with confidence level used of 0.95 was run for the altruistic regime to compare the crowding rates across reward amount. Reward (0 – 50) was categorized into five groups (0-10, 11-20, 21-30, 31-40, and 41-50). The results are presented in Table 15. The contrast estimates are the difference in % cooperation between reward groups. We see the contrast estimates are not evenly increasing or decreasing, suggesting increase rate in crowding among groups. The data suggest that the image score does contribute to motivation crowding, with incomplete crowding across the altruistic regime and a mix of complete and incomplete crowding across image score values in the cost-benefit regime. Further, the rates of crowding vary by reward level and image score.

Table 4-10 ANOVA results

ANOVA results

contrast	estimate	SE	df	t.ratio	p.value
3 - 1	-28.4	0.406	59971	-69.975	<.0001
3 - 2	30.2	0.406	59971	74.439	<.0001
3 - 4	-42.3	0.406	59971	-104.344	<.0001
3 - 5	-53.9	0.396	59971	-136.051	<.0001
1 - 2	58.6	0.406	59971	144.413	<.0001
1 - 4	-13.9	0.406	59971	-34.369	<.0001
1 - 5	-25.5	0.396	59971	-64.430	<.0001
2 - 4	-72.5	0.406	59971	-178.782	<.0001
2 - 5	-84.1	0.396	59971	-212.242	<.0001
4 - 5	-11.6	0.396	59971	-29.252	<.0001

Optimized social scenario

In both cost-benefit and altruism regime, a starting reputation score of 2 produced optimum levels of cooperation (92.547%, and 85.53% respectively) (Tables 4-11 and 4-12). This suggests

that future studies which wish to identify optimum cooperation thresholds should consider starting reputation values other than Nowak's neutral values (Nowak and Sigmund, 1998).

Table 4-11. ANOVA results

Reward.cat	Image Score	lsmean	SE	df	lower.CL	upper.CL
3	3	45.06	0.662	14271	43.76	46.35
1	3	21.68	0.662	14271	20.38	22.98
2	3	26.05	0.662	14271	24.75	27.35
4	3	65.48	0.662	14271	64.18	66.78
5	3	73.5	0.645	14271	72.23	74.76
3	1	-1.83	0.662	14271	-3.13	-0.53
1	1	-25.2	0.662	14271	-26.5	-23.91
2	1	-20.83	0.662	14271	-22.13	-19.54
4	1	18.59	0.662	14271	17.3	19.89
5	1	26.61	0.645	14271	25.35	27.88
3	2	57.09	0.662	14271	55.8	58.39
1	2	33.72	0.662	14271	32.42	35.02
2	2	38.09	0.662	14271	36.79	39.39
4	2	77.52	0.662	14271	76.22	78.81
5	2	***85.53**	0.645	14271	84.27	86.8
3	4	36.78	0.662	14271	35.49	38.08
1	4	13.41	0.662	14271	12.11	14.71
2	4	17.78	0.662	14271	16.48	19.08
4	4	57.2	0.662	14271	55.91	58.5
5	4	65.22	0.645	14271	63.96	66.49
3	5	2.17	0.662	14271	0.87	3.47
1	5	-21.21	0.662	14271	-22.51	-19.91
2	5	-16.84	0.662	14271	-18.14	-15.54
4	5	22.59	0.662	14271	21.29	23.89
5	5	30.61	0.645	14271	29.34	31.87

An optimum social condition in the cost-benefit regime arises from the model at reward category 5 and image score i = 2, and low privacy (Table 4-11).

Table 4-12. ANOVA results

Reward.cat	Image Score	lsmean	SE	df	lower.CL	upper.CL
3	3	46.607	0.1845	299871	46.245	49.968
1	3	82.409	0.1845	299871	82.047	82.771
2	3	33.547	0.1845	299871	33.186	33.909
4	3	66.653	0.1845	299871	66.292	67.015
5	3	74.918	0.1797	299871	74.566	75.270
3	1	-3.390	0.1845	299871	-3.751	-3.028
1	1	32.412	0.1845	299871	32.051	32.774
2	1	-16.450	0.1845	299871	-16.811	-16.088
4	1	16.656	0.1845	299871	16.295	17.018
5	1	24.921	0.1797	299871	24.569	25.274
3	2	56.744	0.1845	299871	56.383	57.106
1	2	***92.547**	0.1845	299871	92.185	92.908
2	2	43.685	0.1845	299871	43.323	44.046
4	2	76.791	0.1845	299871	76.429	77.152
5	2	85.056	0.1797	299871	84.703	85.408
3	4	38.246	0.1845	299871	37.885	38.608
1	4	74.049	0.1845	299871	73.687	74.410
2	4	25.187	0.1845	299871	24.825	25.548
4	4	58.293	0.1845	299871	57.931	58.654
5	4	66.558	0.1797	299871	66.206	66.910
3	5	1.603	0.1845	299871	1.241	1.965
1	5	37.405	0.1845	299871	37.044	37.767
2	5	-11.457	0.1845	299871	-11.818	-11.095
4	5	21.649	0.1845	299871	21.288	22.011
5	5	29.914	0.1797	299871	29.562	30.267

An optimum social condition in the altruistic regime arises from the model at reward category 1 and image score i = 2, and low privacy. Future studies exploring the range of possible starting reputation values might study a more refined image score number. This study utilizes whole numbers for starting values, but fractions of whole numbers would likely yield different results. Finally, the results would likely change if other image score calculation methods, such as Bayesian, were used. Such future studies would be valuable to support a range of participatory sensing environments.

4.5 Discussion

4.5.1 Motivation crowding and incentives

Our data align with well-established studies on warm glow giving toward public good (Andreoni 1998) by showing incomplete crowding due to altruism. The results support the work of others by showing that cooperation can be optimized by combining incentives (reputation and rewards) for motivating cooperation in participatory sensing (Holleis et al., 2012), and the findings do not disagree with previous work establishing the role of altruism for encouraging participation in crowdsourcing and citizen science activities (Liu et al., 2016). Although data reveal that lower thresholds exist for reward, particularly under conditions of cost-benefit regime, Malawi has limited funds available. Therefore, while the ideal reward may be one amount, the reality is that that they are confined to providing a lower financial rate of reward. To compensate, encouraging altruism to overcome the low payment barrier is critical. In terms of combining incentive mechanisms, such as altruism and monetary reward, the research supports recent work on the benefits of such combinations for motivating participation in crowdsensing activities (Gugerell et al., 2018). In addition, this research suggests new approaches to solving the cold start problem by adjusting initial image score values.

Also important to note, decreased numbers of cooperation may not be bad, as public good value depends upon both the quantity *and* quality of data produced. Unfavorable behaviors in which people "cheat" is particularly harmful in the case of monitoring the water system in Malawi. Incorrect information regarding a water well, for example, might negatively affect funding for a community or impact the water source which a community uses. If incorrect data is entered, people may falsely believe a water source to be safe when, in fact, it is not. This can lead to illness and possibly death. Image scoring is especially important for monitoring and eliminating cheating behavior from the system. If the likelihood of cheating is high in a given situation, then public good value might be higher with few participants who are high contributors (Drenner et al., 2008).

Rogers outlines an innovation adoption curve which shows that early adoption of a given innovation is very low (Rogers, 1967). In Malawi, the few pilot projects incorporating participatory sensing have indeed found that initial participation is challenging. Considering this scenario, we adjusted free rider percentage to the highest rate found in the literature of 20% and found that the general relationship between reward and cooperation held true, but higher reward levels were required to incentivize free riders to participate. This might represent a real-life

dilemma in which both payment is difficult due to poverty and reward is important to incentives, such as found in Malawi.

To track the sensing behavior for the purpose of quality assurance or compensation, individual behavior must be tracked in some way. However, privacy is an extremely important factor in many sensing situations. In Malawi, each NGO and governmental agency overseeing participatory sensing will have different desires and regulatory pressures for transparency or privacy. The subject matter of the sensing activity can dramatically affect the need for privacy, such as reporting on government activity or reporting domestic abuse. In these sensing environments, additional privacy is needed. This added privacy affects cheating behavior and other behavioral outcomes, therefore incentives must be adjusted accordingly.

This study can support sensing application designers' decisions around payment, reputation and privacy conditions to optimize cooperation. Although lying outside of the scope of this study, these findings might be used as a basis for discussions when designing user experience and user interface of mobile applications. Finally, optimization should be done on a case by case basis, and participatory sensing applications might be optimized for privacy, certain reward amount, threshold of cooperation, or threshold for value of public good.

4.5.2 Limitations of the Study

The current study is limited due to its exploratory nature. For simplicity, the model uses three simplified scenarios: altruism, cost-benefit and hybrid. The three scenarios represent the real world, but do not *replicate* the real world. This study was exploratory with the purpose of identifying general aggregate themes. Future studies could take a phenomenon-based approach which would account for details that would better *replicate* the real world. In addition, the model is a contained system with a few externalities. Future studies could include externalities and additional randomization which would represent the variation found in the real world.

Parameterization and agent interaction are also simplified in the model. The parameters are tested across a discrete range of values. For example, reward is tested at whole numbers between 0 and 50. Future studies could test the parameters across a continuous range of values, which may produce more nuanced results. Further, the way in which agents interact with one another is purely indirect. Specifically, the current model assumes random pairing which represents anonymous digital interaction. Future studies could include intentional pairing or some hybrid. Future studies

could also include other scenarios, or different thresholds for reward in a hybrid scenario, or randomized thresholds.

4.5.3 Future Research

Based on Resnick et al. (2000) we chose a scaled integer system from 1-5 because a binary value would likely be insufficient in a P2P environment where all peers are untrusted, but we want to rank peers based on the likelihood of reliability. However, if we were to assume that all should be neutral or trusted (reputation score > 2) then another system might be acceptable. For example, when people are assumed to be bad and selfish and given low reputation, the people who do cheat are quickly eliminated because poor decisions are weighted in the image score (increment = -1). The person who is cheating and making poor choices stays at the bottom in a cycle. When people are assumed to be good and all assigned a perfect score reputation, cheaters have more opportunities to cheat and still maintain a relatively high reputation, especially if they do not get caught. In such an environment, because costs are lower and their payoff is higher, they are able to compare to others and win and dominate the landscape.

In addition to reliability, data quality is also important. Other studies have shown that although agents participate, the quality is low and incorrect data is submitted. The TRELLIS system (Gil and Ratnakar, 2002) keeps separate ratings for the likelihood a peer cooperates on a transaction (referred to as its "reliability") and the accuracy of its opinions or recommendations (its "credibility"). Future testing may benefit from testing a two-level score.

4.6 Conclusion

By modeling a participatory sensing scenario inspired by qualitative research data from Malawi, this study analyzes the effects of reward, reputation and privacy on cooperation. The results can help us understand the relationship between motivation strategy and behavioral dynamics, better identify thresholds for reward that lead to adequate participation while maintaining quality of data and work toward sustainable participatory sensing applications in Malawi and other hard-hit areas of climate change.

This study found that when in a cost-benefit regime, the conventional warm-glow behavioral models are not supported, but the altruistic regimes in the model supported the "warm

glow" hypothesis. We found that starting image score impacts cooperation and leads to motivation crowding in unanticipated ways, specifically an optimum at $i = 2$ for both cost-benefit and altruistic regimes. This suggests that future studies might consider starting image score at values other than baseline or neutral values. Crowding-out is incomplete across image score and reward values in the altruistic regime. The data also suggest that the image score does contribute to motivation crowding, with incomplete crowding across the altruistic regime and a mix of complete and incomplete crowding across image score values in the cost-benefit regime. Further, the rates of crowding vary by reward level and image score.

When considering optimum scenarios within the model, an optimum social condition in the cost-benefit regime arises from the model at reward category 5 and image score I = 2 and low privacy. An optimum social condition in the altruistic regime arises from the model at reward category 1 and image score I = 2 and low privacy. This work is directly applicable in Malawi, where the few pilot projects incorporating participatory sensing have indeed found that initial participation is challenging. In poorer areas where reward might be required, it is possible that the regime will shift to one of a cost-benefit. In such a regime, higher reward levels are required to incentivize free riders to participate. This might represent a real-life dilemma in which both payment is difficult due to poverty and reward is important to incentives. Image score changes from i = 3 to i = 2, for example, might represent an opportunity to improve the cost-benefit regime and altruism regime, should such a regime exist.

This study can support sensing application designers' decisions around payment, reputation and privacy conditions to optimize cooperation. Although lying outside of the scope of this study, these findings might be used as a basis for discussions when designing user experience and user interface of mobile applications. Finally, optimization would be done on a case by case basis, and participatory sensing applications might be optimized for privacy, certain reward amount, threshold of cooperation, or threshold for value of public good.

5. CONCLUSION

The term innovation has, in its history, been broadly conceived and defined leading to debates and disagreements. It is treated as normative, although in reality it is not conceptualized, discussed or practiced in a consistent way. The term innovation is used throughout research and policy, as well as resilience literature. As a mechanism within the nested processes of adaptation and transformation, innovation is operationalized as a mechanism of resilience

The research shows that it is impossible to decouple the normative nature of innovation from that of sustainability, resilience, adaptation and transformation. We show that the misalignment of innovation goals and innovation activities could, in practice, result in negative consequences. This lack of clarity may lead to unintended outcomes and may result in poor sustainability when implementing innovation in the field. We also focus on factors that may contribute to diffusion of innovation and sustaining innovations in the field. I first provided a synthesis of peer-reviewed literature to better understand how innovation is interpreted and incorporated into resilience literature and how the concept of innovation has been *used* across this literature. I highlight some of the ongoing debates and disagreements that surround innovation within the resilience literature. I then share empirical findings on innovation perceptions and adaption selection in Malawi, Africa. Finally, I model an innovation diffusion challenge and factors that contribute to sustained participation in the innovation program.

This study reveals that while some frameworks of innovation are complementary, others are fundamentally exclusive of one another. The underlying epistemological tensions must be explicitly described and addressed in order to form effective policy and innovation programs. We presented a set of questions which can help interrogate specific cases of innovation to better understand in the context of resilience, and provide example clarifying statements which can be utilized by researchers and policymakers to clarify innovation concepts.

These epistemological differences also show up in the field. Our empirical results from qualitative interviews in Malawi demonstrate that local opinions and goals contradicted the goals of the SDG and were focused on small scale and incremental changes, such as extending existing systems or making systems more robust, instead of radical new innovations which may have led to transformation. Our results also highlight important factors that lead to resilience beyond technology adoption, system optimization, and asset-based water systems, as previously discussed

in the literature. We identified four key factors which play a role in determining the way in which innovations are selected, designed and implemented in Malawi: 1) stakeholder views about adaptation and scalability of innovations, 2) stakeholder regard for local and indigenous knowledge, 3) epistemological position of policymakers and practitioners in Malawi regarding the importance of technology versus social factors in innovation, and 4) the resilience objectives.

We observed a disconnect between the adaptation goals desired by many Malawian communities and the ways in which communities actually responded to water stress. This disconnect led to lack of sufficient water, reduced autonomy and low community capacity for innovation. Such understanding is crucial for reframing the disconnect between desired adaptation outcomes and goals and innovation practices in a way that empowers local communities, achieves the SDG's, and creates resilient socio-ecological regimes. Finally, we found that radical innovation can start at either the grassroots level or in partnership between locals and NGOs, and that innovations can be radical even if the degree of novelty and uniqueness is lower, as long as adoption and societal impact is high.

To better understand these phenomenon, and disconnect between grass-roots efforts and diffusion of innovation (Rogers, 2010), I modeled an innovation scenario, specifically a participatory sensing scenario inspired by qualitative research data from Malawi. The study analyzed the effects of reward, reputation, and privacy on cooperation. The results can help us understand the relationship between motivation strategy and behavioral dynamics, better identify thresholds for reward that lead to adequate participation while maintaining quality of data, and work toward sustainable participatory sensing applications in Malawi and other hard-hit areas of climate change. The study found that when in a cost-benefit regime, the conventional warm-glow behavioral models are not supported, but the altruistic regimes in the model supported the “warm glow” hypothesis. We identified tactical ways to improve real life applications, such as considering alternative payment levels and image scoring systems.

The result of the synthesis, empirical study, and modeling highlight the need for scholars, practitioners and policy makers to be explicit about the normative assumptions associated with *innovation, adaptation and transformation* when proposing policy, programs and implementing new social innovations. Further studies should focus on the normative and descriptive dimensions of innovation and the way in which innovation is incorporated into policies and programs, such as Sustainable Development Goal 9. Such studies will be crucial for moving towards developing

transformative adaptation interventions for promoting resilient and sustainable communities (Buenstorf, 2000; Griggs, David, et al., 2013; Johnson et al., 2018; United Nations, 2015). Alignment among scholars when using the term innovation would lead to meaningful scientific discourse. Clarifying the intent of policymakers will help practitioners evaluate, interpret and operationalize policies. Furthermore, it can guide further research studies on the role of innovation in resilience (Armitage, 2003). New policy should be written in such a way as to shed light on the many facets of innovation and provide a frame of reference to define both the intended innovation outcomes and localized implementation options. Policymakers should supplement local practitioners and decisionmakers in the field with resources for distinguishing, discussing and promoting specific types of innovation. This study can also help those seeking to scale up innovation, such as sensing application designers. Helping inform decisions around payment, reputation and privacy conditions to optimize cooperation is of great priority. This work is directly applicable in Malawi, where the few pilot projects incorporating participatory sensing have indeed found that initial participation is challenging. In poorer areas where reward might be required, is possible that the regime will shift to a cost-benefit regime. In such a regime, higher reward levels are required to incentives free riders to participate. This might represent a real-life dilemma in which both payment is difficult due to poverty and reward is important to incentives, such as found in Malawi.

Future research should include studies which further our understanding of the way in which localized innovation knowledge and norms affect innovation selection. In addition, scholars should also look at mechanisms which can be used to effectively source local knowledge from local stakeholders. Awareness of local knowledge, practices and norms are critical to the success of innovation decision-making processes. Community-based and participatory methods have been found to be effective in obtaining such information, but few of these have been widely successful in Africa (Kshetri, 2016). In order to build sustainable, participatory, and equitable water systems, further research is needed to understand how communities at various scales envision their future and implement both technical and social change (Miller et al., 2014). More research on successful cases and best practices are is needed to enable appropriate innovation development toward the SDGs and most importantly help build adaptable and resilient communities capable of meeting the water sector challenges brought on by climate changes and other stressors.

Explicitly considering the normative dimensions of innovation enables us to better understand the applications and limitations of the concept, identify opportunities for improving interdisciplinary collaborations and to consider different approaches to minimize unintended policy and program outcomes (Johnson et al., 2018). Such synthesis can aid practitioners in identifying and building the adaptive capacity of communities. More cases and field data are needed to better understand the pragmatic application of innovation concepts on the ground. Future field studies might include retrospective analysis of shock, resilience objectives, innovation type and their relationship to resilience outcome. The field of resilience may benefit from a better understanding of innovation's relationship to traps and cycles of dependency. This area of research will likely involve the study of social institutions. From a social science perspective, studies could be conducted to contrast scientific and local opinion on change and innovation.

Together, these endeavors will allow the scholarly and policy communities to move beyond theoretical discussions about which analytical concepts can be better operationalized within which key paradigms, and to address epistemological tensions between normative and descriptive dimensions of these paradigms and concepts. With such endeavors, the scholarly and policy communities will be able to ask questions with high policy relevance—namely how innovation, adaptation, or transformation at different scales contribute to achieving resilience goals. This research can help inform innovation policy, add to future studies on innovation, and support decision-making for real-life implementations of innovation.

APPENDIX A. CODING FRAME

Coding Frame				
MAIN QUESTION: Why do communities choose given adaptation strategies?				
Sub-Question: What shocks and stresses affect water resources in Malawi?				
Code Family	**Code**	**Definition**	**Example**	**Inclusion/Exclusion Criteria**
WATER AVAILABILITY AND USES	W	Based on Rockström, Johan, et al., 2014.		
Water uses	WU	Any use of water, including but not limited to household, agriculture, industry, etc.	"Water is used in the home for cooking and bathing…"	Exclusion: not just that they use water (we use water), but specific applications
Water Quantity	WQT	Any reference to water amount, regardless of water use.	"The water level has dropped.."	WQ/NS: the presence of groundwater is NS, the availability/amount is WQ
Water Quality	WQL	Any reference to water quality, regardless of water use.	"The water is turbid and dirty…"	
Water location/maps	WM	Any reference to the placement, geography, altitude, etc of water systems, natural or manmade. Any reference to maps of water systems. Key is location, not type of system (see adaptation below)	"The well was located between two adjacent villages 20 miles outside of Lilongwe."	

Code Family	Code	Definition	Example	Inclusion/Exclusion Criteria
STRESSES	S			
Stresses &Shocks	SS	EXTERNAL causes of water disturbance, big or small. Anything that affects the provision of sufficient potable water.	Natural disaster, climate change, war, drought, conflict, water table, geology	Will be overlap with causes of Failure (OCF). All SS could be OCF but there are other OCF that are not external but rather internal causes (poor design for example)
Sub-Question: What adaptions emerge as a result?				
Code Family	**Code**	**Definition**	**Example**	**Inclusion/Exclusion Criteria**
ADAPTATION	A	Davidson, Julie L., et al. "Interrogating resilience: toward a typology to improve its operationalization." Ecology and Society 21.2 (2016). Folke, Carl, et al. "Resilience thinking: integrating resilience, adaptability and transformability." Ecology and society 15.4 (2010). Definition: Adaptation is a process of deliberate change in anticipation of or in reaction to external stimuli and stress (Nelson et al, 2007)		
Adaptation strategies	AS	Any response to water stress or reduced water availability aimed at maintaining or restoring water provision.	"The division does not know how to treat salty water so the only option is to drill another borehole on another site until consumable water is found."	

Natural system	ANS	Any natural system or process leading to provision of water.	"We secure water from a nearby river" Ecosystem services: "The soil filters the groundwater.."	Include: sources of water, movement of water, rivers, streams, Lakes WQ vs NS: the presence of groundwater is NS, the availability/amount is WQ.
Current Management	ACM		"..managment not sustainable.." Sampling as a management activity	Inclusion: any instance of management activity, quality of management, or system maintanance.
Future Planning	AFP		"Working with university to plan extension of pipes.."	
Manmade system	AMS	Any manmade system or process leading to provision of water.	"….pump water, piped water or well…"	Include: engineered distribution, collection, storage Exclude: ancillary processes to measure water, document water, testing, etc
Dependencies	AD	Systems analsyis: Any interdependency between any entities, institutions, and among natural and/or manmade water systems. Trying to map how the status of one entity affects and status of another entity	"...pump depends on electricity, created by dam, which depends on Shire, depends on Lake Malawi, which depends on Climate and water boards taking water."	
Relationships	AR	Any relationship between two or more people or organizations including employment, partnership, resource provision.	"The Gates Foundation has provided funding"; "I have a friend on the water board…"	Exclusion: not demographic, population data

Materials + resources	AMR	*NOTE: will overlap with AR above. This is a subset of AR.* Any relationship between two or more people or institutions in which resource provision occurs.	"We secure sand from an NGO in the city"	Include: Examples of NGO, Government, or other third party providing physical resources such as materials for water systems, money, or labor
Communication type/direction	AC	Any mention of communication, oral, written, or otherwise and the direction of said communication.	"The officials require approval and we send plans to the main office.."	
Gender Equity	AG	Any mention of gender including social norms, roles, responsibiities, etc.	"There are two women who are chiefs in this district, and one leads the water board"	
Sub-Question: In what ways do drivers of innovation inform selection of adaption strategy? What forces driving community level selection of innovation for adaptation?				
Code Family	**Code**	**Definition**	**Example**	**Inclusion/Exclusion Criteria**
INNOVATION	I	Norman, Donald A., and Roberto Verganti. "Incremental and radical innovation: Design research vs. technology and meaning change." *Design issues* 30.1 (2014): 78-96. Rogers, Everett M. Diffusion of innovations. Simon and Schuster, 2010.		
Technology-Push Innovation	ITP	Technology-push innovation comes from radical changes in technology without any change in the meaning of products. Technology push innovation definitely does not come from users,	"The government is also advocating the planting of drought resistant maize." - *government, not users, are "advocating" or pushing for the use of certain solution* University technology commercialization is another example.	Include: examples of anyone other than the water user suggesting, advocating, or pushing for specific solution (typically technical in nature). Exclude: Examples of water users demanding certain solution.

Technology-Epiphany Innovation	ITE	Bring a radical change in meaning, enabled by the emergence of new technologies or the use of existing technologies in totally new contexts	Female water users circumventing communication channels to report water issues using mobile phones. Water solutions that do not originate from or depend on government, NGO, or other third party.	Inclusion: New technology than empowers new groups or issues in a new regime of some kind
Market-Pull Innovation	IMP	Starts from an analysis of user needs and then develops products to satisfy them	"We bought a pump to fix the problem, now we are pumping water into two tanks. In addition, we are also working on extending the tap water distribution to the whole camp."	Include: examples in which existing technology or solution is used to remediate a problem.
Meaning-Driven Innovation	IMD	Starts from the comprehension of subtle and unspoken dynamics in socio-cultural models and results in new meanings and languages—often implying a change in socio-cultural or socio-ecological regimes	female-led water committee instead of male reconsidering a waste product as a valuable resource	Exclude: new technology Include: new types of uses of existing technology, resources Include: new social constructs, paradigms, or institutions.
Sub-Question: Under what conditions are different innovation types lead to failure or success?				

Code Family	Code	Definition	Example	Inclusion/Exclusion Criteria
OUTCOME	O	Rockström, Johan, et al. *Water resilience for human prosperity*. Cambridge University Press, 2014.		
Successful adaptation	OS	Any response to water stress or reduced water availability that is successful at reaching intended goals, such as maintaining or restoring water provision.	"We installed the pump five years ago and it still functions today"	Inclusion: adaptation must be measured, proven, or considered by users to have met goals/success.
System failure	OF	Any mention of a water system working in unintented manner in such a way that water provision is impacted	"The well that the church drilled produces salty water and is not used"	
Causes of failure	OCF	Smaller scale, localized causes of failure of a particular system as opposed to large scale shock or systemic stress. Can include natural or physical boundaries and barriers, or institutional norms.	"The water table is too deep in this part and there is bedrock"	

APPENDIX B. SEMI-STRUCTURED INTERVIEW PROTOCOL

INTERVIEW PROTOCOL FOR THE STUDY OF "WATER PROVISION RESILIENCE IN BLANTYRE, MALAWI"
Level 1 Stakeholders and Key Informants

Interviewer:
Interviewee:
Date of interview:
Location of interview:

Thank you for taking the time to talk to me. I am a graduate student at Purdue University working with Drs. Suresh Rao and Zhao Ma. We are doing a study to determine how water authorities and managers make decisions about water systems and water management and/or planning given the population, land use, and climatic changes taking place in the region surrounding Blantyre.

We have four sections for our interview today. In the first section, I'd like to discuss with you the management challenges your organization faces. The second section deals with how you and your organization have dealt with drought in the past and how you plan to deal with drought in the future. The third section is about how you and your organization are planning for and/or thinking about climate change, population growth, and land use change. And I'd like to end with a few questions about the kinds of information and models you are using to inform your decision-making. This interview should take a little over one hour.
Everything we discuss during the interview will be kept strictly confidential and your name and organization will not be revealed to anyone beyond the research team. For the purpose of data coding and analysis, it will be really helpful for me to record this conversation. Do you feel comfortable with this? If not, please let me know now. Again, thank you for your willingness to participate in this interview. Unless you have any questions, let's go ahead and get started.

SECTION 1: BACKGROUND ON INTERVIEWEE AND ORGANIZATION
To begin, I'd like to ask a few questions about your role at [organization] and some of the basic management challenges your organization faces.

1. We read on your website that you [do the following] here at [organization]. Is this still your major responsibility? Is there anything else you are responsible for managing and making decisions about?

2. What are the most pressing management challenges your organization faces?
Prompt: What are the year-to-year, short-term planning challenges faced by your organization?
Prompt: What are the five-to-ten-year, long-term planning challenges faced by your organization?
Prompt: Among these management challenges, which are considered top priorities for your organization to address?

3. How does [organization] work with other local, state, and governmental agencies to address the challenges we just talked about facing your organization?
Prompt: If not, what prevents your organization from working collaboratively with other agencies?

At different scales?

SECTION 2: DROUGHT PREPAREDNESS

Next, I'd like to ask some questions about how you and your organization have managed drought in the past and what lessons for the future you have learned from those experiences.

4. Please characterize the droughts in your region:

Prompt: What is the frequency?
Prompt: What is the duration?
Prompt: What is the intensity?

5. What have you and your organization learned about dealing with drought from previous experiences?

Prompt: What are the tradeoffs you have to make during droughts?
Prompt: What has your organization done in response to previous droughts that has better prepared you to deal with future droughts?
Prompt: What more do you wish your organization could be doing to better deal with drought?
Prompt: What prevents your organization from doing this?

6. What concerns do you have about your organization's capacity to deal with future droughts and water scarcity?

Prompt: What is the threshold that needs to be crossed for a drought to become an unmanageable emergency?
Prompt: In your opinion, how many consecutive years of drought can your organization handle given your current capacity and resources?

7. How do droughts affect your organization's interaction with other local, state, and federal agencies?

Prompt: What enables you to work effectively across agencies and scales in times of drought?
Prompt: What prevents you from being able to work effectively across agencies in times of drought?

8. How does this effect water usage?

Prompt: During droughts, what uses take precedent over others? (Industry, agriculture, household?)
Prompt: Are certain people excluded or marginalized due to this change?

SECTION 3: BUILT WATER INFRASTRUCTURE

9. What do built systems look like in and around Blantyre?

Prompt: Do you believe your water quantity is sufficient?
Prompt: Do you believe your water quality is sufficient?
Prompt: Do you believe your water education is sufficient?
Prompt: Do you believe your water sources are sufficient?
Prompt: Distribution of technology:
    Are systems centralized or distributed?
Prompt: What types of treatment systems are used?
Prompt: What types of collection systems are used?
Prompt: What types of distribution systems are used?
Prompt: What is the water used for?
    Please describe uses and relative amounts used for each?

SECTION 4: THINKING ABOUT AND PLANNING FOR CHANGE
Going forward, climate and other hydrological, ecological, and social changes may have an impact on your organization's ability to manage water. Now, I'd like to talk a little more about how your organization is planning and/or thinking about the future with respect to the different changes that are occurring or projected to occur across Southern Malawi.

10. What is the nature of the discussion within your organization about climate change?

11. You travel in the water circles and listen to the discussions among water managers. What is your current understanding of the predicted impacts of climate change in the Blantyre region?

12. What is your organization doing to manage and plan for climate change?
Prompt: If nothing, what prevents your organization from doing anything?
Prompt: What do you wish your organization were doing to address the potential impacts of climate change?

13. What needs to happen for your organization to more effectively manage and plan for climate change?
Prompt: What information would help your organization make decisions?
Prompt: What types of collaboration with the research community or other local, state, and federal agencies would help your organization?
Prompt: What policy changes or actions by the state legislature would you like to see?
Prompt: What institutional changes would you like to see?
Prompt: What infrastructural changes would you like to see?
Prompt: Is the current built infrastructure managed by your organization set up to deal with shifts in precipitation from snow to rain and earlier spring runoff?

14. In your opinion, how does climate change create new management and planning challenges for your organization?
Prompt: In particular, how does climate change create challenges for delivering agricultural water to farmers and ranchers?
Prompt: Given that we live in an arid state with frequent droughts, is climate change a new problem for your organization?
Prompt: How does climate change make existing problems worse?

15. What are the biggest barriers your organization faces with respect to efforts to adapt to climate change?
Prompt: What role does the state legislature play in determining your ability to adapt?
Prompt: What are the technically feasible climate adaptation strategies you have identified but are not implementing?

16. How does the rapidly expanding population around Blantyre create new management and planning challenges for you organization?
Prompt: How would climate change make dealing with population increases more complicated?
Prompt: What is your agency doing to manage and plan for population change?
Prompt: What are the barriers that prevent your organization from dealing with population increases?

17. How does urbanization and land use change, and in particular, the urbanization of

agricultural land create new management and planning challenges for your organization?
Prompt: How would climate change make dealing with urbanization and land use change more complicated?
Prompt: What is your agency doing to manage and plan for urbanization and land use change?
Prompt: What are the barriers that prevent your organization from dealing with urbanization and land use change?

18. How does urbanization effect the type of built infrastructure?
Prompt: Are systems more centralization or more distributed?

SECTION 5: CURRENT USE OF INFORMATION AND MODELS
I have just a few more questions about the information and models your organization is using to make water management decisions.

19. What information is your organization using to predict water supply, both year-to-year and on a longer-term basis?
Prompt: Where do you get the information?
Prompt: How to ensure quality?
Prompt: How many people are consulted when making a decision?
At household?
Community?
Village?
Region?

20. What information is your organization using to predict water demand, both year-to-year and on a longer-term basis?

21. How is your organization coupling water supply and demand models?

22. How is your organization modeling dynamic changes in hydrologic, ecological, and social systems when predicting water supply and demand?

Prompt: How is your organization taking into consideration these dynamic changes in future water management and planning?
Prompt: If your organization is not doing it currently, what is preventing your organization from considering these dynamic changes?

APPENDIX C. LOGIC TABLE

MAIN RESEARCH QUESTION: Why do communities choose given adaptation strategies?

Literature	Research Questions	Theory Paradigm	Research Methods	Analysis Codes
Adaptation, Resilience, Vulnerability	What shocks and stresses affect water resources in Malawi, and what adaptation strategies emerge as a result?	*Resilience:* (Ostrum, 2007, 2007); *Adaptation*: (Folke, 2010); (Davidson, 2010); Rockström, Johan, et al., 2014.	Interviews (INT): Community stakeholders; Key informants Participant Observations (PO): water committee decisions; water point source construction	*Water uses Water Quantity Water Quality Water location/maps Stresses &Shocks Adaptation strategies Natural system Manmade system*
Diffusion of innovation, Decision-making	What forces driving community level selection of adaptation strategy?	*Diffusion of Innovation* (Rogers, 2007, 2007)	Interviews (INT): Community stakeholders; Key informants Participant Observations (PO): water committee decisions; water point source construction	*Adaptation strategies Current Management Future Planning Dependencies Relationships Materials + resources Communication type/direction Gender Equity*
Radical Innovation, (Norman and Verganti, 2012?..)	What types of innovation are used as adaptation strategies in Malawi at the community level?	*Radical Innovation,* (Norman and Verganti, 2012?..)	Interviews (INT): Community stakeholders; Key informants Participant Observations (PO): water committee decisions; water point source construction	*Technology-Push Innovation Technology-Epiphany Innovation Market-Pull Innovation Meaning-Driven Innovation*
Adaptation, Vulnerability	Under what conditions do different innovation types lead to failure or success?		Interviews (INT): Community stakeholders; Key informants Participant Observations (PO): water committee decisions; water point source construction	*Successful adaptation System failure Causes of failure*

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