RESEARCH GAPS AND OPPORTUNITIES FOR CLIMATE CHANGE ADAPTATION IN NETWORK ANALYSIS

By

Sophia Nguyen Chau

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Fisheries and Wildlife—Master of Science

2020

ABSTRACT

RESEARCH GAPS AND OPPORTUNITIES FOR CLIMATE CHANGE ADAPTATION IN NETWORK ANALYSIS

By

Sophia Nguyen Chau

Mitigating the negative impacts of climate change such as sea level rise, drought, and species extinction requires effectively mobilizing social and ecological resources across geographic distances. Climate change adaptation practitioners need to understand climate change from a systems perspective, whereby the ecological and social components involved are viewed as interacting and interrelated components of a system that together yield consequences for both human and non-human life. Network analysis, a set of techniques that allows for quantitative and qualitative depiction of the relationships between system components and how they give rise to emergent phenomena, has the potential to help address contemporary sustainability challenges such as climate change adaptation. Adaptation practitioners have already begun using network analysis with the goal of improving their adaptation efforts, but the literature to guide their practice is young.

The first chapter of my thesis addresses this problem by reviewing network analysis studies about climate change adaptation. I identified research gaps and opportunities related to the type of network analysis, adaptation sectors, geographic scale, number of systems, study objectives, and proposed network interventions. In the second chapter, I developed a framework called the metacoupled network approach that can help network analysis studies address these research gaps. Such a framework will not only guide network analysis studies in climate change adaptation but also provide a useful framework for understanding other complex social-ecological challenges.

This thesis is dedicated to the two loves of my life –
Eggieplant and Connor Rosenblatt.
You bring me endless joy and laughter!

ACKNOWLEDGEMENTS

I would first like to thank my major advisor, Jianguo ‘Jack’ Liu, and my two committee members, Ken Frank and Mark Rey. I am grateful for their support and guidance throughout my time at MSU. I admire the dedication they bring to their work and to their students.

I am forever grateful for my colleagues, many of whom I know will be lifelong friends. Veronica Frans, Ming Lei, Yuqian Zhang, Clara Graucob, Emily Liljestrand, and Tessaliz Quiles Degaldo always had my back and made my time at MSU rewarding and fun.

Thank you to my teammates at SESYNC, who greatly enriched my grad school experience. Miram Aczel, Jacob Bukoski, Natali Ramirez-Bullon, Elizabeth Golebie, Mimi Gong, and Noah Teller taught me how to be both a leader and team-player and helped me grow as a scholar.

Natalie Ambrosio, Mallory Dreyer, and Rachel Jones were always just a phone call away. They have been a constant source of support and wisdom and carried me through the toughest weeks.

Thank you to my family, who constantly cheered me on and are my #1 fans in all my endeavors. I am also grateful for my many mentors over the years who have helped me become the person I am today.

I also acknowledge funding from the National Science Foundation’s Graduate Research Fellowship Program and Michigan State University’s University Distinguished Fellowship.

Lastly, I would like to thank Eggieplant and Connor Rosenblatt, to whom this work is dedicated. They have been with me every step of the way and bring me much joy and laughter. Thank you for always believing in me and for your love and patience.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Climate change is impacting systems worldwide, with many adverse consequences for life on earth. One in six known species is threatened by climate change (Urban 2015), and shifts in ecosystems are altering the vital resources and services they provide to people (Walther et al. 2002). Ecological regime shifts and altered biotic dependencies due to climate change (e.g., Walther 2010; Woodward et al. 2010; Alexander et al. 2016; Schleuning et al. 2016) are driving geographic shifts in human populations (e.g., Warner et al. 2009; Black 2011; Cattaneo et al. 2019). The need for social-ecological systems to adapt, or adjust favorably, to climate change is clear, but the complexity and global scale of climate change pose a significant challenge to adaptation research and practice.

An important component to climate change adaptation is successfully mobilizing social and ecological resources (e.g., social capital, ecosystem services) to attenuate the negative impacts of climate change. To do so requires an understanding of how system components interact and give rise to system dynamics such as natural resource depletion, and the successful adoption of adaptation practices. Successfully adapting to climate change often requires an understanding of how multiple social-ecological systems interact with each other both nearby and faraway (e.g., trade, human and wildlife migration, adaptation funding).

Network analysis, which conceptualizes system components and their interactions as nodes and linkages of a network, has the potential to help address contemporary sustainability challenges because it provides methodological tools that can be used to identify network structures and interactions associated with different social-ecological outcomes. There are three kinds of network analyses that are relevant to my thesis: social network analysis, ecological network analysis, and social-ecological network analysis.

Social network analysis provides theory and methodologies to analyze social structures and interactions between people and assumes that analyzing relations among social entities can yield better explanations of social phenomena such as the spread of certain behaviors and beliefs (Chiesi 2001). Social network analysis uses regression and cluster analysis to answer questions related to network structure and dynamics (Chiesi 2001). For example, it can be used to determine how individuals choose with whom they interact and whether there are social subgroups in the network. It can also be used to identify central actors (popular individuals who are connected to a relatively high number of other social entities in the network) and bridging actors (individuals who have connections in multiple subgroup), which can be key for disseminating a variety of resources (e.g., information, advice, finance) throughout the network.

Ecological network analysis is similar in concept to social network analysis. It is most commonly used to model stocks and flows to determine how complex interactions between ecosystem components affect who ecosystem dynamics. Ecological network analysis is often applied to food webs and to assess habitat connectivity (e.g., Horn et al. 2019, Fenu and Pau 2018)

Finally, social-ecological network analysis was developed to integrate social and ecological network analysis. In addition to studying structures and relationships within social systems and within ecosystems, social-ecological network analysis examines interactions between social and ecological systems and their components. Take for example a fishing community. Social network analysis could be used to study the relationships among different fishers, including with whom they interact to coordinate harvesting (e.g., timing and location of fishing activities, species of fish to harvest, and amount of fish to harvest); ecological network analysis can be used to assess the marine food web and trophic interactions; and social-ecological network analysis can be used to determine the impact of harvesting activity on the stability and biodiversity of the ecological food web.

Climate change adaptation practitioners have begun using network analysis to inform their work, but the literature to guide their practice has only emerged within the last decade. Additionally, the world is becoming increasingly connected through globalization, and interactions between distant people and places are often different in nature and have different causes and effects from interactions between people and places that are nearby. There is thus a need for a framework that reflect these complexities to guide network analysis research in climate change adaptation.

In Chapter 1 of this thesis, I performed a literature review of studies applying network analysis to climate change adaptation. I assessed the extent to which the current body of research contributes to understanding climate change adaptation as a complex social-ecological phenomenon under a globalized world. Specifically, I identified research gaps and opportunities related to the type of network analysis, adaptation sectors, geographic scale, number of systems, study objectives, and network interventions. In Chapter 2, I developed a framework for network analysis research that integrates multiple social-ecological systems interacting across geographic distances. My framework is called the metacoupled network approach and can be used to help address conceptual and methodological gaps in the network analysis and climate change adaptation literature.

LITERATURE CITED

LITERATURE CITED

Alexander, J.M., Diez, J.M., Hart, S.P., and Levine, J.M. 2016. When Climate Reshuffles Competitors: A Call for Experimental Macroecology. *Trends in Ecology and Evolution,* 31(11):831-841.

Black, R. 2011. Migration as adaptation. *Nature,* 478:447-449.

Cattaneo, C., Beine, M., Frohlich, C.J., Kniveton, D., Martinez-Zarzoso, I., Mastrorillo, M., Millock, K., Piguet, E., Schraven, B. 2019. Human Migration in the Era of Climate Change. *Review of Environmental Economics and Policy,* 13(2):189-206.

Chiesi, A.M. 2001. "Network Analysis," in Neil J. Smelser and Paul B. Baltes (eds.), *International Encyclopedia of the Social & Behavioral Sciences,* Elsevier.

Fenu, G., and Pau, P.L. 2018. Connectivity analysis of ecological landscape networks by cut node ranking. *Applied Network Science,* 3(22).

Horn, S., de la Vega, C., Asmus, R., Schwemmer, P., Enners, L., Garthe, S., Binder, K., Asmus, H. 2017. Interaction between birds and macrofaunal within food webs of six intertidal habitats of the Wadden Sea. *PLoS ONE,* 12(5):e0176381.

Schleuning, M. et al. 2016. Ecological networks are more sensitive to plant than to animal extinction under climate change. *Nature Communications,* 7:13965.

Urban, M.C. 2015. Accelerating extinction risk from climate change. *Science,* 348(6234):571-573.

Walther, G.-R. 2010. Community and ecosystem responses to recent climate change. *Philosophical Transactions of the Royal Society B,* 356.

Walther, G.-R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T.J.C., Fromentin, J.-M., Hoegh-Guldberg, O., and Bairlein, F. 2002. Ecological responses to recent climate change. *Nature,* 416:389-395.

Warner, K., Ehrhart, C., Sherbinin, A. de, Adamo, S., and Chai-Onn, T. 2009. In search of shelter: mapping the effects of climate change on human migration and displacement. Climate Change CARE International. London: UK.

Woodward, G., Benstead, J.P., Beveridge, O.S., Blanchard, J., Brey, T., Brown, L.E., Cross, W.F., Friberg, N., Ings, T.C., Jacob, U., Jennings, S., Ledger, M.E., Milner, A.M., Montoya, J.M., O'Gorman, E., Olesen, J.M., Petchy, O.L., Pichler, D.E., Reuman, D.C., Thompson, M.S.A., Van Veen, F.J.F., and Yvon-Durocher, G. 2010. Ecological Networks in a Changing Climate. *Advances in Ecological Research,* 42:71-138.

CHAPTER 1:

A REVIEW OF STUDIES APPLYING NETWORK ANALYSIS TO CLIMATE CHANGE ADAPTATION

1.1 Abstract

Climate change poses one of the greatest challenges for human well-being and environmental sustainability. Sea level rise, more frequent and intense droughts, wild fires, and hurricanes, and the spread of vector-borne diseases are among some of the climate change impacts to which life on earth must adapt to survive. Climate change adaptation scholars and practitioners have begun using network analysis to identify potential strategies to improve adaptation planning and implementation, but the literature to guide their practice has only emerged within the last decade. In this chapter, I conducted a literature review of studies applying network analysis in the context of climate change adaptation to assess the extent to which the current body of research contributes to understanding adaptation as a complex social-ecological phenomenon. I identified and discussed the types of network analysis performed, the sectors and geographic scales addressed, the number of systems analyzed, and the objectives of studies as they relate to climate change adaptation, while highlighting research gaps and opportunities.

1.2 Introduction

Social and ecological subsystems (i.e., systems within a social-ecological system) determine whether and how humans and other species adapt to climate change. Social subsystems are important for generating human resources such as social capital, trust, and reciprocity (Adger 2003), which contribute to the capacity of social-ecological systems to adapt to climate change in different ways. For example, human resources are crucial for generating knowledge, developing and deploying technology, and prioritizing adaptation policies and implementation (Adger et al. 2007; Klein et al. 2014). Adaptation practitioners face many constraints in human resources including limited human capital, challenges in communication and information dissemination, and conflicting values and beliefs (Moser and Ekstrom 2010). Ecological subsystems also inherently shape climate change adaptation. Climate change manifests as biophysical processes such as sea level rise and changes in the spatial and temporal distribution of droughts and hurricanes (e.g., Seneviratne et al. 2012) to which people and other life forms must adapt to survive. Ecological responses to climate change including species range shifts (Chen et al. 2011), biodiversity extinction (IPBES 2019), and altered ecosystem dynamics (Scheffer et al. 2001) directly impact social subsystems by exacerbating crop failure, disease outbreaks, natural disasters, and climate migration.

Network analysis, in which systems and their interacting components are conceptualized as nodes and linkages of a network, is a powerful tool that allows users to disentangle the relationships between components in complex systems. Social network analysis (Wasserman and Faust 1994) and ecological network analysis (Wulff et al. 1989) are two related methodologies with potential to contribute to adaptation theory and practice.

Social network analysis can be used to understand how human resources constrain and enable adaptation. It allows for identifying and quantifying patterns in social relations between individuals or groups, and how these lead to behavioral or belief changes in members belonging to a network. Social network analysis can help identify interventions to improve learning and collaboration between adaptation practitioners, e.g., leveraging the social position of influential or highly-connected individuals in a network to rapidly disseminate information or resources related to climate change adaptation. Adaptation practitioners have begun using social network analysis to identify barriers to adaptation and opportunities to leverage human resources for adaptation. For instance, the Consultative Group for International Agricultural Research (CGIAR)—the world's largest global agricultural research organization—conducted several social network analyses on seed networks in Africa to understand the influence of farmers' social connections on their access to seeds and seed conservation (e.g., Zebrowski et al. 2018; Otieno et al. 2018).

Ecological network analysis is similar in concept to social network analysis. It models stocks and flows (e.g., biomass and energy transfers in food webs) to determine how complex interactions between ecological components affect ecosystem dynamics (e.g., Ings et al. 2009). For example, Horn et al. (2017) used ecological network analysis to assess the impact of shorebirds on the local food web in the Wadden Sea. Each species in the food web was represented by a network node. Such species included different shorebirds, fish and other prey species, and benthic invertebrates. Meanwhile, biomass transfer between the different species were represented by network linkages. Ecological network analysis revealed the effect of shorebirds on trophic interactions and system functioning.

Recognizing the need to integrate social-ecological systems in understanding and addressing contemporary sustainability issues, some scholars have combined social network analysis and ecological network analysis into social-ecological network analysis (Janssen et al. 2006; Norberg and Cumming 2008; Cumming et al. 2010). Social-ecological network analysis allows for simultaneously modeling social and ecological networks and interactions within and among them. Individual network nodes can represent either a social or ecological entity, and network linkages can represent a variety of flows including trust, information, natural resources, seed dispersal, and pollution (Janssen et al. 2006). Because network and system structures are linked to their processes (e.g., Dunne 2006), network analysis can provide a practical tool for adaptation practitioners to shape adaptation outcomes by leveraging and modifying network nodes and linkages.

The potential of network analysis to address complex social-ecological challenges such as climate change adaptation is receiving increasing attention both in research and in practice (Havlin et al. 2012), but the literature representing vigorous and sound research to guide practitioners has only emerged within the last decade. In response, I conducted a literature review of studies applying network analysis in the context of climate change adaptation and consider the extent to which current network concepts and applications contribute to understanding climate change adaptation in today's interconnected world. I also identify research gaps and opportunities.

1.3 Methods

1.3.1 Literature search

To identify relevant studies for the literature review, I conducted a literature search for peer-reviewed and grey (e.g., dissertations, theses, reports, conference proceedings) literature on network analysis and climate change adaptation, following steps with exclusion and inclusion criteria (Table 1.1). These steps are based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Moher et al. 2009; Biesbroek et al. 2018).

Table 1.1 Process step of the literature search and selection process for peer-reviewed and grey articles.

Steps	*Peer-reviewed literature*	*Grey literature*
1. Boolean search	Scopus and Web of Science search in keywords and abstract for the phrases (climat* change adapt*) AND (network analysis). Removed overlapping articles. (August 2018)	Google Scholar and OAlster search in full record for the phrases (climat* change adapt*) AND (network analysis). Removed overlapping articles. (September 2018)
2. Abstract screening	Excluded articles without explicit reference to climate change adaptation and network analysis in abstract.	Excluded articles without explicit reference to climate change adaptation and network analysis in abstract.
3. Full-text screening	Excluded articles that did not perform network analysis or not about climate change adaptation.	Excluded articles that did not perform network analysis or not about climate change adaptation.
4. Reference checking	Forward checking: searched for other articles that cite included articles (Google Scholar). Backward checking: searched for other articles based on reference lists of included articles.	Forward checking: not available for grey literature. Backward checking: searched for other articles based on reference lists of included articles.
5. Final selection	Included only peer-reviewed articles written in English on climate change adaptation that performed network analysis.	Included only grey articles written in English on climate change adaptation that performed network analysis.
6. Follow-up search	Repeated steps 1-5 to search for any newly published peer-reviewed articles. (July 2019)	Repeated steps 1-5 to search for any newly published grey articles. (July 2019)
Total number of articles	45	23

First, I conducted a Boolean search for articles containing the phrases "climat* change adapt*,"and "network analysis" in the title, keywords and/or abstract across all available years. I used Scopus and Web of Science for peer-reviewed articles, and Google Scholar and OAlster for grey articles. Asterisks were used in the search terms to include articles with any variation of the search terms (e.g., climate, climatic). I merged peer-reviewed articles found using Scopus and Web of Science and removed any overlapping articles. I did the same for grey articles found through Google Scholar and OAlster.

Next, I manually screened abstracts and removed articles that did not explicitly reference both climate change adaptation and network analysis. I then performed a full-text screening and excluded articles that did not perform network analysis or were not about climate change adaptation. Studies were included in the results whether they performed quantitative network analysis, qualitative network analysis, or a mixed-methods approach. Following Dupuis and Biesbroek (2013), I defined adaptation as "the process leading to the production of outputs in forms of activities and decisions taken by purposeful public and private actors at different administrative levels and in different sectors, which deals intentionally with climate change impacts, and whose outcomes attempt to substantially impact actor groups, sectors, or geographical areas that are vulnerable to climate change." To focus on the most relevant articles, I excluded articles solely focused on mitigation, disaster risk reduction, hazards, and/or resilience that did not explicitly discuss climate change adaptation.

I performed a reference check to identify articles that may have been overlooked in the initial search. Forward checking was performed in Google Scholar (using the "Cited by" search tool) to identify papers that cited the initial set of papers, and backward checking was performed by screening the reference lists of initial papers.

Only articles written in English on climate change adaptation that performed social, ecological, or social-ecological network analysis (as opposed to policy networks analysis, for example) were included in the final selection. For research that appeared in both the peer-reviewed and grey literature, only the peer-reviewed article was included. The initial search for papers was conducted in August 2018. To search for articles that were published after that, I conducted the search again in July 2019. I found five additional papers.

Articles included in the final selection were read thoroughly to characterize elements relevant to integrating social-ecological systems. These elements include the type of network analysis (social, ecological, social-ecological), the number of systems and geographic scales addressed, sectors, study objectives, and proposed network interventions.

1.3.2 Analysis

The following section describes the criteria for my analysis and categorization of articles (Table 1.2).

I categorized the type of network analysis (social, ecological, or social-ecological) performed based on the term used in the study. For example, if a study referred to its network analysis as "social network analysis," I categorized this as social network analysis.

I determined the number of systems addressed based on the number of geographic entities and how it treated these entities relative to each other. If a study was a comparative study of two or more geographic entities, I considered the study as addressing multiple systems. Often, studies explicitly specified that they were performing a comparative analysis or case studies. In the case that a study involved multiple geographic entities but did not specify that it was a comparative analysis or case studies, I considered it as involving multiple systems if the study differentiated the geographic entities (e.g., by regional climate, government structure) and/or compared networks between the geographic entities. If the study examined interactions between actors belonging to multiple systems, I categorized the study as involving multiple, interacting systems.

I characterized the geographic scale of each study into one of four categories: subnational scale, national scale, international scale, and multiple, interacting scales. I defined subnational scale as involving one or more subnational units, e.g., municipalities, cities, districts, states; national scale as involving one country; international scale as involving multiple countries, e.g., international organizations; and multiple, interacting scales as involving one or more of the previous geographic scales, with actors that share ties or relations across those scales, e.g., representatives from countries around the world interacting at the U.N. Climate Talks.

I defined a sector as a distinct topical area related to climate change adaptation. Most articles addressed one of five sectors: agriculture, natural resource management, natural disaster risk management, tourism, and human health. I defined agriculture as the cultivation of plants and livestock; natural resource management as efforts to sustainably use natural resources such as forests, water, land, and fisheries; natural disaster risk management as efforts to mitigate the detrimental effects of natural phenomena related to climate change on people, including flood, wildfire, and sea level rise; tourism as travel, or activities done while traveling, for pleasure; and human health as focusing on the impacts of climate change on the physical, mental, or social wellbeing of human communities (e.g., vector-borne diseases, heat waves). For articles that did not address a specific sector, I categorized these as “general adaptation” (e.g., social network analysis of actors involved in a city’s adaptation policies). Lastly, I considered articles that focused on more than one sector as including multiple sectors.

I identified a study's objective based on its stated research question(s) or purpose(s) for performing network analysis.

I defined proposed network interventions as recommendations for changing network structure, dynamics, or characteristics to achieve or improve desired adaptation outcomes.

Table 1.2 Definitions of criteria used for analyzing and categorizing articles.

Criteria	*Definitions*
Type of network analysis	Type of network analysis performed
Social	Study specified "social network analysis"
Ecological	Study specified "ecological network analysis"
Social-ecological	Study specified "social-ecological network analysis"
Number of systems	Number of geographic entities
One	A single geographic entity, named by study
Multiple	Comparative analysis of multiple geographic entities
Multiple, interacting	Comparative analysis including actors interacting across multiple geographic entities
Geographic scale	Geographic extent of network analysis
Subnational	Sub-national unit(s) (e.g., municipalities, cities, districts, states)
National	One country
International	Multiple countries
Cross-scale	Actors sharing ties or relations across multiple geographic scales
Sector	Topical area related to climate change adaptation
General adaptation	Unspecified sector, adaptation broadly defined
Agriculture	Cultivation of plants and livestock
Human health	Focused on mitigating detrimental climate change impacts on human physical, mental, and social wellbeing (e.g., heat waves, malnutrition)
Natural disaster risk management	Mitigating detrimental effects of natural phenomena related to climate change on human communities (e.g., flood, wildfire, sea level rise)
Natural resource management	Sustainable human use of natural resources (e.g., forests, water, lands, fisheries)
Tourism	Travel, or activities done while traveling, for pleasure
Multiple	Focused equally on more than one sector
Objective	Research question(s) or purpose(s) for performing network analysis
Proposed network intervention	Recommendations for changing network structure, dynamics, or characteristics to achieve or improve desired adaptation outcomes

1.4 Results & Discussion

There were 68 studies, 45 peer-reviewed and 23 grey, that applied network analysis in the context of climate change adaptation. The first two articles appeared in 2010, and the number of articles generally increased through 2016 but has since declined (Fig. 1). This decline could be due to limited theory and concepts to guide network research specific to climate change adaptation and a paucity of studies evaluating the value of network analysis for adaptation practice (e.g., Groce et al. 2019). Research that develops and tests theories about how network structure and dynamics constrain or facilitate climate change adaptation is needed.

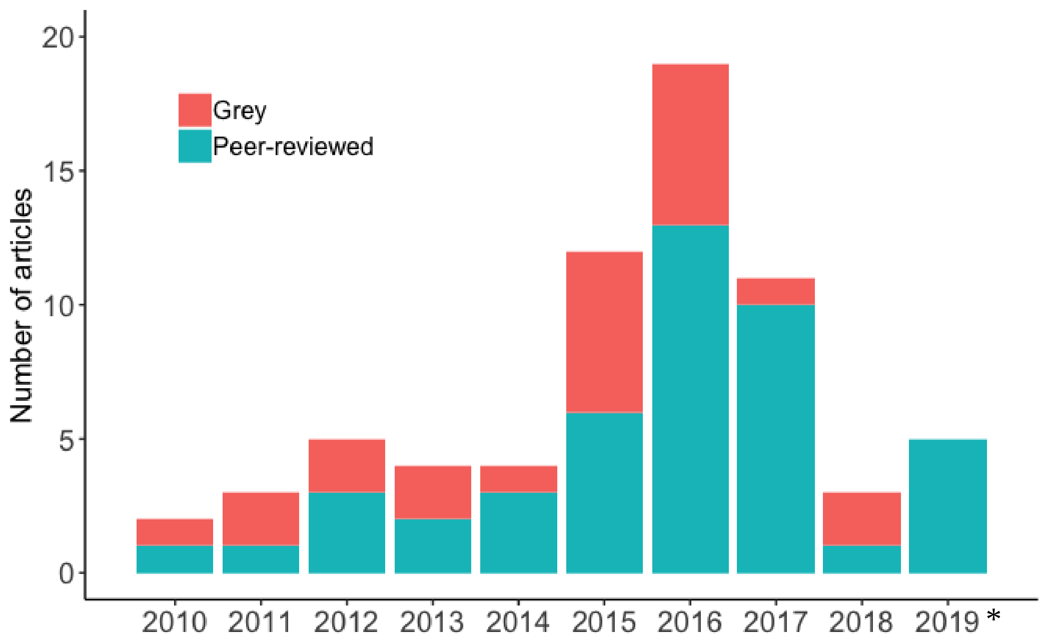

Figure 1.1 Number of peer-reviewed and grey articles on network analysis and climate change adaptation. *Includes only articles published through July 2019.

1.4.1 Types of network analysis

Surprisingly, all of the articles I reviewed performed social network analysis, with no studies applying ecological network analysis or social-ecological network analysis in the context of climate change adaptation (Fig. 1.2A). This represents a significant research gap and opportunity for further scholarship. Ecological network analysis could be used to understand how the structure and dynamics of ecological networks shape whether and how ecosystems adapt to climate change (e.g., successful adaptation to a new stable state, regime shift, ecosystem collapse). For example, studies could identify ecological relationships that should be maintained in a specific ecosystem for the ecosystem to persist under climate change, or the minimum level of habitat connectivity that is needed to sustain a viable wildlife population that needs to migrate due to climate change. Socio-ecological network analysis could yield insights on network structures and processes that influence the adaptation of social-ecological systems. For example, studies could compare the short- and long-term adaptive capacity of social-ecological systems that receive social and material resources (e.g., technology, labor, money, etc.) from both adjacent and distant systems to that of systems that only receive resources from either adjacent or distant systems.

A sole focus on social networks analysis by articles in my literature search reflects a conceptual research gap in the broader literature. Traditionally, most research has considered social and ecological systems separately and has not explicitly accounted for interrelationships between people and the environment (Rosa and Dietz 1998). Significant progress has been made in the last decade to integrate social-ecological systems through the development of concepts, theory, and practice (e.g., Liu et al. 2007; Bodin and Tengo, 2012; Liu et al. 2013). More research employing social-ecological networks analysis would contribute to bridging this conceptual gap and help advance systems science and sustainability research.

1.4.2 Number of systems and geographic scales

Nearly three-quarters (72%) of the articles were limited to a single system (Fig. 1.2B), and many were case studies. About one-quarter of articles (24%) addressed multiple systems, but only 4% of studies involved multiple, interacting systems (Fig. 1.2B). Studies involving multiple systems mostly did so for the purpose of comparison, rather than studying their interactions (e.g., Juhola and Westerhoff 2011; Ingold and Balsiger 2015; Jha et al. 2016). For example, Juhola and Westerhoff (2011) compared the governance of adaptation between two countries that differed in their current stage of adaptation. There were only three studies that examined interactions between actors belonging to multiple systems.

Most articles (84%) presented studies conducted at the subnational scale (Fig. 1.2C). About a handful (8%) were conducted at the national level, and one study was conducted at the international level (4%). There was also only one study (4%) that assessed social networks across multiple, interacting geographic scales. (Fig. 1.2C) In that study, Ingold and Pflieger (2017) examined the extent to which individual social actors were involved in both the national and international climate change adaptation policy spheres.

Current applications of social-ecological network analysis largely do not study multiple systems interacting across geographic scales (subnational, national, international) and distances (local, adjacent, distant). This may reflect a research gap in which studies are not examining existing interactions between social-ecological systems, or may reflect the reality that there are few cases of adaptation in which systems for coordination among multiple systems are set up before disaster strikes. One exception to this is the coordination in wildfire response within and among the United States, Australia and New Zealand. The three countries have been exchanging firefighting resources for over 15 years (NIFC 2020). This is possible through the U.S. Wildfire Suppression Assistance Act and aid agreements between the three countries. Similar command structures, training, and physical requirements among the countries allow firefighters from New Zealand and Australia to easily adapt to firefighting in the United States, and vice versa.

Additionally, the fire season in the United States occurs at a different time than the fire season in Australia and New Zealand, allowing the countries to concentrate firefighting resources in one region at a time.

Adapting to the intensifying impacts of climate change will require greater coordination across subnational, national, and international scales like in the example provided above. Network analysis studies that integrate social and ecological systems across multiple geographic scales would contribute greatly to understanding how the structure and dynamics of complex social-ecological systems can constrain or facilitate adaptation to climate change and highlight opportunities to improve adaptation outcomes.

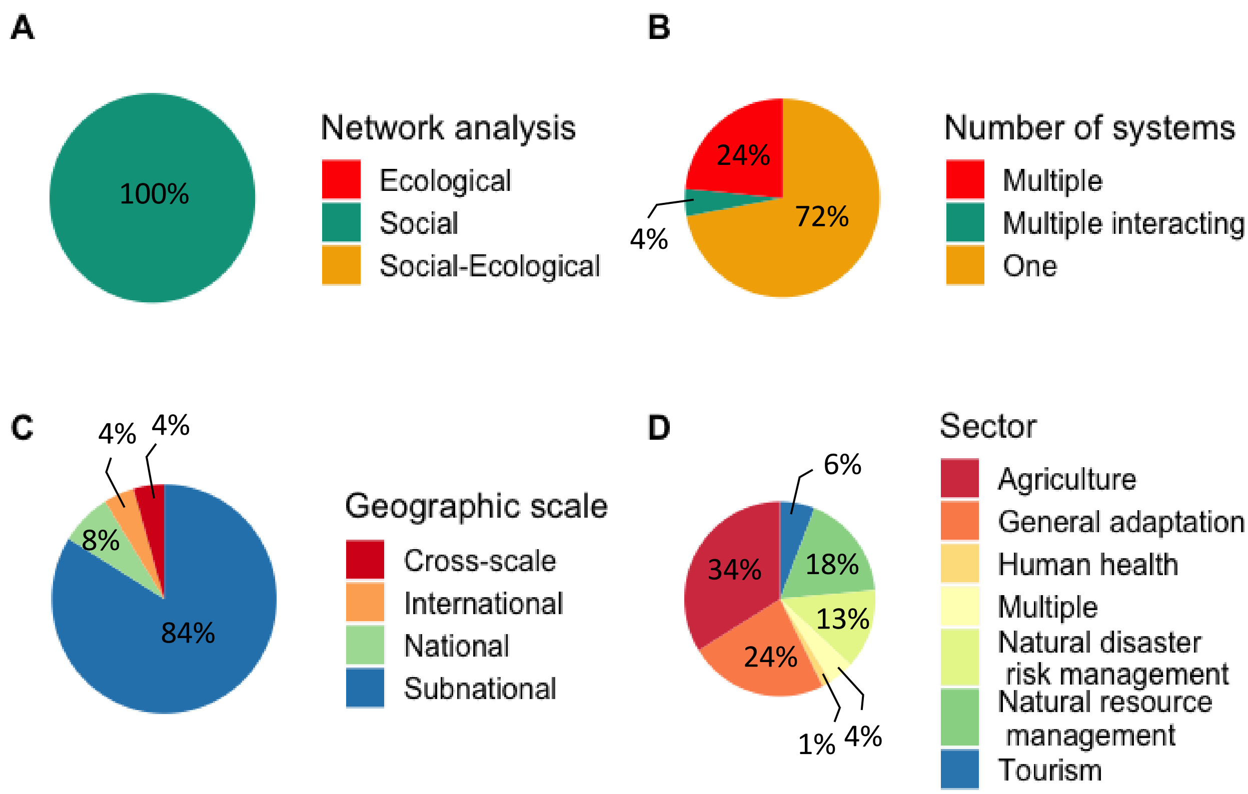

Figure 1.2 Categorization of studies evaluated in the literature review based on four criteria. Studies were characterized by (A) type of network analysis, (B) number of systems, (C) geographic scale, and (D) adaptation sector.

1.4.3 Sectors

Sixteen (24%) articles did not specify a sector (addressed general adaptation). The three most common sectors addressed among studies specifying a sector were agriculture (34%), natural resource management (18%), and natural disaster risk management (13%) (Fig 1.2D). Other, less common sectors included tourism (6%) and human health (1%). One study (4%) focused equally on multiple sectors. Agriculture was the most common sector overall and within both the peer-reviewed and grey literature. Half (48%) of the grey articles focused on agriculture and many were associated with national governments or research centers (e.g., German Federal Ministry for Economic Cooperation and Development) or international organizations (e.g., Consultative Group for International Agricultural Research), illustrating that social network analysis is already being used to inform adaptation practice. Reasons for this may be because agriculture is on the front lines of climate change and is directly tied to human health and wellbeing, and because social networks (e.g., seed exchange, knowledge transfer, human labor, micro-loans) are vital to subsistence farming. Meanwhile, nearly a third (27%) of the peer-reviewed literature addressed agriculture, followed closely by articles on natural resource management (22%). The understudied sectors such as tourism and human health, as well as sectors that were absent from the literature such as and energy, infrastructure, and biodiversity could benefit from more research.

1.4.4 Study objectives

Generally, the main objective of studies was to use social network analysis to understand how social network structure constrained or facilitated adaptation (e.g., La Jeunesse et al. 2015; Mikhail et al 2010; Juhola and Westerhoff 2011). Measures of network centrality, density, cohesiveness, and clustering were among the most commonly examined for their role in mediating exchanges of knowledge, information, and other resources (e.g., monetary) among social actors (e.g., Kettle et al. 2017; Fatorelli and Di Gregorio 2016). Studies also identified and described the role of actors who shared a relatively high number of interactions with other actors (central actors) (e.g., Cunningham et al. 2016), actors who connected different subgroups (bridging actors) (e.g., Horning et al. 2016, Kettle et al. 2017), and actors who were key to resource dissemination and motivating other actors to adopt certain behaviors (opinion leaders) (e.g., Joseph et al. 2016). Studies commonly sought to determine the level of horizontal integration (interaction between different stakeholders within a governance level) and vertical integration (interaction across governance levels) in governance networks (e.g., Russell 2015; Ingold et al. 2014). Roles of informal and formal networks in disseminating climate change information and building adaptive capacity were compared and contrasted (e.g., Cunningham et al. 2016; Ingold et al. 2010). Formal networks often involve policymakers, government officials and NGOs, while informal networks are comprised of friends, family, and neighbors.

Current network research provides initial insights into how different social network structures may influence adaptation. For example, horizonal and vertical integration of governance levels as well as highly dense networks facilitate adaptation by increasing collaboration, communication, and trust between diverse stakeholders (Schmitt et al. 2013; Frey et al. 2018). Bridging actors who connect actors between subgroups play an important role in adaptation by improving information dissemination (Cunningham et al. 2016). In contrast, centralized networks in which most of the linkages are formed around a few key actors, and networks with low density can pose an obstacle to collective action and hinder the diffusion of information and resources, leading to low adaptive capacity (Schmitt et al. 2013; Horning et al. 2016).

Network research on climate adaptation would benefit from expanding beyond analyses primarily focused on network structure. Most studies aimed to use social network analysis to understand how the structure of social networks facilitated or constrained adaptation. While this is useful for identifying structural patterns associated with different adaptation outcomes, statistical network models using longitudinal data can demonstrate the causal effect of network structure and interactions between network actors or components on adaptation. Future studies could use existing tools in social network analysis such as selection models (e.g., Frank and Yasumoto 1998; Spillane et al. 2012; Frank et al. 2013) and influence models (Frank and Fahrbach 1999; Friedkin 2002) to test and quantify the causal effect of network structure and interactions on different adaptation processes and outcomes. Both types of models are based on regression analysis. Specifically, selection models could be used to quantitatively determine how social actor characteristics (e.g., relative expertise, network location, gender, age) influence network interactions (e.g., frequency of interactions, kinds of flows exchanged in interactions, reciprocity, etc.), while influence models can quantify how interactions among social actors influence the behavior of individuals. For example, a selection model could determine whether two farmers are more likely to exchange seeds if they are of the same gender and have different seed varieties and levels of adaptive capacity. Such studies would lend greater support for inferences about causes and effects in network dynamics and their roles in shaping adaptation.

1.4.5 Network interventions

Studies frequently identified the strengths and weaknesses of network structures, followed by proposals for network intervention and implications for adaptation (e.g. Schmitt et a. 2013; Dowd et al. 2014). Commonly proposed network interventions included targeting central and bridging actors in outreach efforts to facilitate rapid dissemination of climate change information (e.g., Schmitt et al. 2013; Horning et al. 2016; Aberman et al. 2011a, 2011b), engaging a diverse set of actors (indigenous peoples, NGOs, government officials, businesses) for more inclusive and effective adaptation implementation (e.g., Mikhail et al. 2010; Somda et al. 2016); building greater vertical and horizonal integration in adaptation governance (i.e., coordinating across local to global levels, and coordinating among multiple governance entities within a level) (e.g., Somda et al. 2016); and filling in missing network links by connecting actors who were previously unconnected (e.g., Abid et al. 2017). However, none of the reviewed studies actually implemented the proposed network interventions. Future studies to evaluate the effectiveness and consequences of network interventions for climate adaptation would greatly facilitate practitioners who wish to leverage network analysis. Such studies would also help demonstrate the utility of network analysis for adaptation, potentially garnering renewed interest in this topic.

1.4.6 Limitations

This literature search faces a few limitations. First, some relevant studies may have been overlooked because databases index a limited number of journals and publishers. To address this limitation, I used some of the most comprehensive databases for my literature search. I used Scopus and Web of Science for peer-reviewed articles and Google Scholar and OAlster for grey articles. Scopus covers journals in the life sciences, social sciences, physical sciences, and health sciences, and Web of Science has similar coverage, including cross-disciplinary research. Google Scholar is considered an important source for grey literature (Haddaway et al. 2015; Hagstrom et al. 2015). However, because Google Scholar is not comprehensive (e.g., Gehanno et al. 2013; Bramer et al. 2013), it should not be the only source used for a review of grey literature (Gehanno et al. 2013; Bramer et al. 2013; Haddaway et al. 2015; Bramer et al. 2016). I therefore also used OAlster to search for grey literature, which catalogues millions of open access collections worldwide. I acknowledge that there may still be some articles that were overlooked, but this likely does not impact my conclusions in the following section regarding conceptual gaps in the literature. Second, this literature search is also limited to articles written in English, which may have excluded some otherwise relevant studies.

Further, my literature search may have overlooked studies that performed network analysis but did not refer to it using that specific term. For example, Albert et al. (2017) calculated different network metrics including betweenness centrality and density in their assessment of habitat connectivity for multiple species under different climate change and land use scenarios. But because the study did not mention the term "network analysis," it did not show up in any of the searches in this literature review. My conclusions therefore apply only to studies in which the authors specified they performed "network analysis."

Due to feasibility and time constraints on how many publications I could review, I opted to use "network analysis" instead of just "network" in the search terms. This limited the returned papers to the most relevant ones.

My literature search returned no studies applying ecological network analysis or socio-ecological network analysis in the context of climate change adaptation. To ensure that this was not due to the choice of the search terms, I performed a subsequent search in Web of Science and Scopus using the phrases "climate change adapt*" and "ecological network" instead of "network analysis." Between the two databases, there were nine unique articles returned. However, the articles did not match all of the criteria for inclusion in my literature search. For example, some studies discussed ecological networks but did not perform network analysis and/or were not about climate change adaptation (e.g., Bellard et al. 2014; Synes et al. 2015). A quick scan of articles from a search in Google Scholar using these same phrases indicated similar results. Using the phrases “climate change adapt*” and “socio-ecological network analysis” or “social ecological network,” and variations of these phrases using the word “environmental” instead of “ecological” did not return any articles from both databases. A quick scan of articles from a Google Scholar search using these phrases did not reveal any relevant articles.

1.5 Conclusion

The literature applying network analysis in the context of climate change adaptation is very limited both in number and scope. Studies focus solely on social networks, with no studies using ecological network analysis or social-ecological network analysis. Further, the majority of studies were performed on a single system at the subnational scale, with only a few studies examining multiple, interacting systems across different geographic scales. A framework that allows for examining the components and dynamics of social-ecological systems interacting across geographic scales is needed to guide network analysis research in climate change adaptation.

LITERATURE CITED

LITERATURE CITED

Aberman, N., Alemu, T., Birner, R., and Haglund, E. 2011a. A Stakeholder Map for Climate Change Adaptation in Ethiopia's Agriculture Sector.

Aberman, N., Birner, R., and Ali, S. 2011b. A Stakeholder Map for Climate Change Adaptation in Bangledesh’s Agriculture Sector.

Abid, M., Ngaruiya, G., Scheffran, J., Zulfiqar, F. 2017. The role of social networks in agricultural adaptation to climate change: implications for sustainable agriculture in Pakistan. *Climate*, 5(4):85.

Adger, W.N. 2003. Social capital, collective action, and adaptation to climate change. *Economic Geography*, 79(4):387–404.

Adger, W.N., S. Agrawala, M.M.Q. Mirza, C. Conde, K. O’Brien, J. Pulhin, R. Pulwart, B. Smit, and K. Takahashi. 2007. Assessment of adaptation practices, options, constraints and capacity. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 717-743.

Albert, C.H., Rayfield, B., Dumitru, M., and Gonzalex, A. 2017. Applying network theory to prioritize multispecies habitat networks that are robust to climate and land-use change. *Conservation Biology*, 31(6):1383-1396.

Bellard, C., Leclerc, C., Leroy, B., Bakkenes, M., Veloz, S., Thuiller, W., and Courchamp, F. 2014. Vulnerability of biodiversity hotspots to global change. *Global Ecology and Biogeography*, 23(12):1376-1386.

Biesbroek, R., Berrang-Ford, L., Ford, J.D., Tanabe, A., Austin, S.E., and Lesnikowski, A. 2018. Data, concepts and methods for large-*n* comparative climate change adaptation policy research: A systematic literature review. *WIREs Climate Change*, 9:e548.

Bodin, O. and Tengo, M. 2012. Disentangling intangible social-ecological systems. *Global Environmental Change,* 22(2):430-439.

Bramer, W. M., Giustini, D. and Kramer, B.M.R. 2016. Comparing the coverage, recall, and precision of searches for 120 systematic reviews in Embase, MEDLINE, and Google Scholar: a prospective study. *Systematic Reviews,* 5:39.

Bramer, W.M., Giustini, D., Kramer, B.M.R., and Anderson, P.F. 2013. The comparative recall of Google Scholar versus PubMed in identical search for biomedical systematic reviews: a review of searches used in systematic reviews. *Systematic Reviews,* 2(115).

Chen, I.-C., Hill, J.K., Ohlemuller, R., Roy, D.B., and Thomas, C.D. 2011. Rapid Range Shifts of Species Associated with High Levels of Climate Warming. *Science,* 333(6045):1024-1026.

Cumming, G.S., Bodin, O., Ernstson, H., and Elmqvist. 2010. Network analysis in conservation biogeography: challenges and opportunities. *Diversity and Distributions,* 16(3):414-425.

Cunningham, R., Cvitanovic, C., Measham, T., Jacobs, B., Dowd, A.-M., and Harman, B. 2016. Engaging communities in climate adaptation: the potential of social networks. *Climate Policy,* 16(7):894-908.

Dowd, A.-M., Marshall, N., Fleming, A., Jakku, E., Gaillard, E., and Howden, M. 2014. The role of networks in transforming Australian agriculture. *Nature Climate Change,* 4:558-563.

Dunne, Jennifer A. The network structure of food webs. In: Ecological Networks: Linking Structure to Dynamics in Food Webs. Edited by M. P, Dunne JA. Oxford: Oxford University Press. 27-86.

Dupuis, J. and Biesbroek, R. 2013. Comparing apples and oranges: The dependent variable problem in comparing and evaluating climate change adaptation politics. *Global Environmental Change,* 23(6):1476-1487.

Fatorelli, L. and Di Gregorio, M. 2016. Policy Actor's Discourses and Interactions Coalitions on the Climate Mitigation and Adaptation Domains -- A Brazilian Case Study.

Frank, K.A. and Fahrbach, K. 1999. Organizational Culture as a Complex System: Balance and Information in Models of Influence and Selection. Special Issue of *Organization Science on Chaos and Complexity*, 10(3):253-277.

Frank, K.A., Muller, C., and Mueller, A.S. 2013. The Embeddedness of Adolescent Friendship Nominations: The Formation of Social Capital in Emergent Network Structures. *American Journal of Sociology,* 119(1):216-253.

Frank, K.A. and Yasumoto, J.Y. 1989 Linking Action to Social Structure within a System: Social Capital within and between Subgroups. *American Journal of Sociology,* 104(3):642-686.

Frey, K. and Ramirez, D.R.C. 2018. Multi-level network governance of disaster risks: the case of the Metropolitan Region of the Aburra Valley (Medellin, Colombia). *Journal of Environmental Planning and Management,* 62(3):424-445.

Friedkin, N. 2002. Social Influence Network Theory: Toward a Science of Strategic Modification of Interpersonal Influence Systems. In National Academy Press: Dynamics Social Network Modeling and Analysis: Workshop Summary and Papers.

Gehanno, J.F., Rollin, L., and Darmoni, S. 2013. Is the coverage of Google Scholar enough to be used alone for systematic reviews. *BMC Medical Informatics and Decision Making,* 13(7).

Groce, J.E., Farrelly, M.A., Jorgensen, B.S., and Cook, C.N. 2019. Using social-network research to improve outcomes in natural resource management. *Conservation Biology,* 33(1):53-65.

Haddaway, N.R., Collins, A.M., Coughlin, D., Kirk,S. 2015. The role of Google Scholar in evidence reviews and its applicability to grey literature searching. *PLoS ONE,* 10(9):e0138237.

Hagstrom, C., Kendall, S., and Cunningham, H. 2015. Googling for grey: Using Google and Duckduckgo to find grey literature. In *Abstracts of the 23rd Cochrane Colloquium. Cochrane database systematic reviews supplements*, 1-327.

Havlin, S., Kennett, D.Y., Ben-Jacob, E., Bunde, A., Cohen, R., Hermann, H. 2012. Challenges in network science: applications to infrastructures, climate, social systems and economics. *European Physical Journal Special Topics*, 214**:**273–293.

Horn, S., de la Vega, C., Asmus, R., Schwemmer, P., Enners, L., Garthe, S., Binder, K., Asmus, H. 2017. Interaction between birds and macrofaunal within food webs of six intertidal habitats of the Wadden Sea. *PLoS ONE,* 12(5):e0176381.

Horning, D., Bauer, B.O., and Cohen, S.J. 2016. Missing bridges: Social network (dis)connectivity in water governance. *Utilities Policy*, 43(A): 59-70.

Ingold, K., Balsiger, J., and Hirschi, C. 2010. Climate change in mountain regions: how local communities adapt to extreme events. *The International Journal of Justice and Sustainability,* 15(7):651-661.

Ingold, K. and Balsiger, J. 2015. Sustainability principles put into practice: case studies of network analysis in Swiss climate change adaptation. *Regional Environmental Change,* 15(3):529-538.

Ingold, K. and Pfleiger, G. 2017. Two Levels, Two Strategies: Explaining the Gap Between Swiss Nationand International Responses Toward Climate Change. *European Policy Analysis,* 2(1):20-38.

Ings, T.C. et al. 2009. Ecological network—beyond food webs. *Journal of Animal Ecology,* 78: 253–269.

IPBES. 2019. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science- Policy Platform on Biodiversity and Ecosystem Services. E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo (editors). IPBES Secretariat, Bonn, Germany.

Juhola, S. and Westerhoff, L. 2011. Challenges of adaptation to climate change across multiple scales: a case study of network governance in two European countries. *Environmental Science & Policy,* 14(3): 239-247.

Janssen, M.A., Bodin, O., Anderies, J.M., Elmqvist, T., Ernston, H., McAllister, R.R.J., Olsson, P., and Ryan, P. 2006. Toward a Network Perspective of the Study of Resilience in Social-Ecological Systems. *Ecology and Society,* 11(1):15.

Jha, Y., Welch, E., Ogwal-Omara, R., Halewood, M. 2016. How are the meso-level expert organizations connected to farmers and among themselves? Comparing Rakai (Uganda) and Lushoto (Tanzania). CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

Joseph, O., Fred, M., Philip, N., William, O., and Gerald, M. 2016. Applying social network analysis, centrality measures in identification of climate change adaptation opinion leaders. *International Journal of Agricultural Research, Innovation and Technology*, *6*(1):1-7.

Kettle, N.P., Trainor, S.F., Loring, P.A. 2017. Conceptualizing the Science-Practice Interface: Lessons from a Collaborative Network on the Front-Line of Climate Change. *Frontiers in Environmental Science,* 5(33).

Klein, Richard J. T., Guy F. Midgley, Benjamin L. Preston, Mozaharul Alam, Frans G. H. Berkhout, Kirstin Dow, and M. Rebecca Shaw. 2014. 'Adaptation opportunities, constraints, and limits', in C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, UK and New York: Cambridge University Press, pp. 899-943.

La Jeunesse, I., Cirelli, C., Sellami, H., Aubin, D., Deidda, R., and Baghdadi, N. 2015. Is the governance of the Thau coastal lagoon read to face climate change impacts? *Ocean and Coastal Management,* 118: 234-246.

Liu, J., Dietz, T., Carpenter, S.R., Alberti, M., Folke, C., Moran, E., Pell, A.N., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C.L., Schneider, S.H., and Taylor, W.W. 2007. Complexity of Coupled Human and Natural Systems. *Science,* 317(5844):1513-1516.

Liu, J., Hull, V., Batistella, M., DeFries, R., Dietz, T., Fu, F., Hertel, T.W., Izaurralde, R.C., Lambin, E.F., Li, S., Martinelli, L.A., McConnell, W.J., Moran, E.F., Naylor, R., Ouyang, Z., Polenske, K.R., Reenberg, A., de Miranda Rocha, G., Simmons, C.S., Verburg, P.H., Vitousek, P.M., Zhang, F., and Zhu, C. 2013. Framing Sustainability in a Telecoupled World. *Ecology and Society*, 18(2): 26.

Mikhail, M., Fenci, A., Naruchaikusol, S., and Kemp-Benedict, E. 2010. Innovation and diffusion of sustainable agriculture water resource management in a changing climate: A case study in Northeast Thailand. Stockholm Environment Institute. Research Report.

Moher, D., Liberati, A, Tetzlaff, J., and Altman, D.G. 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Research Methods & Reporting*, 339:b2535.

Moser, S.C. and Ekstrom, J.A. 2010. A framework to diagnose barriers to climate change adaptation. *Proceedings of the National Academy of Sciences,* 107(51): 22026-22031.

National Interagency Fire Center (NIFC). 2020. “International Support in Wildland Fire Suppression.” Accessed 08 Jul 2020.

Norberg, J. and Cumming, G. 2008. Complexity theory for a sustainable future. (New York: Columbia University Press).

Otieno G, Lacasse H, Fadda C, Reynolds TW, Recha JW. 2018. Social Seed Networks for Climate Change Adaptation in Western Kenya. CCAFS Info note. Wageningen, Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

Rosa, E.A. and Dietz, T. 1998. Climate Change and Society: Speculation, Construction and Scientific Investigation. *International Sociology*, 13:421.

Russell, J. 2015. Complex Climate Change Adaptation Network in Bhutan; How Actor Type Impacts Actor Inclusion and Clustering. Thesis. University of Bern, Switzerland.

Scheffer, M., Carpenter, S., Foley, J.A., Folke, C., and Walker, B. 2001. Catastrophic shifts in ecosystems. *Nature*, 413:591-596.

Schmitt, E., Comoe, H., and Barjolle, D. 2013. Social Networks Analysis of the Ivorian Agricultural Sector Regarding Adaptation to Climate Change. *Journal of Socio-Economics in Agriculture* (Until 2015: Yearbook of Socioeconomics in Agriculture), 6(1):81-108.

Schleuning, M. et al. 2016. Ecological networks are more sensitive to plant than to animal extinction under climate change. *Nature Communications*, 7:13965.

Seneviratne, S. I., Nicholls, N., Easterling, D., Goodess, C. M., Kanae, S., Kossin, J., ... Zwiers, F. W. 2012. Changes in climate extremes and their impacts on the natural physical environment. In *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change* (Vol. 9781107025066, pp. 109-230). Cambridge University Press.

Somda, J., Zougmore, R., Sawadogo, I., Bationo, B.A., Partey, S.T. 2016. Setting partnership for climate change adaptation in the CCAFS Yatenga site, Burkina Faso: Analysis of gaps and opportunities. CGIAR Research Program on Climate Change, Agriculture and Food Security.

Spillane, J.P., Kim, C.M., and Frank, K.A. 2012. Instructional Advice and Information Providing and Receiving Behavior in Elementary Schools: Exploring Tie Formation as a Building Block in Social Capital Development. *American Educational Research Journal,* 49(6): 1112-1145.

Synes, N.W., Watts, K., Palmer, S.C.F., Bocedi, G., Barton, K.A., Osborne, P.E., and Travis, J.M.J. 2015. A multi-species modeling approach to examine the impact of alternative climate change adaptation strategies on range shifting ability of a fragmented landscape. *Ecological Informatics*, 30:222-229.

Wasserman, S. and Faust, K. 1994. Social network analysis: Methods and applications. New York: Cambridge Press.

Wulff, F., Field, J.G., Mann, K.H. (eds). 1989. Flow Analysis of Marine Ecosystems. Springer-Verlag, Berlin, p. 284.

Zebrowski, W.M., Lacasse, H.K., Otieno, G., Reynolds, T.W., LaValle, N., Baker-Wacks, E., and Klein, E. 2018. Social seed networks and climate change adaptation in East Africa. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

CHAPTER 2:

INTRODUCING THE METACOUPLED NETWORK APPROACH

2.1 Abstract

Network analysis conceptualizes a system and its interacting components as a network with nodes connected to each other by edges. Researchers and practitioners highlight its potential as a powerful tool for addressing social-ecological challenges such as climate change adaptation, but published network analysis studies on climate change adaptation focus only on social networks (as opposed to ecological networks or social-ecological networks) and are largely limited to analyzing a single network at one locality. Successfully adapting to climate change often requires an understanding of how multiple social-ecological systems interact with each other both nearby and faraway (e.g., trade, human and wildlife migration, adaptation funding). To address this research gap, I introduced the metacoupled network approach, which combines the metacoupling framework with network analysis. The metacoupling framework integrates multiple interacting social-ecological systems and helps to systematically define systems and their components (agents, flows, effects, causes), while network analysis conceptualizes systems as networks and provides methodology to quantify their structure and dynamics. I then identified potentially fruitful climate change adaptation research directions for studies aiming to apply the metacoupled network approach and demonstrate its application.

2.2 Introduction

The literature discusses the potential of network analysis to contribute to understanding the interrelationships in complex systems and facilitate more integrated research and policymaking for climate change adaptation (e.g., Ingold et al. 2010), but existing studies largely do not integrate social-ecological systems. There are no studies that simultaneously examine social-ecological interdependencies within and between two or more neighboring or distant systems in the context of climate change adaptation. I help to address these research gaps by developing the metacoupled network approach through combining the metacoupling framework with network analysis.

2.3 The Metacoupled Network Approach

The metacoupling framework developed by Liu (2017) is used to systematically describe interactions within and among local, adjacent, and distant coupled humans and natural systems.[1] It is an expansion of the telecoupling framework (Liu et al. 2013), which was developed to integrate multiple, distant, interacting social-ecological systems (the metacoupling framework is more comprehensive because it also considers *adjacent* systems). By allowing for systematically describing social-ecological systems and their components (agents, flows, causes, and effects), the metacoupling framework fosters a more holistic understanding of complex challenges in human wellbeing and environmental sustainability. The systems and components individual to each study depend on variables such as data availability, scientific significance, researchers'

[1] The term "coupled humans and natural systems" is more inclusive of different types of interactions than the term "social-ecological systems." In addition to social and ecological interactions, coupled human natural systems considers all kinds of other human-nature interactions such as political and socioeconomic interactions. I use the term "social-ecological systems" throughout to be consistent with the established network analysis literature, but consider all kinds of human-nature interactions in using this term.

interest, and available time and resources. (Liu 2017) Due to the framework's flexibility, it can be applied to many different study contexts.

The integration of social and ecological systems remains a key challenge for network analysis research in fields such as conservation biology and natural resource management (e.g., Cumming et al. 2010). Most network analysis studies focus on one type of system (social or ecological) within one geographic location. Social-ecological network analysis has recently been developed to help address this challenge (e.g., Baggio et al. 2016; Sayles and Baggio 2017; Sayles et al. 2019), but studies applying it have only focused on a single system in one geographic context and do not explicitly differentiate the causes and effects of systems interacting nearby from that of systems interacting distantly. To fill these research and conceptual gaps, the metacoupling framework can be applied to social-ecological network analysis to achieve a more integrated and holistic network analysis approach than established network analysis frameworks (Table 2.1).

Table 2.1 Comparison of traits between different network analysis frameworks.

Traits	*Social Network Analysis*	*Ecological Network Analysis*	*Social-ecological Network Analysis*	*Metacoupled Network Approach*
Scope	Social network structure and dynamics	Ecological network structure and dynamics	Social-ecological network structure and dynamics	Social-ecological network structure, dynamics, and interactions between multiple social-ecological networks
Number of systems	Typically a single system, or comparative study of multiple systems	Typically a single system	Typically a single system	Multiple interacting systems (e.g., receiving, sending, and spillover systems)

Table 2.1 (cont'd)

Traits	*Social Network Analysis*	*Ecological Network Analysis*	*Social-ecological Network Analysis*	*Metacoupled Network Approach*
Geographic scale (subnational, national, international, cross-scale)	Typically one geographic scale	Typically one geographic scale	Typically one geographic scale	Cross-scale, with systems interacting nearby and faraway
Agents/Nodes	Individuals or groups of people, organizations	Species, organisms, populations, ecologically connected areas	Social and ecological agents/nodes	Social and ecological agents/nodes
Flows between systems and subsystems	Finance, knowledge, information, technology	Energy, materials, species, DNA	Social and ecological flows, within and between social and ecological systems (e.g., natural resources, ecosystems services)	Social and ecological flows, within and between social and ecological systems nearby and faraway (e.g., trade commodities)
Causes for flows	Homophily, knowledge exchange	Parasitism, predator-prey, symbiosis, mutualism, reproduction	Social, ecological, and social-ecological causes e.g., support human livelihoods	Global social, ecological, and socio-ecological causes, e.g., globalization, international trade
Effects of flows	Learning, collaboration, communication, social capital, trust	Cascading effects, trophic levels, evolution, extinction	Social, ecological, and social-ecological effects, e.g., (un)sustainable natural resource management	Global social, ecological, and socio-ecological effects, e.g., climate change, spillover effects, displacement of social-ecological burdens
Research examples	Bodin and Crona 2008; Prell et al. 2009; Primmer 2011; Garcia-Amada et al. 2012	Schuckel et al. 2015; Schleuning et al. 2016; Creamer et al. 2016	Janssen et al. 2006; Bodin & Tengo 2012; Baggio et al. 2016; Sayles and Baggio 2017	Schaffer-Smith et al. 2018

The metacoupled network approach I introduced (Fig. 2.1) accommodates multiple social-ecological networks interacting nearby and faraway. It provides a clear framework for systematically defining social-ecological systems and their components (agents, flows, causes, and effects), while using established methodology from different types of network analysis (social, ecological, social-ecological) to quantify system components. The following paragraphs explain in further detail each of the five components of the metacoupled network approach.

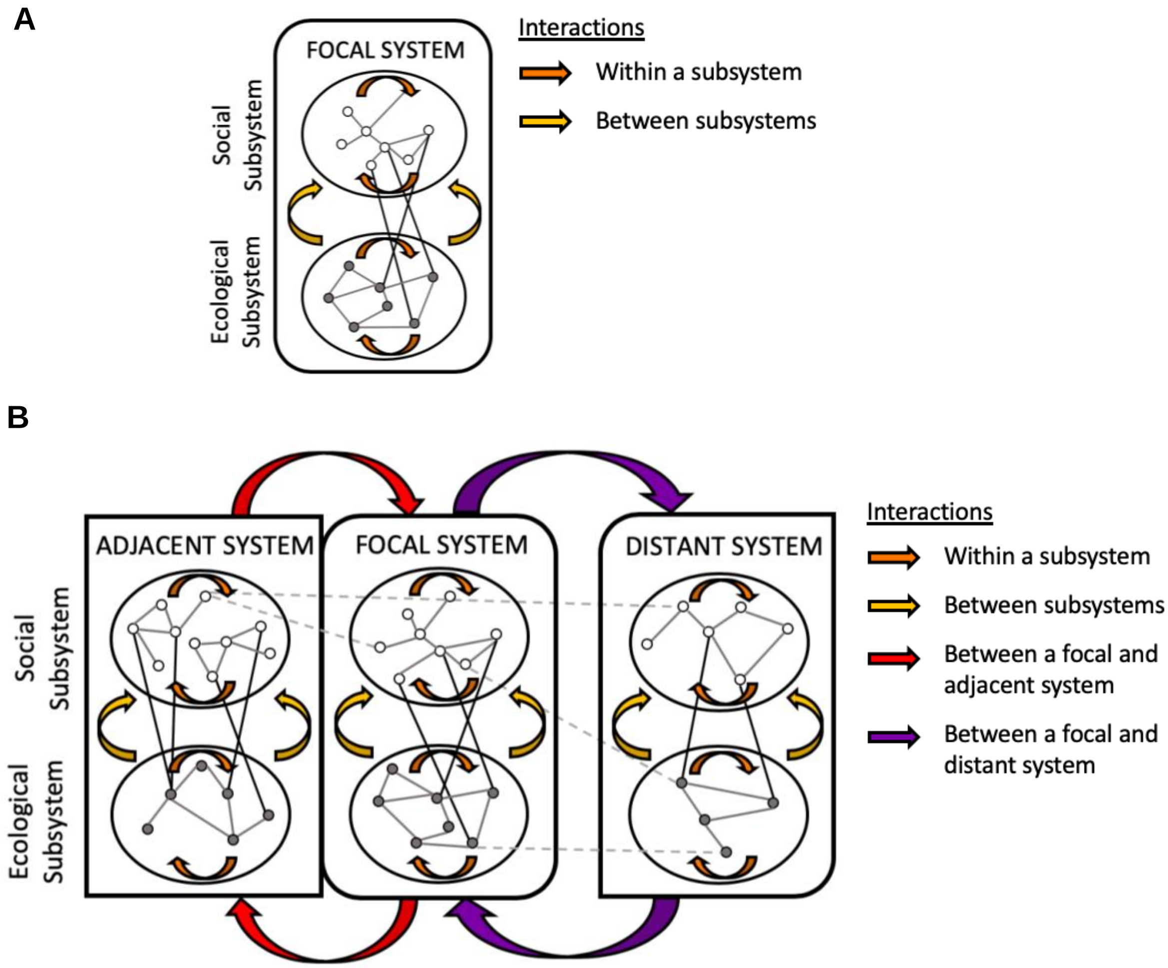

Figure 2.1 Schematic diagrams comparing the traditional social-ecological network analysis framework to the metacoupled network approach. (A) Traditional social-ecological network framework for studying interactions within a single social-ecological system. Arrows represent interactions within social and ecological subsystems (orange) and interactions between subsystems (yellow). (B) Social-ecological network analysis applied under the metacoupling framework, in which a focal system interacts with adjacent and distant social-ecological systems. Arrows represent interactions within social and ecological subsystems (orange), between subsystems (yellow), between a focal system and an adjacent system (red), and between a focal system and a distant system (purple).

2.3.1 Systems

The metacoupled network approach can accommodate multiple interacting systems, which can be further labeled as sending, receiving, and spillover systems depending on the direction and effects of flows. A sending system is a system from which flows originate, and a receiving system is the recipient of flows coming from the sending system. A spillover system is indirectly impacted by flows traveling between a sending and receiving system. An example of this are the regions affected by migratory birds. In summer, many birds (flows) migrate north to their breeding grounds (receiving system) from their more southern non-breeding habitat (sending system). Along the way, they many have many stopover points (spillover systems) for resting and feeding. In winter when the birds migrate south again, the direction of the flows is reversed, and the sending system becomes the receiving system, and the receiving system becomes the sending system. As demonstrated, these labels change when the direction of flows changes or when flows begin or cease. Although the labels may seem arbitrary because they are impermanent, they can help researchers be aware of when and how system dynamics change, and how these changes may shift social-ecological dynamics within and among the different kinds of systems.

2.3.2 Agents

In the metacoupled network approach, social agents such as individuals, groups of people, or organizations can be represented by network nodes, as in social networks analysis. Ecological agents such as non-human species, organisms, and populations can also be represented by network nodes, as in ecological network analysis. Agents mediate the flows between and among systems. They can interact within their respective social or ecological subsystem, between subsystems through social-ecological interactions, and between adjacent and/or distant social-ecological systems. How agents mediate flows is influenced by various social, ecological, and social-ecological causes and effects.

2.3.3 Flows

Flows are mediated by agents interacting with each other within and among different systems and represent different kinds of social, ecological, and social-ecological interactions. Social flows, or flows within and between social subsystems and systems, might include finance, knowledge, information, and technology, whereas ecological flows, or flows within and among ecological subsystems and systems, can be energy, nutrients, and species. Natural resources, ecosystem services, and pollution are some examples of social-ecological flows between social and ecological subsystems and systems. In some cases, agents can simultaneously be represented as flows such as in the case of migrating people and wildlife.

2.3.4 Causes

Common causes for social flows include homophily (the tendency of people to interact with those who are similar to them) (McPherson et al. 2001), inoculation (convincing someone to adopt a belief or practice), and the desire for knowledge, accountability, or affiliation (Contractor and DeChurch 2014). Interdependencies between organisms such as parasitism, predator-prey relationships, and symbiosis can create ties, or linkages. Social-ecological flows are often caused by the need for people to support their livelihoods by cultivating the land and managing natural resources. The metacoupled network approach considers all the aforementioned causes for interactions as well as causes for interactions that occur between faraway systems that may be otherwise overlooked. For example, globalization increasingly connects people and places across the globe through air travel, the Internet and social media, and international trade.

2.3.5 Effects

Similarly, the effects of flows that can be considered in the metacoupled network approach include those from traditional network analysis frameworks and those that differ in intensity or frequency as a result of the geographic distant between two agents or systems. Social flows often yield learning, social capital, and trust. Ecological flows can lead to cascading effects, energy transfer through trophic levels, and succession from one ecological community to another. Social-ecological flows can result in deforestation, restoration, biodiversity conservation, and climate change. The metacoupled network approach explicitly considers spillover effects whereby flows between a sending and receiving system indirectly influences a spillover system (e.g., migratory bird stopover, oil spill by tanker in transit) (Liu et al. 2013).

2.4 Applying the Metacoupled Network Approach

Some current cases of climate change adaptation involve multiple social-ecological systems interacting across geographic scales and distances. For example, during the wildfires in California in August 2018, firefighters came not only from across the state, but also from almost two dozen other states, Australia, and New Zealand. Local and adjacent regions also provided resources such as fire engines, bulldozers, and airplanes. (Cooper and Elias 2018) Resources from adjacent and distant regions strengthened the adaptive capacity of California in fighting wildfires. As another example, local adaptation is linked to the global arena through international adaptation funding efforts that support adaptation in communities across the globe including the United Nations Framework Convention on Climate Change's Adaptation Fund, Least Developed Countries Fund, and Green Climate Fund. Further, as habitats shift and no longer provide adequate resources for some species and populations, people and wildlife are adapting by migrating across political and geographic boundaries. They movement is linking systems in increasingly complex ways and leading to socioeconomic and environmental effects in origin and destination regions, as well as those through which migrants travel (Pecl et al. 2017; Rigaud et al. 2018).

Studies applying the metacoupled network approach would contribute to understanding how dynamics in complex social-ecological systems facilitate or constrain adaptation in a globalized world. They would generate new and timely research questions on important topics related to climate change adaptation (Table 2.2). For example, the metacoupled network approach can be applied to understand how coral translocation (intentional movement of a species by humans from one area to another) to help coral adapt to warming and increased acidity of ocean waters impacts social-ecological networks from the local to global level. Coral translocations may negatively impact the livelihoods of communities that were historically located near coral reefs and expose them to storm surges, but may lead to new ecotourism opportunities for recipient systems of the translocated coral. By applying the metacoupled network approach, researchers can identify all the relevant social actors and ecological components of the system and their interactions that would be impacted by coral translocation from a focal system to an adjacent system. Figure 2.2 illustrates how this can be done but is by no means inclusive of all the relevant, important systems components and interactions that may be considered in an actual network analysis study.

Table 2.2 Potentially fruitful climate change adaptation research topics and phenomena that can be systematically studied through a metacoupled network approach.

Potential topics	*Example metacoupled network phenomena*
Biodiversity conservation	Coral translocation (by people) from an area where the water temperature is too warm to sustain their symbiotic relationship with zooxanthellae to a distant region with cooler waters impacts the sending and receiving social-ecological systems differently. The livelihoods of communities

Table 2.2 (cont'd)

Potential topics	*Example metacoupled network phenomena*
	that were historically located near coral reefs could be negatively impacted due to a loss of fisheries and ecotourism, and increased exposure to storm surges. Communities near the coral's new location may benefit from ecotourism and erosion control.
Climate migration	People and wildlife may migrate to nearby places under local climate change impacts, but may need to migrate to distant places given more widespread climate impacts. To and from where they migrate depend on the social-ecological dynamics of the sending system relative to the receiving system.
Food security	Countries that largely depend on imported food may need to increase their domestic food production given climate change impacts (e.g., drought, flooding) abroad that limit food production in exporting countries, and vice versa.
Human health	Adapting to shifts in vector-borne diseases under climate change requires an understanding of vector-to-vector interactions (ecological network), person-to-person interactions (social network), and vector-to-person interactions (social-ecological network), as well as the movement of vectors and people across space and time in response to climate change (migration).
Natural disaster response	Adjacent countries tend to have similar resource levels than distant countries. Material and human resources from nearby systems to a focal system may lead to a fast response immediately after a natural disaster, but aid from a distant country with greater resource levels in terms of technology and finance may be necessary to build a focal system's long-term capacity to adapt to climate change.

Another example of adaptation topics that the metacoupled network approach could help to examine is how resource flows to a focal system from adjacent versus distant systems impact natural disaster response. Material and human resources flowing from nearby systems to a focal system may lead to a quick response immediately after a natural disaster, but aid from a distant country with greater capacities (technology, finance) may be necessary for long-term adaptation of the focal system. Traditional network analysis questions can provide a starting point for scholars and practitioners, but they should be considered in the context of more integrated questions to identify important systems and system components and dynamics that might otherwise be overlooked.

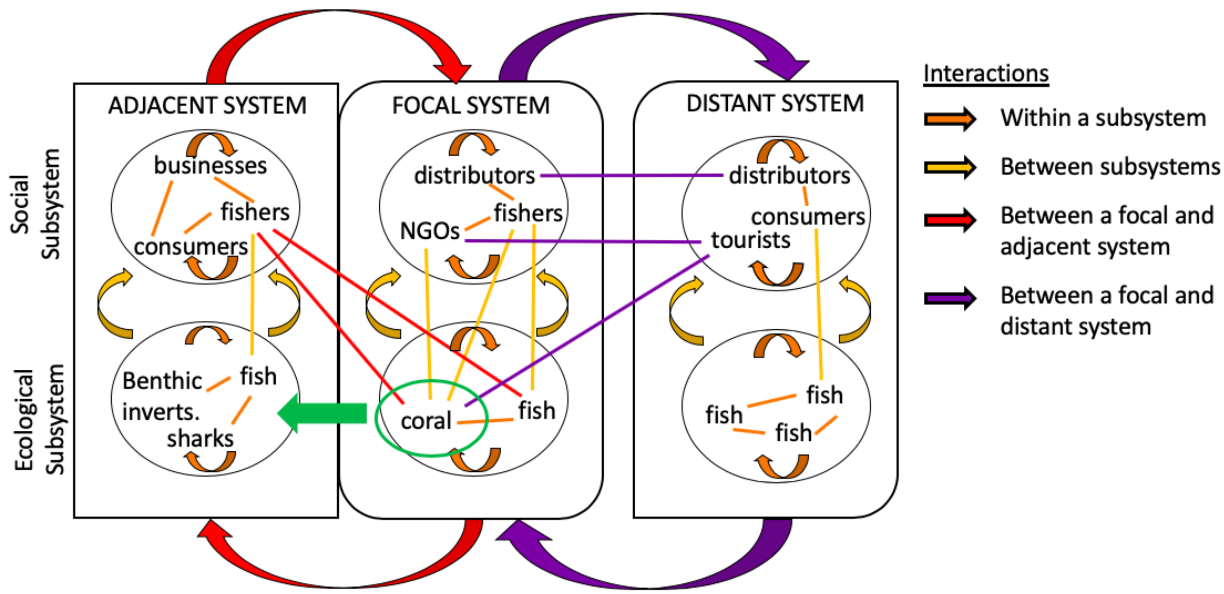

Figure 2.2 A demonstration of how the metacoupled network approach may be applied to delineate the relevant social actors, ecological components, and interactions in a metacoupled system centered around a coral reef. Each layer, or color, represents a different kind of interaction within or between subsystems and systems. The green arrow represents the translocation of coral from the focal system to an adjacent system that may be more suitable for corals.

The metacoupled network approach can help address challenges associated with the metacoupling framework before it was combined with network analysis. Among the most significant challenges of the metacoupling framework is operationalization and quantification (Kapsar et al. 2019). Several tools and approaches have been developed to facilitate operationalization and quantification including an ArcGIS Toolbox called the Telecoupling

Toolbox (Tonini and Liu 2017), which contains a suite of geoprocessing tools for integrating socioeconomic and environmental analysis of social-ecological systems across multiple scales, and the Telecoupling GeoApp (McCord et al. 2018), a web-GIS platform with mapping and analysis tools to study multiple interacting social-ecological systems. Although these tools have "telecoupling" in their names, they can easily be applied in the metacoupling framework to study adjacent and distant systems simultaneously.

Another major challenge with the metacoupling framework is attributing causality, which is critical for accurately assessing the consequences of metacoupled dynamics and for identifying intervention points to improve the governance and management of metacoupled systems (Carlson et al. 2018). Social network analysis and ecological network analysis borrows tools from many other fields for attributing causality including regression analysis, structural equation modeling, and experimental evidence (Mouw 2006; Bodin et al. 2019). Researchers can use these same tools to demonstrate causality in social and ecological networks when applying the metacoupled network approach, but attributing causality between social-ecological networks remains a challenge. Real-world phenomena in complex social-ecological systems can have multiple causal processes occurring simultaneously, and there is often a fine line between overly complex explanations and oversimplification (Bodin et al. 2019). There are also practical limitations in collecting quality longitudinal social and ecological network data. One way of strengthening causality attribution is to apply a variety of approaches and infer insights through multiple lines of evidence. Experimental evidence as well as simulation studies can also provide valuable contributions. (Bodin et al. 2019)

The metacoupled network approach can integrate bottom-up and top-down system processes. For example, influence models used in social network analysis to demonstrate causality are regression models that use longitudinal data. Most frequency, influence models take as independent variables data on an individual actor's *a* behavior at time *t*-1 and the behavior of actors who interacted with actor *a* between time *t* and time *t*-1, to determine their influence on actor's *a* behavior at time *t.* This kind of data represents bottom-up processes in which interactions at the individual level lead to emergent phenomena at the network level (e.g., school-wide adoption of computers as an educational tool by teachers as a result of teachers sharing their classroom pedagogy with each other). One can also include in the model independent variables that represent top-down forces that influence an actor's behavior, such as climate change (e.g., changes in air temperature and precipitation) or economic variables (e.g., changes in the price of gas).

2.5 Conclusion

The metacoupled network approach provides a framework to guide the study of complex social-ecological systems in a globalized world. It helps researchers to consider multiple systems interacting across geographic scales and distances and provides methodology to capture bottom-up as well as top-down processes in a network analysis framework. Its holistic approach encourages researchers to consider system components and interactions that are often overlooked as traditional frameworks primarily consider a single system within a geographic context. The approach can be used to guide the development of methodology and theory on how social-ecological interactions involving multiple systems lead to different consequences for human and non-human life. Applied to a wide range of contexts, the metacoupled network approach could make a valuable contribution to network analysis research and the broader fields of sustainability and systems science.

LITERATURE CITED

LITERATURE CITED

Baggio, J.A., BurnSilver, S.B., Arenas, A., Magdanz, J.S., Kofinas, G.P., and De Domenico, M. 2016. Multiplex social ecological network analysis revealshow social changes affect community robustness more than resource depletion. *Proceedings of the National Academy of Sciences*, 113(48):13708-13713.

Bodin, O., Alexander, S., Baggio, J., Barnes, M., Berardo, R., Cumming, G., Dee, L.E., Fischer, A.P., Fischer, M., Mancilla Garcia, M., Guerrero, A.M., Hileman, J., Ingold, K., Matous, P., Morrison, T.H., Nohrstedt, D., Pittman, J., and Sayles, J.S. 2019. Improving network approaches to the study of complex social–ecological interdependencies. *Nature Sustainability*, 2:551-559.

Bodin, O. and Crona, B.I. 2008. Management of Natural Resources at the Community Level: Exploring the Role of Social Capital and Leadership in a Rural Fishing Community. *World Development*, 36(12):2763-2779.

Bodin, O. and Tengo, M. 2012. Disentangling intangible social-ecological systems. *Global Environmental Change,* 22(2):430-439.

Carlson, A.K., Zaehringer, J.G., Garrett, R.D, Silva, R.F.B., Furumo, P.R., Rey, A.N.R., Torres, A., Chung, M., Li, Y., and Liu. J. 2018. Toward Rigorous Telecoupling Causal Attribution: A Systematic Review and Typology. *Sustainability,* 10(12):4426.

Contractor, N.S. and De Church, L.A. 2014. Integrating social networks and human social motives to achieve social influence at scale. *Proceedings of the National Academy of Sciences,* 111(Suppl 4):13650-13657.

Cooper, Jonathan J. and Paul Elias. “14,000 Fight California Fires, Some from Prisons or Overseas.” *Chicagotribune.com*, Chicago Tribune, 08 Aug 2018, www.chicagotribune.com/nation-world/ct-california-wildfires-20180808-story.html.

Creamer, R.E., Hannula, S.E., Van Leeuwen, J.P., Stone, D., Rutgers, M., Schmelz, R.M., de Ruiter, P.C., Bohse Hendriksen, N., Bolger, T., Bouffaud, M.L., Buee, M., Carvalho, F., Costa, D., Dirilgen, T., Fransciso, R., Griffiths, B.S., Griffiths, R., Martin, F., Martins da Silva, P., Mendes, S., Morais, P.V., Pereira, C., Philippot, L., Plassart, P., Redecker, D., Rombke, J. Sousa, J.P., Wouterse, M., and Lemanceu, P. Ecological network analysis reveals the inter-connection between soil biodiversity and ecosystem function as affected by land use across Europe. *Applied Soil Ecology,* 97:112-124.

Cumming, G.S., Bodin, O., Ernstson, H., and Elmqvist. 2010. Network analysis in conservation biogeography: challenges and opportunities. *Diversity and Distributions,* 16(3): 414-425.

Garcia-Amado, L.R., Perez, M.R., Iniesta-Arandia, I., Dahringer, G., Reyes, F., and Barrass, S. 2012. Building ties: social capital network analysis of a forest community in a biosphere reserve in Chiapas, Mexico. *Ecology and Society,* 17(3):3.

Ingold, K., Balsiger, J., and Hirschi, C. 2010. Climate change in mountain regions: how local communities adapt to extreme events. *The International Journal of Justice and Sustainability,* 15(7): 651-661.

Janssen, M.A., Bodin, O., Anderies, J.M., Elmqvist, T., Ernston, H., McAllister, R.R.J., Olsson, P., and Ryan, P. 2006. Toward a Network Perspective of the Study of Resilience in Social-Ecological Systems. *Ecology and Society*, 11(1):15.

Kapsar, K.E., Hovis, C.L., da Silva, R.F.B., Buchholtz, E.K., Carlson, A.K., Dou, Y., Du, Y., Furumo, P.R., Li, Y., Torres, A., Yang, D., Wan, H.Y., Zaehringer, J.G., and Liu, J. 2019. Telecoupling Research: The First Five Years. *Sustainability,* 11(4): 1033.

Liu, J. 2017. Integration across a metacoupled world. *Ecology and Society,* 22(4): 29.

Liu, J., Hull, V., Batistella, M., DeFries, R., Dietz, T., Fu, F., Hertel, T.W., Izaurralde, R.C., Lambin, E.F., Li, S., Martinelli, L.A., McConnell, W.J., Moran, E.F., Naylor, R., Ouyang, Z., Polenske, K.R., Reenberg, A., de Miranda Rocha, G., Simmons, C.S., Verburg, P.H., Vitousek, P.M., Zhang, F., and Zhu, C. 2013. Framing Sustainability in a Telecoupled World. *Ecology and Society,* 18(2):26.

McCord, P., Tonini, F., and Liu, J. 2018. The Telecoupling GeoApp: A Web-GIS Application to Systematically Analyze Telecouplings and Sustainable Development. *Applied Geography*, 96, pp. 16-28.

McPherson, M., Smith-Lovin, L., and Cook, J.M. 2001. Birds of a Feather: Homophily in Social Networks. *Annual Review of Sociology,* 27:415-444.

Mouw, T. 2006. Estimating the Causal Effect of Social Capital: A Review of Recent Research. *Annual Review of Sociology,* 32:70-102.

Pecl, G.T., Araujo, M.B., Bell, J.D., Blanchard, J., et al. 2017. Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science,* 355(6332):eaai9214.

Prell, C., Hubacek, K., and Reed, M. 2009. Stakeholder Analysis and Social Network Analysis in Natural Resource Management. *Society & Natural Resources*, 22(6):501-518.

Primmer, E. 2011. Policy, project and operational networks: channels and conduits for learning in forest biodiversity conservation. *Forest Policy and Economics,* 13:132-142

Rigaud, K.K., de Sherbinin, A, Jones, B., Bergmann, J., Clement, V., Ober, K., Schewe, J., Adamo, S., McCusker, B., Seuser, S., and Midgley, A. *Groundswell: Preparing for*

Internal Climate Migration. Washington, DC: The World Bank. https://www.worldbank.org/en/news/infographic/2018/03/19/groundswell---preparing-for-internal-climate-migration

Sayles, J.S., and Baggio, J.A. 2017. Social–ecological network analysis of scale mismatches in estuary watershed restoration. *Proceedings of the National Academy of Sciences,* 114(10):E1776-E1785.

Sayles, J.S., Mancilla Garcia, M., Hamilton, M., Alexander, S.M., Baggio, J.A., Ficsher, A.P., Ingold, K., Meredith, G.R., and Pittman J. 2019. Social-ecological network analysis for sustainability sciences: a systematic review and innovative research agenda for the future. *Environmental Research Letters,* 14(9):093003.

Schaffer-Smith, D., Tomscha, S.A. Jarvis, K.J., Maguire, D.Y., Treglia, M.L., and Liu, J. 2018. Network analysis as a tool for quantifying the dynamics of metacoupled systems: an example using the global soybean trade. *Ecology and Society,* 23(4):3.

Schleuning, M. et al. 2016. Ecological networks are more sensitive to plant than to animal extinction under climate change. *Nature Communications,* 7:13965.

Schuckel, U., Kroncke, I., and Baird, D. 2015. Linking long-term changes in trophic structure and function of an intertidal macrobenthic system to eutrophication and climate change using ecological network analysis**.** *Marine Ecology Press Series,* 536:25-38.

Tonini, F., and Liu, J. 2017. Telecoupling Toolbox: Spatially explicit tools for studying telecoupled human and natural systems. *Ecology and Society*, 22 (4):Art11.

CONCLUSION

In this thesis, I assessed the potential of network analysis, which conceptualizes systems and their components as nodes and linkages of a network, to contribute to climate change adaptation scholarship and practice in a globalized world. I also identified research gaps and opportunities and developed a framework to guide future research on this topic.

In Chapter 1, I reviewed the literature and assessed the extent to which current research on this topic integrates multiple social-ecological systems interacting nearby and faraway. I found that current studies are limited in number and in scope. All of the studies I reviewed performed social networks analysis, with no studies applying ecological network analysis or social-ecological network analysis. Most studies also examined only a single system at the subnational scale. There were few studies that looked at multiple, interacting systems at the national and international scales. Only one study performed social network analysis across multiple geographic scales. Further, all of the studies assessed social network structure, with no studies demonstrating causality even though methodological tools (e.g., selection and influence models) exist to do so.

These research gaps indicate that current research does not reflect the complexities of social-ecological systems in a globalized world where many people and places are increasingly connected across multiple geographic scales. Climate change and its impacts often span multiple geographic scales, and impacts on one system often reverberate to other systems. Further, coordinating resources across multiple systems can increase the adaptive capacity of social-ecological systems. Successfully coordinating social and ecological resources to adapt to climate change requires an understanding of interactions between multiple social-ecological systems and their consequences for environmental sustainability and human wellbeing. A framework that allows for examining the components and dynamics of social-ecological systems interacting across geographic scales is needed to guide network analysis research in climate change adaptation.

In Chapter 2, I developed the metacoupled network approach in response to the research gaps identified in Chapter 1. I developed the approach by integrating the metacoupling framework (used to explicitly identify the multiple, interacting coupled human and natural systems and their components involved in a particular research context) with social-ecological network analysis. The metacoupled network approach helps to address some key limitations of the metacoupling framework and social-ecological network analysis before I integrated them. Social-ecological network analysis enables one to operationalize and quantify the metacoupling framework as well as demonstrate causality. Meanwhile, the metacoupling framework encourages network analysis scholars to consider interactions within and among the multiple social networks, ecological networks, and social-ecological networks involved in a particular study context, rather than focusing only on either social networks or ecological networks.

The metacoupled network approach I developed can be used to develop climate change adaptation theory and reignite network analysis research on adaptation. It also contributes more broadly to network analysis and the fields of sustainability and systems science.