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More Than The Sum of Their Parts: Coordination In Dynamic Social Networks

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# “More Than The Sum of Their Parts: Coordination In Dynamic Social Networks”

DISSERTATION

submitted in partial satisfaction of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in Sociology

by

Selena Margarita Livas

Dissertation Committee:
Chancellor’s Professor Carter T. Butts, Chair
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2023

# DEDICATION

I want to dedicate this dissertation to my Mom, Roseanne Romaine. You never let me think my goals were out of reach. You navigated years of college for me despite having few resources and little help. You were unable to finish college yourself due to financial circumstances, and yet you worked tirelessly so that I could afford my dreams. This dissertation is a result of your hard work, your patience, and most importantly, your love.

Thank you.

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- Weining Shen, Jiang, Xiwen, **Selena M. Livas**, Fan Yin, Sayantan Banerjee, Carter T. Butts. (2023) “Structure recovery and trend estimation for dynamic network analysis.” *Stats Data Science Views.*

# ABSTRACT OF THE DISSERTATION

"More Than The Sum of Their Parts: Coordination In Dynamic Social Networks"

By

Selena Margarita Livas

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University of California, Irvine, 2023

Chancellor's Professor Carter T. Butts, Chair

This dissertation investigates coordination as a key component of social systems, from a network of international environmental governance to a localized response to disaster. Chapter 2 is a study of international environmental agreement (IEA) co-ratification. I focus specifically on mixing effects and how these demonstrate a shift in the global configuration of cooperative behavior within this context. Chapter 3 dives deeper into this network, looking more closely at the structural factors influencing ratification of IEAs, including factors at the agreement level. The goal of this chapter was to better understand the formation of new ratification ties over time, while making several methodological contributions as well. Finally, Chapter 4 is a study of dynamic communication patterns across 17 localized first responder networks in the midst of a disaster. We utilized a recently developed tool for relational event model simulation to study the resilience of these networks as they reorganized in the face of varied disruption. This dissertation pushes for the view of social systems as interconnected and specifically demonstrates the advantages of studying coordination from this perspective. I hope it spurs future research on these topics, especially in the realm of environmental degradation as it is ever more often encompassing both regulation and disaster response.

# Chapter 1

# Introduction

Coordination and cooperation are key aspects of social interaction. Both are often used in achieving joint goals. These goals range in scale along with their coordinative processes from micro to macro. This work explores two extreme ends of the spectrum with micro communication patterns between small groups of first responders to macro scale cooperation between countries working on managing shared natural resources. An important aspect of both processes is the interdependence of actors and their connections. If one responder speaks to another, it is likely to elicit a response from that same actor, or perhaps a third may chime in with information for the initial responder. Both may be more likely to proceed the initial communication than an unrelated set of actors speaking next. Similarly, a country may choose to join an agreement if an ally had previously joined, which might be more likely than if a feuding country had signed on. These are both examples of dependent processes. Coordination does not happen by individuals making decisions in a vacuum or regardless of what others are doing, it is inherently a process of interdependent decision making, which is frequently dynamic across time.

This dissertation explores two distinct settings of coordination and cooperation. This work contributes to the literature by studying these processes as an evolving system and uses innovative network techniques to analyze both. More specifically, this work is focused on successful coordination and the factors that influence it. In my second and third chapters, I study the entire history of multilateral international environmental agreement ratification between 208 countries, past and present. This work uses a broader set of IEAs and time periods than previously studied, spanning the years 1857 to 2022. My second chapter focuses on prior theories that have been tested as drivers of independent ratification behavior. I instead collapse the system into a one-mode network and study the co-ratification patterns over time. In doing this I can test the theories within the context of the dyad, investigating how various mechanisms increase or decrease the average number of agreements ratified by pairs of countries. In my third chapter I go back to the full bipartite system of countries and agreements. I test prior theories that have been used mostly in models that assume independence and add in mechanisms of dependence as well as agreement level characteristics that have been previously excluded. This entire analysis was only made possible by an original data collection process specifically conducted for this dissertation in which I hand coded each agreement for country inclusion. This was a necessary step, as without it we could not measure the likelihood of ratification. In addition to expanding the data I used as well as using a model that does not assume independence, I also constructed new terms to be used in my models, which allowed me to test mechanisms in the bipartite context that could not be included before. This chapter pushes the field forward and opens up greater possibilities for future studies, both substantively and methodologically.

Lastly, the fourth chapter moves to the context of disaster communication in which we study 17 closed radio communication channels of first responders during the 2001, September 11th attack on the World Trade Center in New York City. Using a newly available general purpose simulator for relational event models, we test how these networks respond to disruption by removing actors and allowing the networks to reorganize. Prior work on human social systems has focused on robustness, in which they take an aggregate network, remove nodes or edges, and find which techniques cause the most or quickest fragmentation. By letting the networks change post node removal, we allow for unexplored options beyond fragmentation and see how the structure evolves as a response to actor loss. We then look at efficiency and explore how much communication volume is spent on the "dead" actors. Finally, we draw on social insect literature and test for the use of reserves in network reorganization. Additionally, we test how structural change, efficiency, and reserve use differ by specialization as some responders were trained for disaster response and others were not. This work is innovative in the field of human social systems, being among the first to understand node removal as a dynamic process, while measuring the ways in which the network re-organizes.

This dissertation spans the spectrum of coordination and studies the extremes using new and more suitable techniques. It advances the literature for both environmental governance and disaster communication, while adding to a broad understanding of cooperation in social systems.

# Chapter 2

# Birds of a Feather Sign Together: Homophily in The International Environmental Agreement Network

## 2.1 Abstract

International environmental agreements (IEAs) are a form of joint action that require coordination and cooperation. The action of ratifying an IEA is influenced by national level characteristics as well as dyadic characteristics of pairs of co-ratifying countries. Exploring how these factors interact can build on our understanding of IEA ratification in the present as well as the past. Moreover, the central sociological theories addressing IEA ratification have implications for how categories of countries co-ratify at different rates, both individually and together. The aim of this study is to explore how these categories are associated with varying rates of co-ratification and how these associations have changed over time. Two sets of network regression models are used to distinguish between three major theories of

global cooperation: world polity theory, world systems theory, and regionalization theory. The secondary goal of this research is to demonstrate how the use of network methods can further our knowledge of various forms of agreement ratification. In this study, I use network data from over 1,300 multilateral IEAs between 206 countries, ranging in signing date from 1857 to 2022. While regionalism is only modestly supported, the results suggest an evolution in the patterning of co-ratification, with a regime change from a world systems configuration to a world society one over the past 30 to 40 years. Lastly, the inclusion of a lagged term, to account for past co-ratification structure, appears to be essential for estimating the effect sizes of these dyadic factors, suggesting the benefits of this specific measure as well as the potential for further network modeling.

## 2.2 Introduction

With the rate of climate change increasing (Masson-Delmotte et al., 2021) along with the abundance of its symptoms, such as water level rise (Cazenave and Llovel, 2010; Nicholls and Cazenave, 2010), increased storm severity (Brimelow et al., 2017), and wildfires (Jones et al., 2020; Goss et al., 2020), the need for global mitigation strategies is stronger than ever. An essential tool for global action is international environmental agreements (IEAs), specifically those that are legally binding. International laws and regulations that reduce and eliminate environmental degradation are necessary in the fight against climate change, yet we currently understand very little about what drives the ratification process outside of individual country level characteristics. To move beyond this understanding, we can begin treating countries as dependent in their actions and understand environmental agreements as a network. The IEA network is made up of a collection of countries (referred to as nodes) and the connections between countries (referred to as edges or ties). In this case, the ties measure the number of IEAs ratified by a given pair of countries (whichever countries the tie is between). When viewed as a network, one can measure relevant metrics at various levels, including, but not limited to, the level of the single country (or node), and the level of the connection (or the edge) between pairs of countries or nodes; these pairs are referred to as dyads. For this research, I focus on the dyad as a unit of analysis, but also incorporate measures at the node (or country) level.

While prior literature does exist on IEA ratification broadly, the bulk of this work has focused on country level characteristics, often asking questions relating to the kinds of effects that may cause an increase or decrease in the likelihood of ratification or asking what factors at the national level are associated with varied rates of ratification. Previous work has found influences of international non-governmental organization membership (Frank, 1999), GDP per capita (Roberts, 1996; Roberts et al., 2004), and domestic political regimes (Congleton, 1992, 2001). While an important step in the study of IEAs, these country level findings are only a piece of the puzzle; global governance is cooperative in nature and involves partnerships, negotiations, and long-standing rapport. From a social network perspective, we have yet to go beyond the initial node level analyses of countries to understand dynamics at the dyadic level. We know little about which countries co-ratify IEAs and which dyadic characteristics are associated with increased or decreased co-ratification. What is most striking about this is that the central sociological theories on globalization imply specific mixing patterns that could be measured at the dyadic level.

More specifically, one would expect particular mixing patterns to arise based on each theory, resulting in homophily effects. Homophily, in networks, is the tendency for ties to form within dyads that share some characteristic in common; or more simply put, it is the concept that "similarity breeds connection" (McPherson et al., 2001). While homophily is central to several theories of global cooperation, this has not yet been tested in any statistically rigorous way within the context of IEAs. In order to fill this gap in the literature, I will focus on two broad research questions: 1. what dimensions of homophily exist in the IEA network? And 2. how has this pattern changed over time?

## 2.3 Background

In order to answer my research questions I focused on three main theories, all of which describe global cooperation and structure, and imply mixing based hypotheses; the first theory tested was regionalism. Regionalism suggests that cooperation is influenced by geographic region or more specifically, that nation-states within the same region are more likely to work together and cooperate politically (Bhagwati, 1992; Zhou, 2011; Kim and Shin, 2002). This effect is thought to arise from shared language and culture, which make negotiation easier and cooperation more likely due to similarity in cultural values. If language is shared, communication of complex issues is less likely to get muddled or miscommunicated through translation or use of a common secondary language. If cultures are more similar, differences in core values or priorities are less likely to hinder the negotiation process. Outside of simply sharing things like language and religion, there are many regional organizations, such as The European Union and the Council of Europe that also create regional channels for communication and even shared bureaucratic norms for negotiations. These shared priorities may be influenced by the physical environment as well, in terms of shared environmental resources, which are affected by distance and shared borders. All of these effects taken together suggest homophily based on geographic region, meaning that those countries in the same region will have more ties to each other than to those in different regions.

The second theory I tested was world systems theory. The current world system has a core-periphery structure (Chase-Dunn and Grimes, 1995; Wallerstein, 1990). The core countries are densely connected to each other through trade and other political actions or alliances, while the periphery is very loosely connected, with more ties to the core than to themselves. While this core and periphery structure is mathematically defined by a strong principal eigenvector, the literature suggests a strong correlation of these roles with other attributes. The attributes that correlate with these roles vary across the literature, but they all tend to be tied to resource control, broadly. The core countries should be those that are economically advantaged and hold positions of power within the global system, while the periphery should be those countries that are economically disadvantaged and hold relatively less power. The two groups are frequently referred to as the "global north" and "global south," but in order to use language that is easily distinguished from geographic categories, these two groups will be referred to as resource advantaged and resource disadvantaged to label the core and periphery, respectively. Likewise, homophily based on these categories will be referred to as resource homophily. Core-periphery structures are defined by mixing patterns and therefore have implied homophily effects, with a high tendency towards homophily in the core and a tendency away from homophily in the periphery. In practical terms, this means that the resource advantaged countries work the most with each other and that peripheral countries work with advantaged countries more than disadvantaged countries.

Unlike the two prior theories, the last theory I tested does not imply a specific type of homophily, but rather a trend in homophilous ties over time. World society theory, also referred to as world polity theory, is defined by the spread and legitimation of global norms. It posits that as globalization increases, countries will become more alike in their actions and will begin to share a global culture as a result. This process happens as countries attempt to legitimate themselves on the global stage by taking actions and participating in ways that abide by the norms for a country (Meyer et al., 1997). In other words, if leaders of countries wish to legitimate their respective countries globally, they will imitate the actions of those countries that are already seen as legitimate; this is a process of isomorphism. There are various mechanisms of isomorphism that have been offered to explain this process in more detail (DiMaggio and Powell, 1983a), and while the mechanism for upholding, reinforcing, and spreading norms is clear, the mechanisms for norm creation are less concrete. One of the commonly proposed drivers for norm creation is the connection of the world culture to the scientific community; it is suggested that scientific research as well as norms created in academic settings inform new policy and disseminate globally. Additionally, global elites are thought to be trained and educated in similar academic settings, which also reinforces a specific kind of culture among them. With this understanding, one may expect IEAs, driven by the science of climate change, to become one of these global norms.

Figure 3.1 shows the increase in multilateral IEA (MEA) prevalence over time; multilateral refers to agreements between three or more countries as opposed to bilateral, meaning between two countries. While this proliferation of MEAs is suggestive of world society theory, the equal involvement of countries in these agreements is also necessary for demonstrating a world society configuration. While this may be due to the mechanisms described above, this might also be influenced by the topics of IEAs themselves. If agreements become more global in nature, due to a growing world culture, this might also bring more countries together over time, reducing the variance in group mixing rates. All points taken together, world society theory would suggest a decrease in homophily effects over time. As countries become more alike as well as more connected, the mechanisms driving the prior two homophily effects should lessen or disappear entirely.

While these theories are often placed in conflict with one another, there is little reason to believe that they cannot coincide nor be the dominant factor at varying points in time. In fact, Yamagata et al. (2017) demonstrated a regime change in the IEA ratification process, occurring after the fall of the Soviet Union, specifically looking at a subset of eight IEAs. They found that prior to this event, it was common for smaller countries to emulate the ratification patterns of either the US or the USSR. However, after this exogenous shock, they find a shift to a world society configuration, where countries had more equal rates of ratifying, regardless of the actions taken by larger countries. This research is not only testing for homophily effects within IEA ratification, but also for shifts over time, including regime changes as well as support for co-occurring hypotheses.

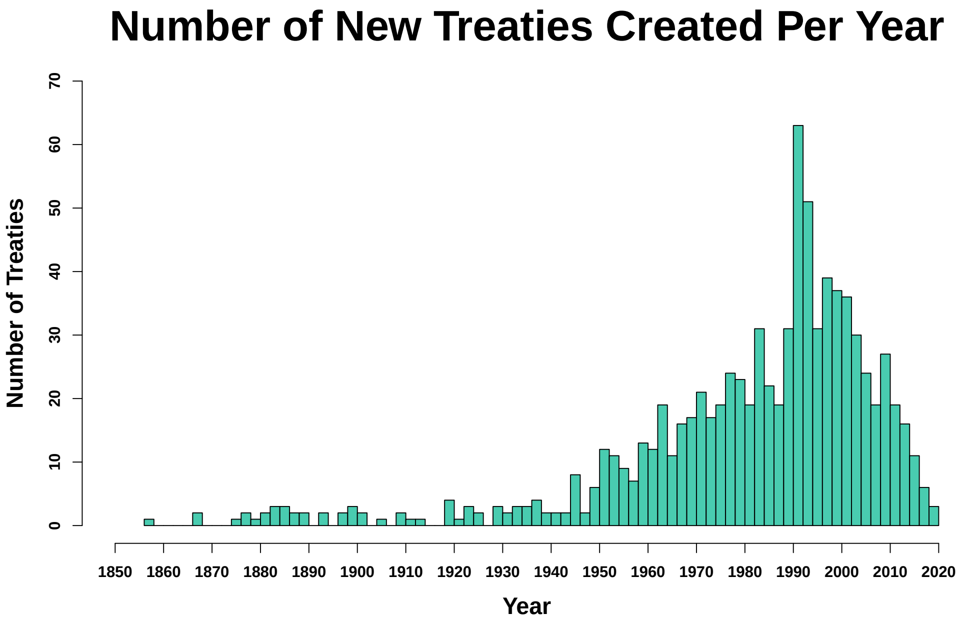

Figure 2.1: Visualization of the frequency of MEAs across all 163 years of data. Dates are relative to the signing year of each MEA.

Prior literature exists to support all three of these theories in regard to their influence on IEA ratification patterns. This research helps to disentangle these effects and build on prior work in two main ways. First, this work includes a broader time period and set of IEAs than previous work has. By using the full history of MEA ratification and with it, all multilateral IEAs on record, this work allows for a deeper understanding of the ratification process. I can test how the effects of interest differ across time periods, rather than within a short time span of several decades, and I can generalize findings to all MEAs, rather than some pre-selected subset. Next, instead of focusing on the rate of IEA ratification by individual countries, I am testing the rates of co-ratification using network models that allow for the inherent dependence present in this type of data. While previous findings point to varying mechanisms, they rely on models with built in assumptions of independence. Knowing that IEA ratification is a cooperative process, born out of lengthy negotiations, implies a need for modeling techniques that lack these assumptions. This work not only tests these theories with factors measured at the dyadic level, but it incorporates and tests node level findings from prior studies as well.

### 2.3.1 Hypotheses

Below, I take the three theories and apply them to the case of International environmental agreements, hypothesizing the effect or effects for each. Regionalism describes a broad homophily effect for same region countries and is supposedly driven by regions of countries having an overlap of culture, which eases cooperation efforts. While there are general reasons for this described above, IEAs, specifically, are likely influenced by region due to shared environmental resources, which create a need for cooperation among geographically proximate countries. Ecological resources frequently cross national boundaries, while being affected by national policies; a classic example would be over-fishing in a shared body of water. In fact, the first MEA on record, the “agreement respecting the regulation of the flow of water from Lake Constance” is an example of regulating a shared body of water, in this case controlling the overflow of it. If countries do not cooperate on policies regarding such a resource, this can damage the resource for all and breed conflict. While this is a common purpose of IEA creation, it is much less likely for these resources to be shared between countries that are far apart geographically. This implies a propinquity effect or homophily based on physical proximity. This effect should remain consistent over time, as geographic regions and shared environmental resources, as well as shared language and culture are relatively static traits.

*H1.* There will be increased co-ratification between same region countries when compared to co-ratification between countries in different geographic regions.

Moving to the second theory, the world systems literature describes global interaction as a core-periphery structure; I am proxying these roles by resource control. These two groups, the resource advantaged and resource disadvantaged, should have clear patterns of homophily. Specifically, the resource advantaged group should co-ratify more IEAs together and the disadvantaged group should co-ratify fewer IEAs together, in reference to resource heterophilous ties (ties between core and periphery countries). In the case of IEAs, there are several reasons to expect world systems positions to influence ratification patterns. First, if other agreements and alliances are structured around world systems positions, they may lead to other agreements such as IEAs being structured similarly; if existing alliances create channels for communication and or infrastructure for agreements, this can ease the process of future negotiations. Additionally, because resource control is often highly correlated with purely financial resource control, it is likely that those countries in the core would have an easier time ratifying IEAs that pose a financial burden, which many do.

*H2.* There will be high levels of homophily among resource advantaged countries, paired with negative homophily among resource disadvantaged countries.

Similar to world systems theory, world society theory has been applied to many acts of global coordination, including international agreements. Much of the growth of international treaties as a means of cooperation appears to stem from the end of the second world war and the formation of international organizations, such as the United Nations. Ratification of IEAs specifically, as well as participation in global environmentalism generally, have been described as legitimating global norms (Frank, 1999; Frank et al., 2000b,0; Hironaka, 2014). Ratification of IEAs is one of the cornerstones of global environmentalism and is rooted in the scientific discourse thought to influence the proliferation of new global norms. This implies that countries should increase their co-ratification over time as they become more embedded in the world culture and as this process further reinforces IEAs as a legitimating action. Westernized, and often wealthier countries have historically been those that are more highly embedded in the world culture. This implies that while a core-periphery structure may exist, it should lessen over time, with more countries participating in legitimating acts, such as treaty ratification. Additionally, as more countries participate in this process, differences in regional rates of co-ratifying should level off, with a larger proportion of countries from various geographic regions ratifying IEAs over time. Generally speaking, as the global cultural aspect of IEA ratification spreads, becoming ubiquitous across countries, the differences in within-group and between-group rates should diminish.

*H3.* There will be a decrease in all forms of regional and resource homophily over time as well as decreases in the effects for node level characteristics.

Figure 2.2 shows the three main hypotheses graphically as stylized adjacency matrices. The matrix represents co-ratification, with the same countries on the rows and columns, and each cell representing the number of co-ratifications between the country on the row and the one on the column. The darker green indicates higher levels of mixing or co-ratifying.

In addition to these three theories is the influence of time. While testing these theories together is important, it is also necessary to account for the influence of prior co-ratification. Co-ratification can be time dependent and may be shaped by prior co-ratification patterns rather than homophily in the current period. There are several reasons to believe that the past may be an important predictor of the future for IEAs specifically. First, IEAs have legal lineages – some are directly related to each other (i.e., amendments) and some are connected through others means (i.e., organizations or a related series of conventions) and this might mean that the co-ratification patterns are influenced by the prior network. Additionally, while diplomatic negotiations can be long and costly, they can set up channels of communication between countries, meaning that those that have previously co-ratified an IEA have established more channels of communication on the topic than those that have not and this may influence future co-ratification patterns, net of any homophily effects.

It is also important to consider that current homophily effects may be the result of prior structure, rather than an ongoing process and it is necessary to disentangle these effects to fully understand homophily in the IEA network. In order to do this, I have tested this effect in combination with the theories described above. These three theories focus heavily

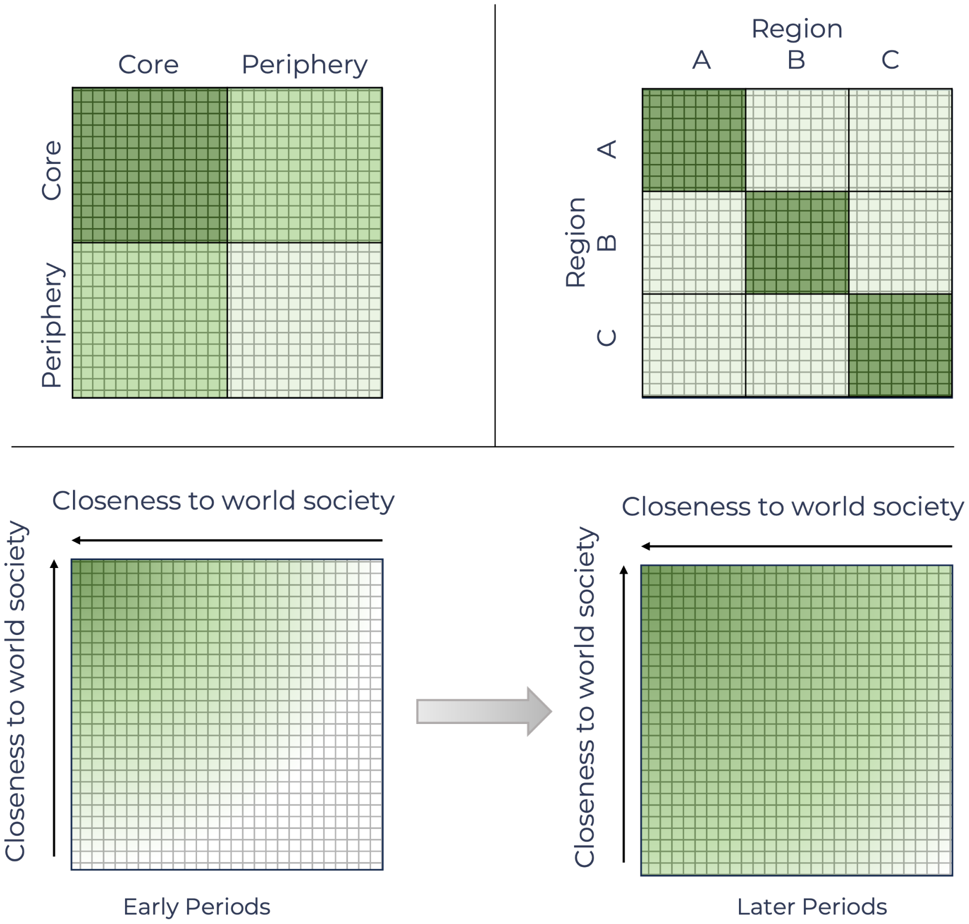

Figure 2.2: Visualization of main hypotheses: upper left shows world systems theory, upper right shows regionalism, and bottom half shows world society theory. Darker green indicates high mixing rates (high co-ratification rates).

on dyadic relationships, but they have not been tested extensively at the dyadic level in the context of IEA ratification. By testing these at the dyadic level and together, one can gain a better understanding of the forces shaping environmental cooperation on an international scale, both historically and presently.

## 2.4 Data and Methods

IEA's can be divided into two broad categories; bilateral environmental agreements (BEAs) are between only two countries, while multilateral environmental agreements (MEAs) are between three or more countries. This research is focused specifically on MEAs; however, it could be naturally extended to the bilateral case. The agreement data comes from the University of Oregon's IEA database, which is the largest database of its kind and provides dates of ratification by country and agreement (Mitchell, 2002-2021). The data was originally coded into 166 treaty-by-country matrices, with one matrix per year, starting with 1857 and running through 2022. Each cell had a 1 or 0 indicating whether or not a given country had ratified a given treaty as of that year. These were then transformed into one-mode, country-by-country matrices with the diagonals set to zero and each off diagonal $ij$th cell containing the co-ratification count between country $i$ and country $j$ as of that year. In order to analyze how the effects of interest change over the entire 166-year period, the individual year matrices were collapsed into 11 broader time periods by adding the single year matrices together. The first time period is from 1857 to 1899, the second time period is from 1900 to 1929, and all remaining time periods are in 10 year intervals, which overlap with a typical decade. 10-year periods were chosen because they are long enough to contain substantial variation among the co-ratification counts, but still narrow enough to pick up on changes in effect size, while being a common reference period for broader contextualization. Decades in the earlier years contained too few treaties to make the analysis informative and were therefore combined to form two larger time slices. The result was 11 co-ratification matrices with each co-ratification count being the number of co-ratifications that occurred within that time period, regardless of the signing years of the related treaties.

This data was coupled with data on geographic-regional categories, geographic contiguity, physical distance, resource based categories, and GDP per capita. The region definitions were adopted from Bandelj and Mahutga (2013), who conducted a similar study for Bilateral Investment Treaties, and adjusted to include all countries in the IEA data, while dividing North and South America. The resource categories were constructed using the CINC measure in the Correlates of War database's National Material Capabilities data, version 6 (Singer and Stuckey, 1972). This measures the amount of resources present globally per year and then weights the amount present in each country. This results in a proportion (0-1) for each country in a given year. This measure allows for variation across time and measures resource control as relative to other countries as opposed to an exogenous amount. In order to construct categories from this data, CINC amounts were averaged across each time period and the resource advantaged group was defined as the top 25% of countries in terms of resource control within each period, while the resource disadvantaged countries were those outside of the top 25%. [1] The contiguity data was taken from the Correlates of War database's Direct Contiguity, version 3.2 dataset (Stinnett et al., 2002). countries were counted as contiguous if they were separated by a land or river border. Physical distance data was taken from the CEPII's GeoDist Datasets using the cepiigeodist package for R (Mayer and Zignago, 2011). Distance is measured in kilometers and is the distance between the official capital cities of each country (or the most populated if needed). Finally, the GDP per capita data comes from the Madison Project (Bolt and van Zanden, 2020); it is reported in per year figures, but was averaged across each time period. This allows us to control for relative economic differences both across countries and across time that may affect the base rate of co-ratification.

The covariates were in the form of country-by-country matrices as well, with both the GDP per capita and resource data being time varying and the geographic categories, contiguity, and distance remaining static across all 11 periods. The 9 regional categories are in the models as both node and edge covariates. The regional node covariates control for the country level tendency to co-ratify based on their geographic region, relative to the reference category of Europe. The regional edge covariates control for homophily based on region and are in reference to heterophilous ties. Contiguity is measured as a binary edge covariate, with 1 indicating that two countries are contiguous and 0 otherwise. Distance is measured as a valued edge covariate, indicating the natural log of the distance between countries in kilometers. The resource categories are present as both node and edge level covariates. The node level

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[1] Various cutoffs were tested, with 25% explaining the largest amount of variation within each time period.

covariate for resource control is present as the tendency for resource advantaged countries to co-ratify, relative to the reference category of resource disadvantaged countries. There are two edge covariates, one measuring homophily among resource advantaged countries and one measuring resource disadvantaged homophily; these two variables are in reference to the hold out category of resource heterophilous ties. Finally, GDP per capita is measured as a node level covariate, indicating the average value per country per period. Lastly, the intercept term in each model indicates the average expected tie strength, or co-ratification count, net of all other variables in the model.

These variables were used to model each of the 11 time periods, resulting in a separate model for each period. In order to address the impact of prior co-ratification on current co-ratification, an additional set of analyses was conducted, which included all of the variables mentioned above, with the addition of a lagged term. This lag term represents co-ratification in the prior time step and is measured using the valued network of the prior period. The direct interpretation of this is a recency effect, or the effect of past ratification-pairings on current ratification pairing patterns. The coefficient can be interpreted as the increase in current co-ratification count associated with an additional co-ratification in the last time period. By conducting both sets of models I can see which effects are directly impacting co-ratification and which are affecting co-ratification through means of the prior structure. It should be noted that because countries vary by founding date, not all countries exist in two adjacent time periods. Because my models require the dimensions of all variables to be equal, each model with a lag term only contains the countries that exist in both time periods. The loss of countries varies between 0.495% and 33.333% with an average of 11.233% across all time periods. A robustness check was conducted to verify that my results are attributable to the addition of a lag term and not this loss of data.

I use a series of network regression models (Krackhardt, 1988) in order to model co-ratification counts, while incorporating longitudinal effects as well as multiple, competing homophily effects at the dyadic level. Network regression works well for valued edge data such as co-ratification counts and allows for both node level and edge level covariates. In conducting this analysis I use the netlm function in the sna package for R (Krivitsky et al., 2003-2022; Butts, 2022). Network regression is similar to OLS regression in that it controls for other variables by testing the correlation between the residuals of two variables. Unlike ordinary regression, which has an assumption of independence and cannot be used to test dependent data (Proctor, 1969), Hubert's QAP, a non-parametric test, is used to test the significance of the model terms, which conditions on the structure of the graph and can therefor handle the intrinsic dependence in the data (Hubert and Shultz, 1976; Mantel, 1967). All models include all regional effects, resource effects, the measure of distance, contiguity, GDP per capita, and an intercept term regressed on the count of co-ratified treaties within the given time period. For each time period, one analysis was conducted *without* the inclusion of a lag term and for each time period, excluding the first, another analysis was conducted *with* the inclusion of the lag term for the prior decade. Across all 11 time periods, this resulted in 21 network regression models, the results of which are discussed below.

## 2.5 Results

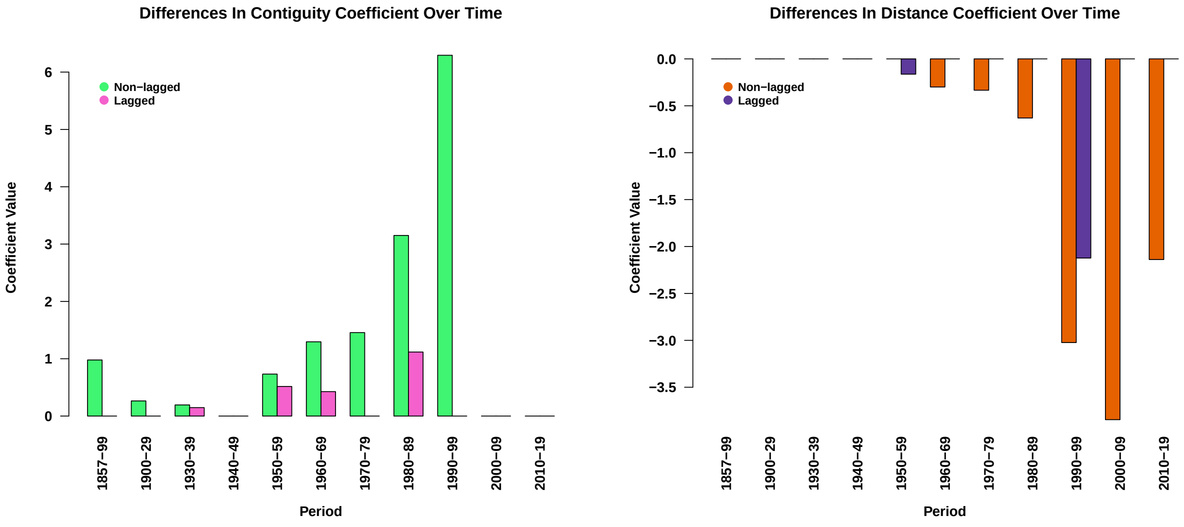

Figure 2.3: Visualization of the coefficient values for both the contiguity and distance terms across all periods, shown side by side. Only significant values are displayed with significance measured at the 0.05 level.

### 2.5.1 Regionalism

Regionalism was captured with three different variables of interest, a categorical variable for geographic region, the log of the distance between countries (measured in kilometers), and a binary variable for contiguity. Looking at the model results without the lag term, there is a strong and consistent European homophily, shown in Figure 2.4, which is significant in all time periods and peaks at 20.97 in the 1990's and then levels off at 7.67 in the present. This means that in the most recent decade, net of other effects, two European countries are expected to co-ratify almost 8 more IEAs than a pair of countries from different regions. However, there are few other significant effects for my regional, categorical variables. In fact, the only other clear trend is a tendency towards heterophilous ties in Eastern Asia, meaning that they co-ratify with countries in other regions more than with countries in their own region. There is also a small positive effect for North America from the 1950's through the

Network Regression Results – All Time Periods (Lag Excluded)

| | 1857-99 | 1900-29 | 1930-39 | 1940-49 | 1950-59 | 1960-69 | 1970-79 | 1980-89 | 1990-99 | 2000-09 | 2010-19 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Intercept | 0.33 | 1.04** | 0.3 | -0.02 | 1.65* | 3.59*** | 4.05** | 9.45** | 51.73*** | 68.9*** | 53.52*** |
| Contiguity | 0.98*** | 0.26** | 0.19** | 0.16 | 0.73*** | 1.3*** | 1.46*** | 3.15*** | 6.29** | 2.28 | 1.55 |
| Distance | -0.05 | -0.08 | -0.01 | 0.05 | -0.11 | -0.3** | -0.33** | -0.63* | -3.02** | -3.85** | -2.14* |
| Europe (H) | 1.08*** | 0.97*** | 0.3*** | 0.44** | 3.76*** | 4.45*** | 6*** | 14.41*** | 20.97*** | 11.5** | 7.67* |
| Asia (H) | -0.07 | -0.28 | -0.06 | 0.63* | 1.44** | -0.35 | 0.1 | -0.87 | -7.13 | -8.38 | -5.9 |
| Africa (H) | -0.04 | 0.01 | -0.07 | -0.07 | 0.14 | 0.8** | -0.24 | 0.32 | -3.11 | -0.81 | -1.64 |
| Oceania (H) | – | 0.24 | -0.08 | 1.97* | 2.24* | -0.4 | 0.07 | 1.31 | -1.01 | -0.45 | 2.97 |
| North Africa & Middle East (H) | -0.14 | -0.22 | -0.13 | -0.03 | -0.16 | 0.45 | 1.01* | -2.28* | -6.69* | -1.66 | -3.35 |
| Post-Soviet-Eurasia (H) | -0.36 | -0.19 | 0.27* | -0.02 | 0.02 | -0.62 | -0.88 | -2.57* | 11.2*** | 5.83 | 2.98 |
| East Asia (H) | -0.58 | -0.52 | -0.14 | -0.09 | -1.3 | -2.97** | -2.28* | -4.02* | -20.39** | -19.02** | -14.41* |
| North America (H) | -0.35 | -0.52* | 0.25 | 2.05** | 1.34* | 1.73* | -0.45 | 0.1 | 5.71 | -5.63 | -3.56 |
| South America (H) | -0.28* | -0.2 | -0.02 | 0.73** | 0.4 | -0.2 | 1.36* | 2.15* | 2.16 | -0.23 | 0.4 |
| Asia | 0.09 | 0.2 | -0.08 | -0.13 | -0.11 | -0.16 | -0.01 | 0.4 | 3.1 | 3.83 | -2.45 |
| Africa | 0.07 | -0.13 | -0.07 | -0.09 | -0.26 | -0.03 | 0.22 | 1.3 | 8 | 7.08 | 0.46 |
| Oceania | 0.11 | 0.23 | -0.15 | 0.42 | 0.58 | 0.42 | 0.78 | 0.14 | 3.99 | 6.35 | 2.77 |
| North Africa & Middle East | 0.03 | 0.21 | 0.03 | -0.08 | -0.48 | -0.15 | 0.36 | -0.07 | 1.23 | 2.46 | -1.21 |
| Post-Soviet-Eurasia | 0.09 | 0.2 | 0.01 | -0.32 | -0.21 | -0.21 | -0.79 | -3.05* | 11.37* | 9.89 | 5.17 |
| East Asia | -0.26 | 0 | -0.24 | -0.2 | -0.2 | -0.29 | 0 | -0.79 | 0.36 | 1.08 | -1.83 |
| North America | 0.07 | -0.06 | 0.02 | 0.44 | 0.21 | 0.68 | 0.53 | -0.17 | 10.81 | 1.65 | -3.66 |
| South America | 0.04 | -0.12 | -0.05 | 0.11 | -0.06 | 0.05 | 1.05* | 2.57 | 15.1** | 10.34 | 6.1 |
| GDP per capita ($1 USD) | 0.01 | 0.06* | 0.01 | 0.04* | 0.02 | 0.05** | 0.07** | 0.18** | 0.45** | 0.17 | 0.06 |
| Advantaged (H) | 0.97*** | 1.05*** | 0.32** | 1.1*** | 2.13*** | 3.35*** | 2.55*** | 6.29*** | 14.62*** | 9.98*** | 7.96** |
| Disadvantaged (H) | 0.02 | -0.36*** | -0.13* | -0.25* | -0.49** | -0.66** | -0.64* | -2.14** | -8.48*** | -5.67* | -5.6* |
| Advantaged | 0.21* | -0.13 | -0.03 | -0.06 | 0.03 | 0.06 | 0.01 | 1.63* | 1.16 | 1.66 | 1.95 |

*Note:* $^{*}$p<0.05; $^{**}$p<0.01; $^{***}$p<0.001, (H) indicates homophily terms

Table 2.1: Results for network regression models *without* the inclusion of a time lag term for the prior period.

1970's, ranging from 1.34 to 2.05, possibly influenced by the cold war era. As for the distance measure, we do see an effect from the 1970's onward and it is negative, meaning that the farther apart countries are, the fewer IEAs they co-ratify on average. This finding offers modest support for the regionalism hypothesis, but indicates that the mechanism for co-ratification may relate more to the subject matter of the agreements than to shared language or culture. This finding is paired with the contiguity effect, which is significantly positive in all but three decades indicating that regionalism is in effect for neighboring countries, likely due to the environmental nature of the treaties at hand.

While these results show some support for regionalism, the models with the addition of the lag term lack this modest support. There are almost no significant effects for all three variables of interest, minus some early positive effects for contiguity and some later effects

Network Regression Results – All Time Periods (Lag Included)

| | 1900-29 | 1930-39 | 1940-49 | 1950-59 | 1960-69 | 1970-79 | 1980-89 | 1990-99 | 2000-09 | 2010-19 |
|---|---|---|---|---|---|---|---|---|---|---|
| Intercept | 0.66 | 0.05 | -0.5 | 1.41* | 1.45 | 1.8 | 5.38* | 37.24*** | 27.23** | 1.3 |
| Contiguity | -0.13 | 0.15* | 0 | 0.52** | 0.43* | 0.12 | 1.12* | -2.09 | -1.75 | -0.18 |
| Distance | -0.04 | 0.01 | 0.1 | -0.16* | -0.12 | -0.12 | -0.24 | -2.12** | -1.39 | 0.55 |
| Europe (H) | 0.89*** | 0.17* | 0.32* | 2.97*** | 0.21 | 1.47*** | 5.99*** | -3.75 | -2.85 | -2.07 |
| Asia (H) | -0.01 | 0.01 | 0.61 | 0.34 | -1.64*** | 0.35 | -0.91 | -5.28 | -2.86 | 0.2 |
| Africa (H) | -0.04 | -0.06 | -0.07 | -0.06 | 0.38 | -1.08** | 0.44 | -3.74 | 1.89 | -0.33 |
| Oceania (H) | – | -0.09 | 1.97* | -0.59 | 0.25 | 0.41 | 0.45 | -3.74 | 1.01 | 2.68 |
| North Africa & Middle East (H) | -0.18 | -0.12 | 0.09 | -0.1 | 0.72** | 0.63 | -3.61*** | -2.98 | 3.55 | -1.92 |
| Post-Soviet-Eurasia (H) | -0.19 | 0.3** | -0.23 | 0.11 | -0.61* | -0.44 | -1.43 | 32.27*** | -2.67 | -2.43 |
| East Asia (H) | -0.27 | -0.05 | -0.34 | -0.77 | -1.28* | 0.06 | -1.09 | -14.25* | -4.29 | -1.25 |
| North America (H) | -0.27 | 0.34* | 1.83** | -1.72** | 1.02 | -0.6 | 1.03 | 5.09 | -9.1* | 1.38 |
| South America (H) | -0.02 | 0.02 | 0.8** | -0.57* | -0.54 | 1.38** | 0.22 | -1.75 | -1.1 | -0.31 |
| Asia | -0.08 | -0.08 | -0.12 | -0.02 | -0.22 | 0.01 | -0.79 | 2.43 | 3.76 | -2.72 |
| Africa | -0.15 | -0.01 | -0.02 | -0.05 | 0.16 | 0.04 | 0.22 | 6.21 | 3.52 | -2.33 |
| Oceania | -0.09 | -0.17 | 0.55 | -0.12 | 0.08 | 0.28 | -1.25 | 3.49 | 4.92 | 0.37 |
| North Africa & Middle East | 0.1 | 0.02 | -0.18 | -0.28 | -0.01 | 0.57 | -1.28 | 1.44 | 4.03 | -1.35 |
| Post-Soviet-Eurasia | 0.28 | 0.01 | -0.32 | 0.33 | -0.05 | -0.69 | -2.56* | 19.24*** | 3 | -0.24 |
| East Asia | 0.12 | -0.2 | -0.2 | 0.25 | -0.17 | -0.15 | 0 | 1.67 | 1.81 | -1.01 |
| North America | -0.03 | 0.06 | 0.48* | -0.42 | 0.55 | -0.13 | -1.61 | 10.91* | -4.48 | -1.17 |
| South America | -0.12 | 0 | 0.11 | -0.2 | 0.01 | 0.86 | 0.4 | 10.52* | 1.81 | 0.3 |
| GDP per capita ($1 USD) | 0.05 | 0.01 | 0.04 | 0.01 | 0.04* | 0.02 | 0.06 | 0.23* | -0.01 | 0.01 |
| Advantaged (H) | 0.87*** | 0.18* | 0.9*** | 1.1*** | 1.23*** | -0.04 | 2.72*** | 4.08 | -0.39 | 1.32 |
| Disadvantaged (H) | -0.28* | -0.08 | -0.21 | -0.23 | -0.32 | -0.15 | -1.04 | -4.67* | 0.1 | -1.52 |
| Advantaged | -0.16 | -0.03 | -0.07 | 0.01 | 0.23 | 0.05 | 1.74*** | -0.46 | 0.13 | 0.32 |
| Period t-1 (Lag) | 0.36*** | 0.15*** | 0.68*** | 1.42*** | 1.18*** | 0.95*** | 1.35*** | 1.71*** | 0.71*** | 0.75*** |

*Note:* $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$, (H) indicates homophily terms

Table 2.2: Network regression results *with* the inclusion of a time lag term for the prior period.

for distance as shown in Figure 2.3. European homophily is still present in some periods, but at much lower values and it is non-significant in the past three decades. This suggests that while regionalism may have had some influence in the past, mostly from negotiating shared resources that cross national boundaries, regionalism plays a surprisingly small part in the modern global network for IEA co-ratification. The models taken together indicate that regionalism may arise from prior structuring of the network and an early tendency towards co-ratification between neighboring countries.

While not in direct support of regionalism, there are a few findings from the regional categories that stand out and may offer insights into general IEA trends. First, there is a massive effect for both increased co-ratification and high homophily among countries in the region of “Post-Soviet Europe and Asia” in the 1990’s. These effects come through in both models; the homophily effect is 11.2 in the non-lagged model and a staggering 32.27 in the lagged model, while the node level effect is 11.37 and 19.24, respectively. There is a similar, but opposite effect for East Asian countries during this decade. There is a strong tendency towards heterophily among these countries with an effect of -14.25 in the lagged model, meaning that they are expected to co-ratify 14 fewer IEAs with each other on average, than with countries in other geographic regions, net of other effects. These findings may suggest a reaction to exogenous shocks, which is discussed below.

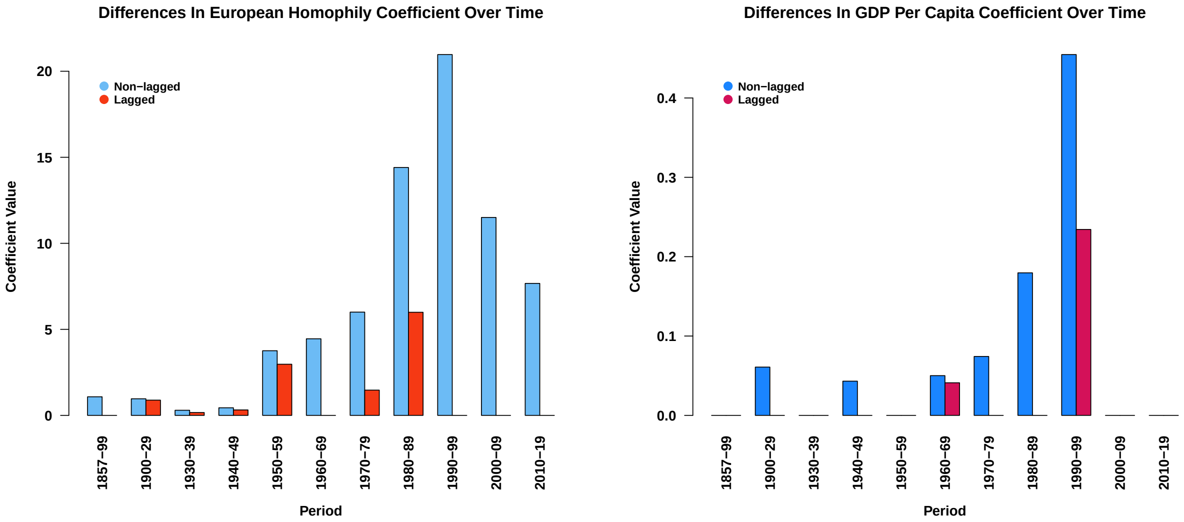

Figure 2.4: Visualization of the coefficient values for both the European homophily and GDP per capita terms across all periods. GDP per capita is measured in units of $1000 USD. Only significant values are displayed with significance measured at the 0.05 level.

### 2.5.2 World Systems

The first set of results shown in Table 2.1, those without the lag term included, tell a clear world systems story. While the resource advantaged countries do not co-ratify at significantly higher rates than the resource disadvantaged countries, we see a distinct core-periphery pattern in terms of the homophily effects. Shown in Figure 2.5, the homophily effect for the resource advantaged countries grows from 0.97 in the late 1800's to 14.62 in the 1990's, leveling off at a relatively high rate of 7.96 through the present. This indicates that in the most recent decade, net of other effects, two resource advantaged countries co-ratify almost 8 more IEAs on average than a pair of differently resourced countries. This pattern is mirrored by the resource disadvantaged group as the tendency away from homophily stays steadily significant, spiking in the 1990's at a level of -8.48, and then leveling off at a relatively high negative value of -5.6 through the present. This means that, presently a pair of resource disadvantaged countries, on average, co-ratify almost 6 fewer IEAs than a pair of differently resourced countries. This pattern of high homophily within the "core" countries, coupled with a high adversity towards homophily in the "periphery" countries is the textbook picture of the modern world system. The consistently high level of European homophily, shown in Figure 2.4, also adds support for the world systems view, as Europe is frequently thought to be over-represented in the core. The last bit of support comes from GDP per capita, also shown in Figure 2.4, being significantly positive for a majority of the models, indicating the increased average tie strength associated with a $1 increase in GDP per capita.

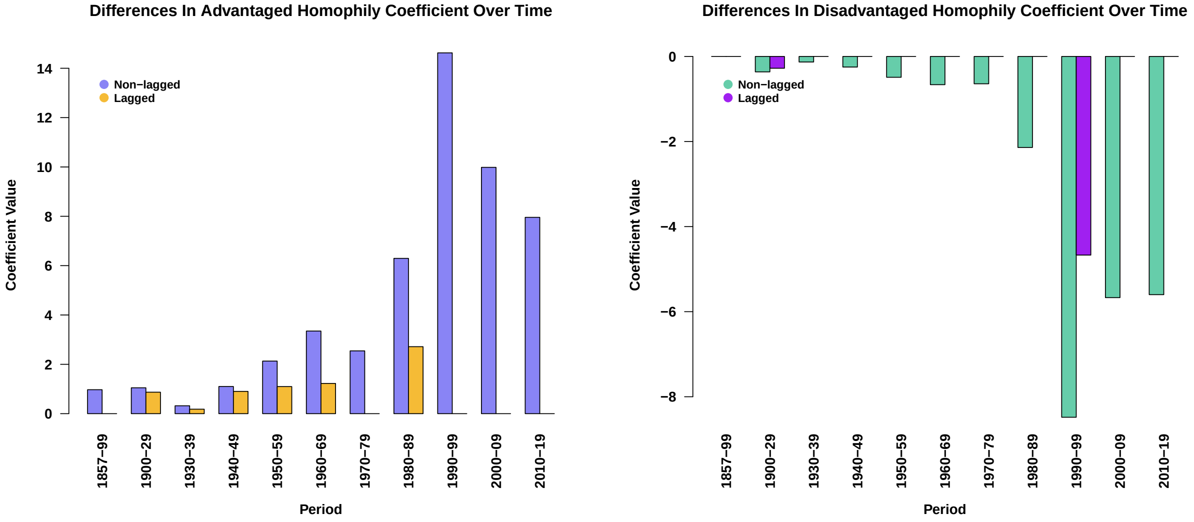

Figure 2.5: Visualization of the coefficient values for both the advantaged homophily and disadvantaged homophily terms across all periods. Only significant values are displayed with significance measured at the 0.05 level.

While this is a clear substantiation of world systems theory, without controlling for time, we are only getting part of the story. Table 2.2 shows the second set of models, which includes the lagged term as a covariate for past co-ratification. These results indicate that the findings in support of world systems theory are largely a result of the past co-ratification network rather than a within-period process. Once I control for the prior network structure, homophily among the resource advantaged countries still shows up through the 1980's, but the effect sizes are drastically smaller in all periods, only reaching 2.72 at its highest amount (compared to 14.62 in the non-lagged models). The spike of the 1990's, along with the high levels of homophily in the following two decades dissipates as a result of the lag term; in fact, there is no significant homophily effect among the advantaged countries for the past three decades in the lagged models. This is coupled with almost no significant effects for the resource disadvantaged countries across all periods in the lagged models. This change is mirrored in the effect for European homophily, which ends after the 1980's, and GDP per capita, which goes from being significant in 6 periods to only 2 periods after the addition of the lag. This does not indicate that the findings of the non-lagged models are incorrect, but rather that the strong effects we see for world systems position are a result of prior co-ratification patterns as opposed to a within-period mechanism. This finding is important, but subtle. While the non-lagged models show strong effects for world systems position, the lagged models help us understand that when isolating the within-period effects, there is an evolution over time from a world systems configuration to a more uniform pattern of co-ratification.

### 2.5.3 World Society

World society theory was not measured directly with a variable of interest as it predicts more about reductions in homophily over time than a specific homophily effect. When looking at the models without a lag term, shown in Table 2.1, we can see that there is a large increase in the intercept term from 1.04 in the early 1900's to a peak of 68.9 in the 2000's, meaning that co-ratification rates have increased drastically over time. Specifically in the 2000's, net of the other variables, a pair of countries is expected to co-ratify 68.9 IEAs within the decade on average, compared to only 1.04 in the almost 20 years between 1900 and 1919. This trend is stark, but unsurprising as the number of IEAs has increased dramatically over the 166 year period. It does however speak to the proliferation of IEAs and the participation in them, which is indicative of world society theory and indicates the normalization and institutionalization of IEAs. Despite the abundance of IEAs in more recent decades, we do not see much of a leveling off of homophily effects; in fact, we see them plateau at relatively high levels. Without at least a decrease in homophily, my first set of results do not show much support for world society theory.

Figure 2.6: Visualization of the coefficient values for the intercept term and lag term across all periods. Only significant values are displayed with significance measured at the 0.05 level.

Looking at the second set of models, the one with the lag included, we still see a large intercept term from the 1980's through the 2000's, which mimics the period of largest growth in IEAs. The effect is more than halved at 27.23 in the 2000's, but this still means that the average expected co-ratification count for a pair of countries is over 27 IEAs, net of the other effects, which is still impressively high. We also see that from the 1990's onward, many of the homophily effects become non-significant in the lagged models. In fact, in the most recent decade, the only significant effect is that of the lag term. This result may be the most striking of all, indicating that once I control for the structure of prior co-ratification, countries are indistinguishable on my variables of interest. This pattern appears to begin in the 1990's. The lack of homophily effects paired with the high intercept term implies a proliferation of IEAs that countries, net of prior co-ratification and regardless of resources or region, are participating in at comparable rates. This key finding supports a shift in the past fifty years to a world society configuration for International Environmental Agreements.

### 2.5.4 Prior Co-ratification

The lagged term in my second set of models was measured as the co-ratification network in the prior time step. This term indicates the increase in current co-ratification count that is associated with a one unit increase in the prior co-ratification count. This term ranges from 0.15 to 1.71, with an average value of 0.92 across all periods. This indicates that on average, each co-ratification in the prior time step is associated with an almost one unit increase in the current time step, meaning that co-ratification is an almost one to one process across periods. It is no wonder with the magnitude of this effect that we see a decrease in the effect sizes for many of the variables of interest. These results show that IEA co-ratification is a process that is shaped largely by prior negotiations and agreements and that much of the current network is structured by prior mechanisms.[2]

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[2] The lagged models had to be run on the subset of countries that were present in both the current period and the prior period due to the constraints of network regression models. In order to make sure that the differences observed between the lagged results, shown in Table 2.2, and the non-lagged results, shown in Table 2.1, were not simply a byproduct of subsetting, I ran my models on the subset of countries for each period *without* the inclusion of a lag term and compared them to the non-lagged results. The effect sizes were all comparable and none of the findings of interest were affected, indicating that the differences were in fact attributable to the addition of the lag and not the removal of countries.

## 2.6 Discussion

Moving from analyses that treat national political action as independent to models that can account for dependence within cooperative behavior is essential to understanding global politics. Many theories of global organization already tacitly involve dependencies, including those that have been used to describe environmental action. Here I have taken one step forward in understanding global environmentalism by modeling mixing effects, while using models that can reliably handle the dependence often present in network data. This was done to better understand what factors influence co-ratification of international environmental agreements over time. This paper is one of the first to model co-ratification counts rather than rates of IEA ratification by individual countries, as well as one of the few to model the full time span of IEA production. This research further informs our understanding of global environmental politics by separately controlling for the prior network, allowing for the disentanglement of effects over time, and offers some broad insights into world society and world systems theory as well as the relationship between the two. Below, I outline the hypotheses tested, and what theoretical frameworks are supported by my results; this is summarized in Table 2.3.

| | | Lag Excluded | Lag Included |
|---|---|---|---|
| H1. | Regionalism | | |
| H2. | World Systems | ✓ | |
| H3. | World Society | | ✓ |

Table 2.3: Table showing which set of models supports each of the three hypotheses tested.

Three central theories were tested alongside each other, regionalism, world systems, and world society theory. In the case of regionalism, there are clear reasons to suspect an impact of geography on pairwise coordination, especially in the case of IEAs, which often handle matters of shared resources. While there is some support for contiguity and distance impacting rates of co-ratification, H1. is poorly supported in these models, showing few regional homophily effects outside of Europe. It appears that contiguity had early impacts on the IEA network and that this effect may have compounded with time, whereas distance impacted co-ratification in the latter half of my time span. The results suggest that shared resource management does influence the pattern of co-ratification, but that the effects have lessened in recent periods. This may be due to the fact that shared resources do not necessarily need to be re-litigated over time and could indicate the progressive decrease in the need for small scale MEAs.

Despite the lack of support for regionalism broadly, there are findings to suggest that exogenous shocks may have region specific impacts. I found that in the 1990's, those countries in the post-soviet European and Asian region had incredibly high levels of homophily along with increased rates of co-ratification. I believe that this finding is likely linked to the fall of the Soviet Union, which would indicate that directly after this shock, countries chose to ratify IEAs at higher rates than other countries and at even higher rates with each other. This would suggest that at least for these countries, IEAs were politically important during a time where new international relations were being developed. These findings potentially point to the use of IEAs for global political legitimation.

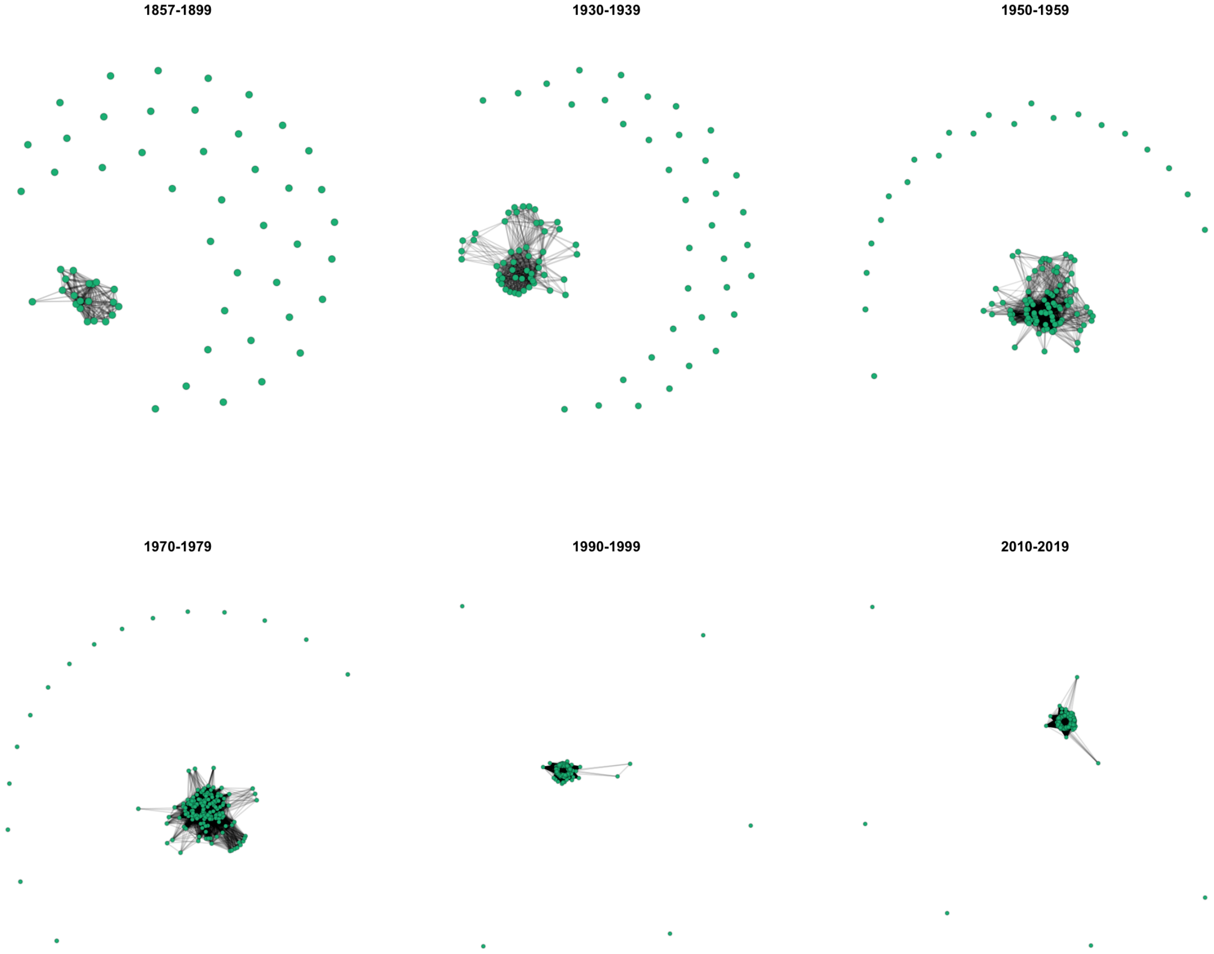

Figure 2.7: Visualization of the MEA co-ratification network over time. Networks are shown for every other period. Isolates are countries that existed during the specified period, but did not co-ratify any MEAs within that period. Ties are within period co-ratifications only, regardless of the signing year of each MEA. Ties are binarized for ease of viewing.

The other outlying effect for regional homophily was among East Asian countries in the same decade. In the 1990's there was a high tendency away from homophilous ties, meaning that, net of other effects, there were far fewer co-ratified treaties between countries within East Asia than there were between countries in other regions. This effect coincides with the 1997 Asian financial crisis that came after decades of economic expansion. This crisis left countries in the region economically unstable (King, 2001) and could have created a reluctance to join inter-region political action that extended to IEAs. Both increased globalization in the early 1990's and an aversion to inter-region coordination in the late 1990's could contribute to a negative homophily effect during this decade. In sum, these findings demonstrate the value of considering exogenous historical shocks when analyzing longitudinal data and point to potential future research to better understand how inter-regional conflicts, economic downturns, and the like can cause reverberations within regional environmental contexts.

My results present a more nuanced depiction of the two remaining theories, world systems theory and world society theory. World systems position seems to have played a large role in shaping the IEA network over time, with strong homophily among resource advantaged countries and strong heterophily among resource disadvantaged countries, along with a separate effect for GDP per capita. The first set of models in particular support H2. and a world systems theoretic lens to understanding IEA co-ratification, where the position in the world system impacts the strength of co-ratifying relationships. Yet, the second set of models provides nuance to our understanding and demonstrates that this effect is not necessarily due to within period mechanisms, but rather an effect that has compounded over time. It seems as though the world system shaped the IEA network from its inception and that these patterns became ingrained, likely through mechanisms that link IEAs to each other or that establish norms or channels of communication between countries (such as the use of amendments and oversight organizations). This is a novel insight that suggests the need for further investigation into these mechanisms as they have resulted in large effects throughout the history of IEAs and into the present.

These results make the benefit of modeling co-ratification with and without a lagged term clear. By accounting for the co-ratification structure of the previous decade, we can see that, beyond creating a backdrop of preexisting relationships and linkages between treaties, the world systems ordering does not appear to be an active exerting force in the present period nor for the preceding two decades. Thus, my second set of models lends support to my last hypothesis (H3.) implicating a world society theoretic paradigm. In fact, by controlling for prior co-ratification, we start to see features of a world society ordering emerge over time, with all homophily effects falling off in the most recent decade, net of the lag term. This finding is particularly remarkable, showing that net of the structure established in the prior decade, there are no effects left in the model that differentiate countries from one another. This shift clearly supports world society theory as it shows that while there are historic patterns of co-ratification that do exert influence in the present, there are no within period effects influencing rates of co-ratification through mixing differences nor through node level characteristics. Net of all historic co-ratification relationships, modern co-ratification is vastly more uniform. IEAs as a norm appear to have saturated the modern global network, which is a key prediction of world society theory.

Furthermore, the results not only support both world systems theory and world society theory, but actually demonstrate an evolution from one paradigm into the other. This finding echoes prior work by Yamagata et al. (2017), who showed a shift in IEA ratification; it went from being driven by the US and USSR to a world society model after the fall of the Soviet Union. While world systems position has historically shaped the IEA network, modern mechanisms of IEA co-ratification now resemble a world society configuration. This shift is demonstrated in Figure 2.7, which shows the binarized network within each decade. Early periods appear to show a textbook core-periphery structure, with a densely connected set of countries in the center, which are loosely connected to another set of countries, who are rarely connected to each other. However, as we go through the decades, we can see the core almost envelope the other countries, not only including an increasing number of countries, but simultaneously becoming denser as it does so, indicating a classic world society configuration. It is also important to remember that these networks are not cumulative, so this is a change in behavior within each decade, not simply an artifact of time.

This work has produced several valuable takeaways. First, it encourages researchers to view these theories in a more complex manner; rather than treating theories as necessarily in contention with one another, it is important to explore how theories may be co-occurring or how parts of different theories may be supported and not others. Societal systems are complex and multifaceted, so too are the answers to the sociological questions we ask. This work not only supports multiple theories that are too often pitted against each other, but I find strikingly strong evidence in favor of both. Secondly, I achieved this by using data that covered the entire time span of IEA production, allowing me to pick up on a change in co-ratification behavior. The use of appropriate methods to model the inherently dyadic nature of country-to-country co-ratification patterns paired with the use of both non-lagged and time-lagged network regression models also rendered these findings visible. This emphasizes the point that while it is important to incorporate time when modeling longitudinal data, it is also important to understand the part of the process that the past is accounting for.

Lastly, this work points to future areas of study. While I modeled co-ratification in a manner that controls for dependence, this does not equate to modeling the dependent processes directly. Future work should attempt to model dependencies, both within time and over time. For co-ratification, this would require the use of more complex modeling schemes and a broader set of covariates. Additionally, there is a need for research that digs deeper into the paradigmatic shift demonstrated here, in order to understand what drove the change in co-ratifying behavior. Research in this vein may be able to point to mechanisms that have influenced other global political processes as well. In terms of limitations, data availability has limited the scope of this study. A first place to expand would be to disentangle the opportunity to co-ratify and the choice to co-ratify. While this is a limitation of the current study, future data collection efforts on eligibility could make this possible. Additionally, testing these results with the addition of other variables, especially those that might capture world society more directly, might be an important next step. Finally, the process of two countries co-ratifying may be separate from the process of individual countries ratifying and withdrawing from individual IEAs, therefore I suggest that future research investigates ratifying and withdrawing behaviors in a way that captures social network dependencies, while also considering factors at the country and treaty level together, in order to fully understand this process.

## 2.7 Conclusion

Here I have shown how the international politics of IEAs has changed over time, supporting both a world systems and a world society theoretic paradigm. Surprisingly, it appears that there is an evolutionary process by which an earlier established world systems configuration gives way to a more uniform world society orientation. Through the use of a social network analytic approach, my study is one of the first to analyze the co-ratification process at the dyadic level. I hope that this analytic approach is extended to other areas of research on global politics where cooperative processes should be better understood, as the extension may generate more surprising results.

# Chapter 3

# Mutually Assured Protection: Analyzing international Environmental Agreements as an Evolving System

## 3.1 Abstract

This research is focused on the drivers of treaty ratification in the context of international environmental agreements (IEAs). I use the full history of IEA ratification from 1857 to 2022 and represent it as a bipartite network of countries and agreements. I test well established theories along with new agreement level and structural variables and I make use of Separable Temporal Exponential Random Graph Models (STERGMs) to model the likelihood of ratification. This is the first paper to control for country eligibility in the ratification process as well as the first to model one mode influences on the bipartite network, within the

ERGM framework. The findings suggest some support for extra-governmental organization membership and little support for world society positions as drivers of ratification. There is however strong evidence of geographic based patterns and well as the influence of agreement level characteristics, such as age and subject. Overall, the findings advance the study of IEAs and suggest new lines of inquiry for future studies.

## 3.2 Introduction

Environmental policy is necessary for the safe and sustainable use of natural resources, and global environmental policy is only possible with the cooperation of multiple countries. international Environmental Agreements (IEAs) are a form of interstate cooperation with clear and measurable participation and are a common form of global environmental policy. The success of an IEA depends largely on the proportion of countries ratifying, and therefore adopting, the terms of the agreement. Due to the shared impact of environmental degradation, the solutions to these problems require joint action. With such high stakes, knowing what drives ratification is of great importance and while multiple approaches have been taken to tackle this question, there are major gaps left in the literature. The goal of this paper is to fill some of those gaps and expand our understanding of international cooperation around the topic of the environment.

Studying why countries ratify agreements by accounting for variation in country level characteristics is a reasonable first approach. Unfortunately, it cannot account for the dependence of countries' decisions on each other's. Agreements are borne out of negotiations and compromise. They also impose new rules that only work if everyone agrees to follow them. No one wants to impose rules on themselves only to have no one else do so, making the self-imposed rules taxing, while ultimately ineffective. Those negotiating IEAs, and any other form of international regulation, are aware of this risk and are likely to weigh this risk when choosing to ratify; it is therefor highly probable that the negotiation process will produce some level of dependence among ratification decisions. Examples of these dependencies might include the influence of pre-existing ratifications on new ratifications or even pre-exisiting diplomatic relationships on the likelihood to ratify the same agreement. These dependencies may also expand beyond the countries to the agreements themselves as they can be linked by both subject and legal lineage. Modeling the combination of country level effects and agreement level effects along with structural variables that capture dependent relationships is necessary for a full understanding of the IEA process and not accounting for these effects will leave models and our understanding of the process incomplete and potentially inaccurate. Having well calibrated models allows us to make well informed and useful policy recommendations and may ease future IEA negotiations.

While many studies represent ratification data as independent observations of countries taking individual actions, this same data can be represented in a relational format, which ushers in the use of network modeling techniques. Ratifying can be represented as a "tie" between a country and an IEA; this process can be dynamic with ties representing a ratification existing as of a certain date and with the network adding more ties as time goes on. The countries and IEAs become two distinct sets of "nodes" and variables can be measured at various levels of the network. Many network modeling techniques are designed for the very purpose of analyzing network dependencies and have the advantage of being able to simultaneously model structural variables and variables at the level of the individual node and tie. Dynamic network models also have the ability to account for change over time and control for past states of the network. This paper will utilize dynamic network models to explore previous explanatory factors with lesser studied structural factors in order to test prior findings along with untested theories of international cooperation. The range of data will also be expanded from previous literature in order to capture the ratification process at the broadest level and across the longest time span possible. This study aims to employ these techniques to answer one central research question, what drives IEA ratification?

The need for international environmental cooperation is becoming ever more apparent. While there is debate over the effectiveness of IEAs, there is some empirical evidence of their positive effects on the environment (Dietz and Kalof, 1992; Haas and Sundgren, 1993), but these agreements are only effective if the terms are enacted. Knowing what drives ratification can aid in the drafting process, making agreements more targeted and more successful from the start.

## 3.3 Background

### 3.3.1 Ratification as an Independent Process

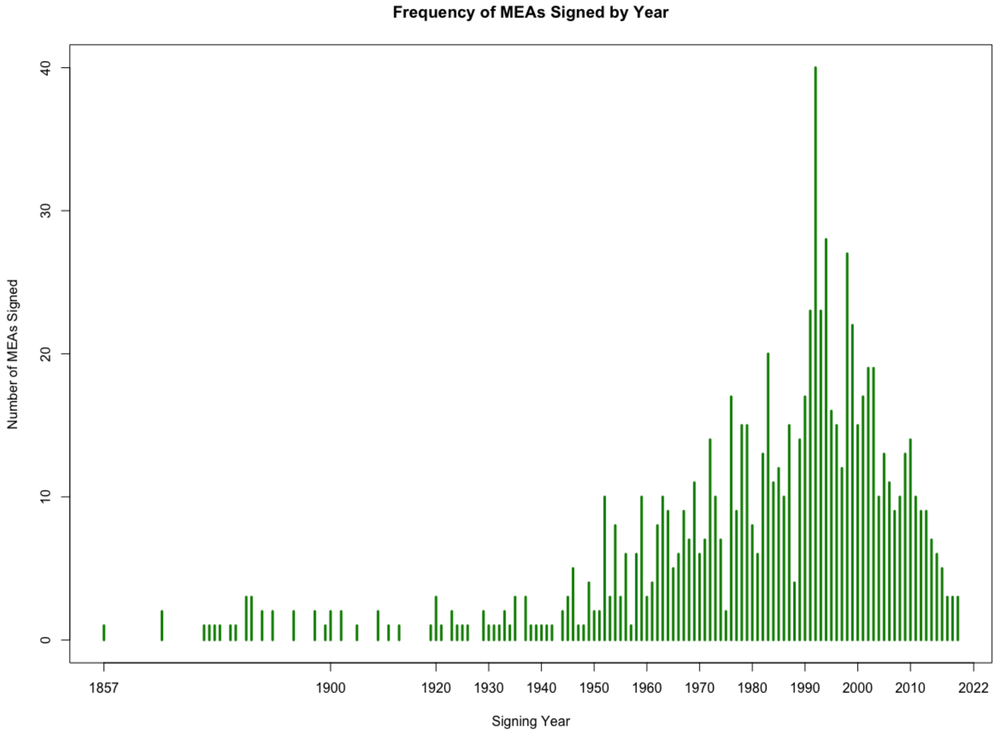

Figure 3.1: Visualization of the frequency of MEAs across the 166 years of data. Dates are relative to the signing year of each MEA.

Since the first international Environmental Agreement in 1857, the number of IEAs has grown

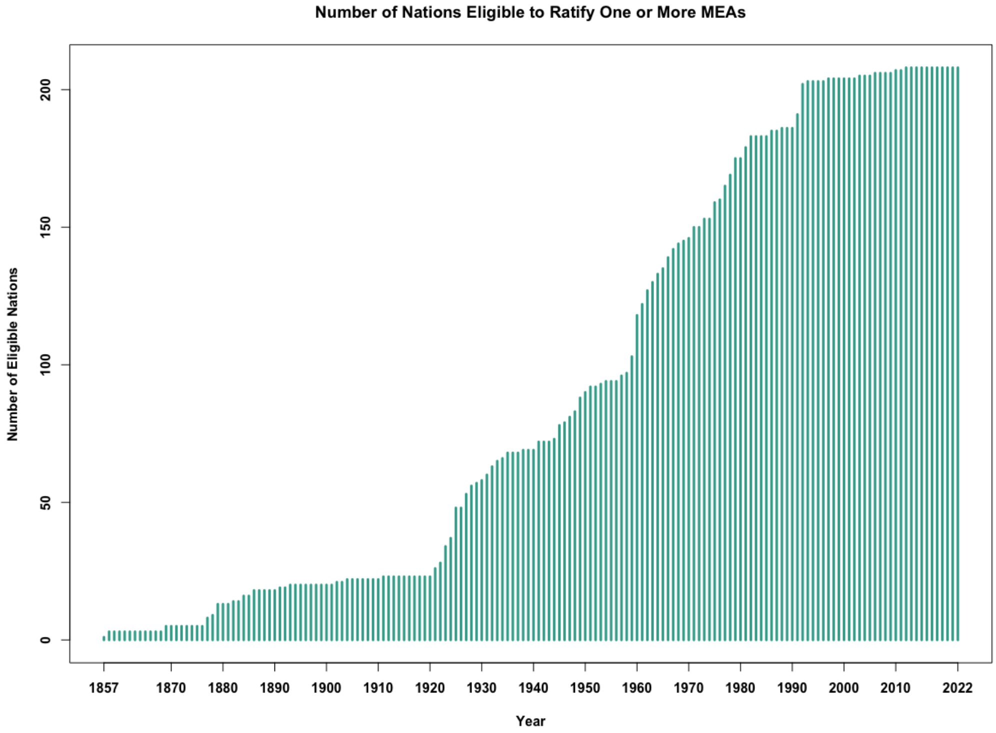

Figure 3.2: Visualization of the number of countries eligible to ratify at least one MEA across all 166 years, from 1857 to 2022.

into the thousands and nearly every modern country has ratified at least one. The first of these agreements concerned the water level of lake Constance and established actions that the riparian states of the lake would take to ensure the health of their shared resource. The most recent agreement was connected to the United Nations Convention on the Law of the Sea and works to conserve marine biological diversity in areas beyond national jurisdiction. Both are regarding shared bodies of water, but at vastly different scales. The scale of IEAs and the sheer number of IEAs has increased tremendously over the past 166 years; it is likely that the drivers of ratification have undergone changes as well. The growth in IEAs can be seen in Figure 3.1 and the number of countries eligible to participate in a given agreement can be seen in Figure 3.2; both have grown at very similar rates. We can also see that the number of eligible countries appears to have begun growing before the growth of MEAs themselves, indicating that agreements were becoming open to a greater number of countries by the 1920's, while treaty production didn't ramp up until at least the mid-

1940's. Along with the proliferation of IEAs themselves, the world has seen a growing trend in environmentalism generally. This can be seen in the growing number of national parks (Gissibl et al., 2012), the increased number of countries requiring environmental impact assessments (Hironaka, 2002) and the growing trend among domestic governments allocating resources and entire departments towards environmental management (Organization, 2021). When taken together, these changes appear to indicate a shift in norms at a global scale. Many sociologists have concerned themselves with the creation and evolution of international norms, including their specific influence on IEAs.

The widespread adoption of institutional mechanisms to enforce such norms, like those listed above, is often liked to the world society theoretic framework. World society theory addresses the shift in global cultural trends, explaining that these shifts do not always arise by force or coercion, but rather by countries attempting to gain legitimacy through the adoption of global norms and behaviors. These norms are thought to be generally set by those "closest to the world society," but the specific mechanisms for the creation of these norms is quite variable. There has been well known work on smaller organization level norm changes that suggest specific mechanisms including, isomorphism, mimetic processes, and normative pressure (DiMaggio and Powell, 1983b). These could potentially be expanded beyond the organizational level to the global stage. In that same vein, many global elites and those in charge of international regulation receive similar training and education through processes of organizational isomorphism, which may also influence IEAs and other forms of international law in particular. Additionally, much of the modern world culture seems to promote science driven policy and this could help explain the adoption of pro-environmental practices and regulations, such as IEA participation.

In order to measure the effects of global level norms on various outcomes, "closeness to the world society" is often proxied by the participation in international nongovernmental organizations (INGOs). Specifically interested in IEA ratification as an outcome, Frank

(1999) looks at the effect of this variable on ratification rates using structural equation models. The finding suggest that the most important explanatory variable was having dense linkages to the world society. All variables were measured as latent variables – capturing the combination of multiple factors. While this measure may capture some of aspects of the world society, the very notion of global influence calls for a dependent measure. To my knowledge, such a measure has not been used within the IEA space.

As is evident from the first 50 years of IEA ratification, environmentalism was not rapidly adopted as a norm. Yamagata et al. (2017) studies the movement to a pro-environmental culture, looking at IEA ratification specifically. By incorporating different time periods, they demonstrate a shift in norms away from two pillars of power towards a world society model. They find that the influence of the USA and USSR are strongest before the fall of the Soviet Union; if either country ratified a treaty, this would increase the likelihood of ratification by strong and weak countries. However, after the fall of the USSR, only weak countries, as they define them, were influenced by those countries' ratification patterns and the growing factor of importance was a country's proximity to the world society. This suggests the need to model different time periods separately to understand the shifts and differences in IEA ratification as they are likely not ubiquitous across time. It also implies an advantage to modeling the full time span of IEA ratification, something few studies have done, often due to a lack of data availability.

The strong influence of wealthier and more powerful countries has been hypothesized often as a competing theory of global norm setting. World systems theory very broadly describes the world as being organized into different systems at different points in time (Chase-Dunn and Grimes, 1995). The modern world system is theorized as a core-periphery structure often dictated by trade, resources, and power. The influence of this core-periphery structure has been hypothesized for IEA ratification specifically as well. Roberts et al. (2004) tested measures of world systems theory against rational choice institutionalism as an explanation for the motivation behind IEA ratification; they conduct a path analysis in order to make claims about the causal mechanisms behind the choice to ratify. Their findings suggest that the overall effect of a disadvantaged position in the world economy is negative on the propensity to ratify IEAs. This finding is consistent with an earlier paper (Roberts, 1996) in which world system position is found to have a similar impact on treaty ratification. There are many reasons to suspect the impact of global resource control in the context of IEAs. In theory, natural resources are frequently extracted from peripheral countries by core countries. This leads the resource advantaged core more likely, and more able, to ratify environmental agreements. If core countries are not domestically producing the raw materials or products that would be affected by an IEA, then it poses less of a burden to ratify. This effect is magnified by the wealth difference between the two groups. As the terms of IEAs often pose some financial burden on the domestic government, it is easier for the wealthier, core countries to take on that burden. The peripheral countries have less incentive and ability to financially handle the terms of an IEA. Additionally, there is said to be trade pressure on these countries as other countries rely on them for cheap exports. It is therefore in the financial interest of both advantaged core and disadvantaged periphery countries to have the periphery ratify fewer IEAs. Lastly, the domestic governments of peripheral countries may experience less pressure from citizens and or be less responsive to citizens desire for environmentalism, which makes them less likely to feel domestic pressure to ratify. Taken together, we may expect both a node level effect for resource control and a dyadic mixing effect for world systems position. While the findings of Roberts et al. (2004) push back against much of the work supporting institutionalism in the context of IEAs, they only study 22 treaties over the course of 53 years. Additionally, the studies are difficult to compare as they use varying time periods and subsets of treaties, which suggests the need for a broader analysis, one that utilizes a larger set of time points as well as a larger set of agreements.

These theories have been tested against various others, the main two being environmental degradation (Nanda, 1983; Sprinz and Vaahtoranta, 1994; Dietz and Kalof, 1992) and political orientation (Congleton, 1992). The first views the push to ratify environmental treaties as a response to domestic environmental degradation. If a country is experiencing heightened levels of environmental degradation, they will be more likely to enact environmental policy on the international level. While the evidence for this theory has been mixed, the use of a control for environmental degradation is warranted. The second theory relates to the political orientation of a country, which is often measured as whether a country is authoritarian or not, or as how democratic a country is. This has been theorized and tested as a factor in IEA ratification specifically. Congleton (1992) theorizes that authoritarian leaders face a higher price for the enactment of an environmental treaty compared to an average citizen or voter. The idea behind this is that in an authoritarian regime, the leader is responsible for the domestic decision to ratify and they must weigh the costs and benefits of such an action. This is in comparison to a democratic regime where the average voter is responsible for weighing the costs and benefits of such a decision, meaning that the consequences are distributed over a larger group of individuals and may be weighed less heavily. While this is admittedly a simplification of domestic environmental politics, Congleton (1992) finds evidence to support this theory. The benefit of this current study is the ability to incorporate these prior findings with new dyadically dependent factors.

### 3.3.2 Ratification as a Dependent Process

Venturing into the realm of treaties as networks, Valente et al. (2015) and Valente et al. (2019) looks at the adoption of the first global tobacco control treaty. The studies treat adoption as a diffusion process and find several factors to be of importance. They too find a significant and positive effect of a country being democratic. They also find some regional effects that either increase or decrease the likelihood of adoption, along with an effect for the length of time the treaty has been around; ratification becomes less likely over time. They also tested dyadic relationships with respect to treaty adoption. General trade networks and specifically tobacco trade networks were significant, with the former being negative and the latter being positive. The main thrust of the paper was the influence of the GLOBALink network on diffusion. GLOBALink is an online forum concerning tobacco control, which is sponsored and hosted by the Union for international Cancer Control (GLOBALink, 2010). The theory was that having preexisting ties around the topic of tobacco control would lead to an increased influence on countries' ratification patterns and they found that shared subscription groups within GLOBALink increased the likelihood of ratification, meaning if a country that subscribed to a GLOBALink group ratified the treaty, those countries in that same group would then be at a higher likelihood for ratification. While GLOBALink is only concerned with tobacco control, there are many international groups that may show similar effects for IEA ratification and in general, the inclusion of one mode country effects seems crucial.

In addition to country relationships, treaties have connections among themselves as well. While not interested in ratification, Kim (2013), has looked at the full IEA network from 1857 to 2012, in order to understand the relationships between treaties and how they vary by time. They specifically focus on the linkages of cross-references between treaties, coding text copies for mentions and creating a directed network of 747 environmental agreements, signed between 1857 and 2012, and the 1001 cross-references among them. The main motivation for the paper is testing whether or not the system of international environmental governance is fragmented. Their findings suggest that the IEA network was sparse and loosely connected until the formation of the United Nations in 1945, which increased the number of treaties, but also fragmentation. However, since the 1970's, fragmentation has decreased and since the early 1990's, agreements have become systematized and interconnected. They also mention that in the 2000's the rates of IEAs reduced, and they propose "negotiation" fatigue as a possible source of this reduction. Additionally, they find that there are distinct clusters of different types of treaties, so we may expect varying rates of ratification by treaty type or even a pattern of homophily among different groupings of treaties, several of which I test for here. Lastly, Kim (2013) divides the history of IEAs into 6 distinct stages, the 1850s to mid-1940s, mid-1940s to mid-1970s, mid-1970s to the 1980s, the 1990s, the 2000s, and the 2010s. Considering that they found the evolution of the one-mode treaty citation network to evolve differently in these different periods, we might expect to see variation in the two-mode model selection grouped by these periods as well.

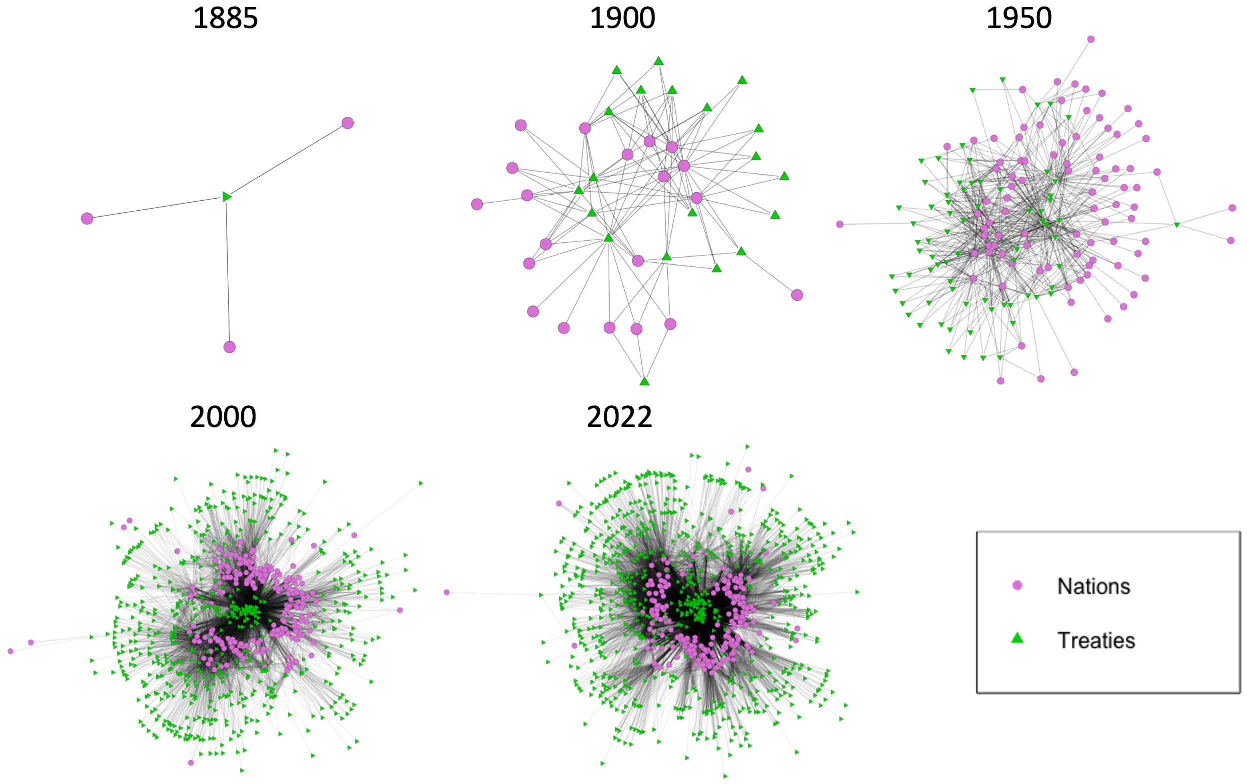

Figure 3.3: Bipartite IEA network over time showing a dramatic increase in both countries and agreements through the present.

The authors emphasize the need to view international environmental governance from a dynamic network perspective and pushes researchers to try and understand its complexities. The previous literature on IEA ratification supplies a wealth of effects and variables to consider, but few have modeled this process as an evolving network. One of the few to do so is Campbell et al. (2019) who measures the influence of countries and IEAs on each other over an almost 30 year period. This paper most closely reflects the aims and approach of the current research, however, there are some key differences to note. First, I expand on their dataset by including all multilateral IEAs (meaning between three or more countries) on record, rather than the subset from 1972 to 2000 that they analyze. Additionally, they employ a network model that only allows for dependence on prior time periods. While this is an important step in the modeling of IEAs, this cannot account for the within time dependence. Knowing that these agreements are often negotiated at summits, and other large gatherings, which is generally followed by signing and ratification within a short period of time, it is likely that there is dependence within years. The approach employed here will allow for dependence within time periods, while measuring similar factors discussed in Campbell et al. (2019).

The authors looked at several types of influence, negative and positive country influence, and negative and positive treaty influence. They find that generally, countries are less likely to be influenced into inaction by democracies, and are more likely to be influenced by states within their same continent, but overall, they report this as an uncommon phenomenon. They find that positive state influence often occurs between countries of similar economic productivity, but also report that it was uncommon. While they hypothesized that treaties could compete with one another, causing a negative influence, or could create linkages and positively influence one another, they unfortunately find little evidence to support either.

While the findings suggest little interconnectedness, this could be due to their data selection process, which they are unclear about, not specifying whether or not they incorporate information on ratification eligibility per country-treaty pair. Additionally because they do not allow for dependence within time, this may be obscuring much of the dependence present in the network.

This work used innovative techniques and strong hypotheses of dependence to study IEA ratification. This research will expand on these findings by testing similar hypotheses within time and over a larger time span, while also incorporating all IEAs to date. The authors also note the following, "Some existing methods for analyzing bipartite networks that evolve over time may allow analysts to assess the structure of a network, but do not allow for the inference of influence networks. Others allow for the inference of influence networks, but do not disentangle within-mode influence and, hence, face interpretation and inferential challenges." Exponential random graph models (ERGMs), which they use in the latter half of their analysis, handle bipartite networks well, even over time, but they do not contain terms for one mode network influence on a bipartite graph. In order to circumvent this issue, I have developed two new ERGM terms that allow for this very analysis, the details of which are discussed in the methods section below. Overall, this study takes prior findings and expands on them by changing the analytic perspective, viewing ratification as a network and testing new structural and treaty factors alongside country level characteristics.

## 3.4 Data

The data for this project was compiled using several different sources. All treaty data is from the University of Oregon's IEA Database (IEADB) (Mitchell, 2002-2021). The IEADB is the largest database of its kind and contains data on all multilateral and bilateral IEAs to date, including signing date, and actions taken by country and year. I chose to only use multilateral IEAs (MEAs) for this analysis in order to narrow the scope of the research, but this work could easily be extended to the bilateral case as well. MEAs are between three or more countries, as opposed to bilateral Environmental Agreements (BEAs) that are only between two countries. Additionally, I excluded any amendments that allowed for tacit acceptance as this does not require new negotiations and is therefor a different process than the drafting of original IEAs. Also, I have only included binding agreements, which require those entities that ratify them to abide by the terms of the agreement once it has entered into force. Lastly, I chose to exclude treaties related to nuclear weapons as the politics surrounding this topic are frequently discussed in non-environmental terms and the factors driving ratification may be anomalous in comparison to the majority of the data, which could obscure the results. After these adjustments, I was left with 844 agreements in total ranging in signing year from 1857 to 2022. These IEAs have all been ratified by some proportion of the 208 countries in my data set. It should also be noted that while the University of Oregon's IEADB separates certain countries by year, such as 'Norway' and 'Norway pre-1905'; I have chosen to collapse these countries into a single entity and all countries are identified by their names as of 2022.

The original data available through the IEADB did not include a risk set for treaties, meaning a list of all countries eligible for ratifying a given IEA. If ties can be present or absent, without the risk set, we only know about the present ties, but not about the absent ones. This piece of information is crucial for any network analysis as without it, we cannot say anything about what influences tie formation. In order to conduct this analysis, I utilized the text copies available through the IEADB and hand coded each treaty for country eligibility; text copies were available for over 90% of all MEAs.

I have arranged the data as a series of 166 bipartite affiliation networks (one per year) where a tie from a country to an agreement represents ratification of that agreement by that country as of that specific year. This data was then divide into twelve broader time periods in order to allow for variation in model selection across time. The first two periods range from 1857 to 1900 and from 1900 to 1930, while the third through tenth periods cover a decade each from 1930 to 2010. While the later periods are divided by decade in order to provide a common reference point, the earlier periods were too sparse to cut at this level. Additionally the last two periods, the eleventh and twelfth cover the years 2010 to 2014 and 2014 to 2022, respectively. This was done due to data availability for the covariates in the most recent years of the dataset. This data was then combined with agreement level factors, including a categorical for the subject of an agreement and a categorical for the agreement type (agreement, amendment, or protocol) along with legal lineage data which links agreements to each other across time.

While the IEADB is an excellent source for treaty related information, the data for the 208 countries had to be collected from other sources. First, data on GDP per capita, per year was collected through the Madison Project (Bolt and van Zanden, 2020). I then supplemented this with data from the World Bank (wor, 2021) in order to improve coverage. Additionally, I used the CEPII's GeoDist Dataset using the cepiigeodist package for R (Mayer and Zignago, 2011) in order to obtain the distance between countries. I also used three references to create a categorical variable for core and periphery nations, Atyabi et al. (2020); Babones (2005) and Chase-Dunn et al. (2000); I used the union of all three lists of core countries in hopes of capturing the broadest definition of what it means to be in the "core". All other covariate information was collected from the Correlates of War Project (cow, 2023), which included data on Intergovernmental Organization Membership (v3.0) (Pevehouse et al., 2020; Wallace and Singer, 1970), trade (v4.0) (Barbieri et al., 2009), contiguity (v3.2) (Stinnett et al., 2002), national energy consumption, military expenditure, and population (v6.0) (Singer and Stuckey, 1972), religion (v1.1) (Maoz and Henderson, 2013), diplomatic exchange (v.2006.1) Bayer (2006), defense agreements (v4.1) (Singer and Small, 1966; Small and Singer, 1969; Gibler, 2009), and militarized interstate disputes(v2.1) (Palmer et al., 2020). While there were a handful of other variables in the national material capabilities dataset (Singer and Stuckey, 1972), they had too much missingness to use in this analysis.

More information on the variables used in this analysis can be found in tables 3.1 and 3.2, which include the source and and a description of how each was measured, with additional information in table 3.3, which includes the format of the variable (continuous, categorical, or dichotomous), whether the variable is dyadically dependent, whether or not the variable changes at each time point or remains static over all periods, and the years covered by each.

## 3.5 Method

In order to model ratification over time, while capturing agreement, country, and structural effects, I used a series of Separable Temporal Exponential Random Graph Models (STERGMs) using the tergm package (Krivitsky and Handcock, 2014,0; Carnegie et al., 2015), which is part of the statnet suite of packages (Krivitsky et al., 2003-2022) for R (R Core Team, 2020a). A STERGM models ties within a network over time, using separate ERG Models to capture tie formation and tie dissolution. Formation and dissolution are modeled as independent from each other within each time step (Krivitsky and Handcock, 2014). Because dissolution is a very rare occurrence in this particular dataset, I have included a control for dissolution, setting the probability substantially low, which allows for the tie formation model to account for this lack of tie dissolution. This approach is different from previous research on IEA ratification because ERGMs, along with other network models, allow for modeling dyadic independent and dyadic dependent effects simultaneously (Goodreau et al., 2009).

There were two major methodological considerations I had to account for in order to conduct this analysis on this particular dataset. First, STERGM requires all networks to be of the same size, meaning that all nodes that appear at any time point in the network must be in the model at every time point in the network. While there are clearly more countries and IEAs present in 2022 than there were in 1857, I have included all countries and all IEAs in all time periods. In order to adjust the model in a way that can handle this varying node set, I have added structural zeros at the dyad level that vary at each time point. As stated above, only certain countries are eligible to ratify each IEA; a structural zero between a country and an IEA signifies the inability of that country to ratify that agreement. Additionally, structural zeroes were put between any IEA or country and all other nodes if the country or agreement did not exist at that time. In order to account for changes in national sovereignty, I used either the year a country gained sovereignty or the year a country first took action on an agreement, whichever came first, as their starting year in the dataset. This method allows the models to adjust to a changing node set, one where not all countries can tie to all agreements and one where countries and agreements both enter the network at various points in time.

The second methodological consideration for this dataset was the fact that the networks are bipartite. While the standard ERGM terms allow for the use of networks as covariates in the one-mode case, there was no term to model the effects of a one mode network on the two-mode network of interest. Such a term is necessary for modeling the effects of say, trade between two countries, on the likelihood of ratifying the same treaty. As many of my variables were of this format, I had to construct a new pair of ERGM terms to use in this analysis. Using the ergm.userterms package for R (Handcock et al., 2018,0; Hunter et al., 2013),I made two terms, 'b1edgcov' and 'b2edgecov', which adds one statistic to the model equal to the sum over all pairs in a given one mode matrix multiplied by the number of shared partners in the bipartite graph. The b1edgecov term is represented as such:

$$t(g) = \sum_{i \in A} \sum_{j \in A \setminus i} \sum_{k \in B} g_{ik} g_{jk} X_{ij} \tag{3.1}$$

For bipartite graph $g$ on vertex sets $A$ and $B$, and fixed (possibly valued) graph $X$ on vertex set $A$. The only difference for the b2edgecov term is that the graph $X$ is on vertex set $B$. The change score for a given edge is then expressed as follows:

$$\Delta_{ik} t(G) = \sum_{j \in A \setminus i} g_{jk} X_{ij} \tag{3.2}$$

By doing this, I was able test the effects of factors within one mode of the network on the tie probability within the two-mode network. In order to prioritize model fit, models were chosen separately for each time period, rather than imposing one set of statistics across all periods. The results of the final model for each period are discussed and compared below.

## 3.6 Results

TERGM Results – First Six Time Periods 1857-1970

| | 1857-00 | 1900-30 | 1930-40 | 1940-50 | 1950-60 | 1960-70 |
|---|---|---|---|---|---|---|
| Edges | -3.985*** | -3.361*** | -3.535*** | -4.538*** | -4.641*** | -3.646*** |
| **World Systems** | | | | | | |
| GDP per capita ($1000) | | | | 0.016 | | |
| Trade (ln) | | | | | | |
| Core | 1.462*** | 0.081 | -0.042 | 0.501** | 0.748*** | 0.673*** |
| Core Homophily | | 0.049 | | | | 0.069*** |
| Periphery Homophily | | 0.013 | | | | 0.089*** |
| **World Society** | | | | | | |
| IGO | 0.027 | 0.030** | 0.023* | 0.056*** | 0.026*** | 0.023*** |
| Joint IGO Membership | | | | | | |
| **Regionalism** | | | | | | |
| Contiguity | 0.980*** | 0.269*** | 0.119. | 0.243** | 0.342*** | 0.256*** |
| Distance (ln) | | 0.005 | 0.006*** | 0.006*** | 0.005*** | -0.004*** |
| Christianity | | | | | | |
| Non-Religious | | | | | | |
| Hindu | | | | | | |
| Religious Homophily | | | | | -0.031*** | |
| **Environmental Degradation** | | | | | | |
| Energy Consumption | 0.086* | 0.042. | 0.057* | | | |
| Total Population (per 1K) | | | | | | |
| **Exogenous Relations** | | | | | | |
| Diplomatic Exchange | | | | -0.042* | -2.03e-14 | -1.76e-14 |
| Militarized Interstate Disputes | | | | | | |
| **Treaty Factors** | | | | | | |
| Treaty Age | -0.512*** | -0.268*** | -0.192*** | -0.256*** | -0.164*** | -0.132*** |
| Lineage | | 0.347*** | 0.372*** | 0.268*** | 0.162*** | 0.256*** |
| Habitat | | | | | | -0.469* |
| Nature | | | | | | |
| Oceans | | | | | -2.478* | 0.483*** |
| Pollution | | | | | | |
| Species | | | | | | -0.692*** |
| Weapons | | | | | | 4.032*** |
| Amendment | | | | | -2.819*** | |
| Protocol | | | | | | -0.479*** |
| Agreement Type Homophily | | | | | | |
| **Popularity Effects** | | | | | | |
| b1 Degree 1.5 | | -0.497 | -1.358** | | | |
| b1 Degree 0.05 | | | | | | |
| b2 Degree 1.5 | | -0.670 | | | 1.199*** | |
| b2 Degree 0.1 | | | | | | |

*Note:* $^{\cdot}$p<0.1;$^{*}$p<0.05; $^{**}$p<0.01; $^{***}$p<0.001, b1 indicates countries, b2 indicates treaties

Table 3.4: Results for temporal exponential random graph models for tie formation from 1857 to 1970, divided into six periods.

Results are shown for the final models for each decade. The coefficients can be found in table 3.4 for the periods covering 1857 to 1970 and table 3.5 for the periods covering 1970 to 2022. If a given period does not contain a specific covariate, it indicates that this term did not fit the data well for that period or was not a significant predictor (any term significant at the 0.1 level or lower was kept in). TERGM results are shown in log odds values and each coefficient value shows the change in the log odds from that variable, all else equal.

TERGM Results – Last Six Time Periods 1970-2022

| | 1970-80 | 1980-90 | 1990-00 | 2000-10 | 2010-14 | 2014-22 |
|---|---|---|---|---|---|---|
| Edges | -4.217*** | -4.139*** | -3.931*** | -4.316*** | -3.940*** | -2.929*** |
| **World Systems** | | | | | | |
| GDP per capita ($1000) | 0.014*** | 0.005 | 0.010*** | | | -0.007*** |
| Trade (ln) | | 0.001*** | 0.0004*** | | | |
| Core | 0.089 | 0.366** | 0.209*** | -0.036 | 0.185 | 0.440*** |
| Core Homophily | 0.068*** | 0.062*** | | 0.048*** | 0.040** | |
| Periphery Homophily | 0.044*** | 0.042*** | | 0.010*** | 0.017*** | |
| **World Society** | | | | | | |
| IGO | 0.013*** | 0.009*** | | 0.002 | 0.003 | |
| Joint IGO Membership | | 8e-04*** | 6e-04*** | 5e-04*** | 4e-04*** | |
| **Regionalism** | | | | | | |
| Contiguity | 0.164*** | 0.224*** | 0.179*** | 0.100*** | 0.086*** | 0.064*** |
| Distance (ln) | -4e-04 | -0.002*** | 9e-04*** | -3e-04 | -7e-04. | 0.002*** |
| Christianity | | 0.215*** | 0.407*** | | | |
| Non-Religious | | 0.452** | 0.645*** | 0.602*** | 0.413. | 0.503** |
| Hindu | | | 0.654*** | | | |
| Religious Homophily | 0.008* | | | 0.003*** | | |
| **Environmental Degradation** | | | | | | |
| Energy Consumption | | | 0.038*** | | -0.022 | |
| Total Population | | 5e-07* | | | | |
| **Exogenous Relations** | | | | | | |
| Diplomatic Exchange | -0.010* | -0.017*** | -0.016*** | -0.014*** | | |
| Militarized Interstate Disputes | | | -0.190*** | | | |
| **Treaty Factors** | | | | | | |
| Treaty Age | -0.097*** | -0.118*** | -0.089*** | -0.070*** | -0.093*** | -0.137*** |
| Lineage | 0.212*** | 0.166*** | 0.227*** | 0.176*** | 0.155*** | 0.122*** |
| Habitat | | | | -0.342*** | | -0.577** |
| Nature | 0.421*** | | | | | |
| Oceans | 0.858*** | 1.054*** | 1.757*** | | 1.502*** | 1.930*** |
| Pollution | | | | | | 0.060 |
| Species | | | | 0.205*** | | -0.492*** |
| Weapons | | -0.642*** | | | | 0.896*** |
| Amendment | | -0.562*** | -1.000*** | | -0.395** | -0.154. |
| Protocol | -0.628*** | -0.064 | -0.421*** | | | -0.035 |
| Agreement Type Homophily | 0.011*** | | | 0.007*** | | |
| **Popularity Effects** | | | | | | |
| b1 Degree 1.5 | -1.176*** | | -0.481** | | | |
| b1 Degree 0.05 | | | | -2.646** | | |
| b2 Degree 1.5 | -0.645*** | 0.314** | -1.448*** | | -0.888*** | -1.992*** |
| b2 Degree 0.1 | | | | -1.212*** | | |

*Note:* ·p<0.1;*p<0.05; **p<0.01; ***p<0.001, b1 indicates countries, b2 indicates treaties

Table 3.5: Results for temporal exponential random graph models for tie formation from 1970 to 2022, divided into six periods.

Starting with our dyad-independent terms, I used variables for GDP per capita, whether or not a country was considered a "core" country, national energy consumption, total population, categorical variables for religion, treaty subject and agreement type, and the number of IGOs a country belonged to in a given year. Across all periods, few of these factors remained in our final models. The most prominent factor was IGO membership, which was significant in 7 of our periods and was consistently positive, meaning that the more IGOs a country was a member of, the more likely they are to ratify an IEA. The effect is highest in the 40's but fluctuates between 0.009 and 0.056. Energy consumption was significant in one third of all periods and is positive in all periods where significant, which means that higher energy use at the national level increases the likelihood to ratify an IEA; this term appears in the first three periods and then again in the 1990's. Total population is not a significant driver of ratification in any period except the 1980's and is significant at the 0.05 level indicating that overall, population is not a major driver of ratification behavior accross time. GDP per capita is significant and positive in the 1970's and 90's, indicating that wealthier countries had higher likelihoods of ratifying IEAs during those times. Interestingly enough, the term is only significant again in the most post-2014 period and is negative, which may indicate a catching up of less wealthy countries. The node covariate for whether a country is considered to be in the "core" is significant in the 1800's, the 1940's to 60's, the 80's and 90's, and then again in the post 2014 period. This term is also always positive indicating a tendency for countries in the core to ratify at higher rates than those in the periphery. The only three religious categories that have significant effects are Christianity, Hinduism, and the non-religious category and they are all positive when present. Hinduism has an effect only in the 90's, whereas the effect for Christianity is present in the 80's and 90's. The non-religious category is significant from 1980 through the present, minus the 2010-2014 period. Overall the dominant religion of a country is not a strong predictor of ratification outside of the late 20th century, unless that country has a strong non-religious leaning. With regards to agreement subject, general nature agreements are more likely to be ratified in only the 1970's. Species treaties are less likely to get ratified in the post-2014 period and the 60's, but are more likely to be ratified in the 2000's. The most variation in subjects comes from weapons treaties, which are less likely to be ratified in the 80's, but more likely in the 60's and post-2014 period. Oceans treaties appear to be the most popular overall, with positive effects from the 60's to the 90's and also in the 2010's; they are negative in the 1950's however. Overall, while it is important to account for these small variations, most of the time, the specific subject of the agreement is not highly influential. Lastly, protocols are less likely to be ratified from the 1960's to 90's and in the post-2014 period, and amendments are less likely to be ratified in the 50's, 80's, 90's, and 2010's, indicating that general agreements are often the most likely type of IEA to be ratified and that amendments are often the least likely to be ratified.

Moving on to the dyad-dependent terms and starting with the "node-match" terms, lineage is consistently significant and positive across all time periods, except for the first, and the effect ranges from 0.122 to 0.372, generally decreasing since the 1900's. This indicates that countries are more likely to ratify agreements that are connected to each other legally. For the two measures of world systems theory, matching in the core and periphery, homophily among core countries is positive and significant in every period from the 1960's to the 2010's, except for the 1990's. Surprisingly enough, homophily among the peripheral countries exhibits the exact same pattern. Next, we do see significant homophily on religion in both the 70's and 2000's, but there is a tendency towards religiously heterophilous two-stars in the 1950's and these effects are small overall. countries also have a tendency to ratify the same type, meaning agreements, protocols, or amendments, in the 70's and 2000's as well. The absence of a subject node-match term indicates that countries are not more likely to ratify the same IEA category, meaning that countries appear to ratify a range of topics instead and that this behavior is consistent across time.

Two geometrically weighted degree terms were tested in each model – one for each mode of the network. Both of these terms are almost always negative when significant and present in the models. This indicates that as countries ratify more agreements and as agreements get more ratifications, both are less likely to tie to another. It is important to remember that these models are within time periods and only considering formation (not existing ties), so this indicates that there is a sharp fall off to the likelihood of ratifying more than a handful of agreements in a decade and to being ratified by more than a handful of countries in a given decade. Some combination of these terms is significant in 8 out of the 12 time periods.

The last set of variables use my b1 edge covariate ERGM term. Here, these measure the effect of an edge variable between countries on the likelihood of ratifying the same agreement. The first set of terms gets at the impact of propinquity – contiguity and the log of the distance in kilometers. Contiguity is positive in every period and appears to decrease slightly over time meaning that countries sharing a border are more likely to jointly ratify IEAs. Surprisingly, distance is significant in all but the first two periods and also alternates between being positive and negative. Taken together, these terms indicate that countries are more likely to ratify the same IEA if they are contiguous, but if they are not, the effect is time period dependent. When positive, the closer they are together, the less likely they are to ratify the same treaty and when negative, closer countries are more likely to ratify the same treaty. The next b1 edge covariate was the log of the total trade volume between two countries in a given year. This term is only significant in the 80's and 90's but it is positive in both, meaning that countries are more likely to ratify the same IEA if they have higher amounts of international trade. Diplomatic exchange is a binary for whether or not there was diplomatic exchange between two countries in a given year. This term is surprisingly negative when present in the 40's and then again from the 70's to the 2000's. The last two variables are the number of IGOs that two countries have joint membership in and whether or not two countries are involved in a militarized interstate dispute (MID). Joint IGO membership is significant and positive from the 1980's to 2014, while MIDs are only a significant predictor in the 1990's and are predictably negative. It's also important to note that the post-2014 period cannot test for the effects of trade volume, MIDs, or joint IGO membership as the data does not include this most recent time period, meaning that the lack of an effect in the model does not indicate the lack of this effect in reality.

The last effect was an agreement covariate for the age of an IEA, measured as the number of years since the signing date. This effect is significant in all periods and shows that the likelihood of ratification decreases as a treaty ages. This effect was largest in the 1980's and the most recent 8 year period.

While there is an abundance of results to digest, taken together, they give us new insights on old theories as well as illuminate future lines of inquiry and policy recommendations.

## 3.7 Discussion

The aim of this study was to expand the scope of international environmental agreement research, specifically asking, what are the drivers of IEA ratification? I combined predictors from well established sociological theories with untested treaty level factors and relational variables. The three theories tested in prior literature were world systems theory, world society theory, and regionalism. I included five variables to capture world systems theory, GDP per capita, Trade flows between countries, whether or not a country was considered in the core (as opposed to the periphery), and within group mixing terms for both core and periphery positions. GDP per capita and trade flows had little influence over ratification likelihood, indicating a lack of support for wealth based ratification patterns. Moving to the world systems positional measures, being in the core is a positive predictor in 4 periods. However, while core homophily is positive in almost every period since the 1960's, it is not significant in the most recent decade and homophily among the peripheral countries is positive in the same periods. Overall, there is little evidence to support world systems theory as it is typically theorized, but the results did reveal two groups of countries that cooperate more within their groups than between; this is a new pattern that should be studied further.

World society theory is more strongly supported by the results, with individual IGO membership being a significant predictor in the early periods and joint IGO membership becoming a significant predictor in later periods. However, it is important to note that neither of these variables were significant in the most recent decade. On the other hand, regionalism comes through clearly in the results, with contiguity being a significant and positive predictor in every period. Oddly enough, distance is also positive in 6 of the 12 periods, indicting that beyond contiguity, countries that are farther apart are actually more likely to co-ratify IEAs, which is a finding that should be the subject of future research. While IEA ratification is in part driven by regionalism, the idea of shared culture being the root of this pattern is not supported.

Beyond these three theories, treaty variables were not previously accounted for when modeling ratification patterns. First, as a treaty ages, the likelihood of ratification decreases, which implies that IEAs need to garner ratifications quickly. We also know that countries that have ratified a treaty in the past are more likely to ratify future treaties that are connected through a legal lineage. While the subject of a treaty is not predictive in the earlier periods, there have been differences since the 1960's, with Ocean treaties being the most likely to be ratified in the latter half of the full time span. Additionally, there are differences in ratifying different types of IEAs and there is little homophily among agreement type indicating a preference towards general agreements, followed by protocols, and lastly, amendments (excluding tacitly accepted ones).

The main structural effects tested were geometrically weighted degree terms, which were frequently significant and almost always negative. This means that agreements are actually less likely to gain more ratifications with the addition of every one and that countries are less likely to ratify more agreements with every new ratification. This may indicate a benefit to targeting nations that are involved in fewer recent treaties and to space out IEAs in order to avoid a burn-out effect for countries in general.

In this study, I expanded the scope of IEA research in several ways. It is one of the first to include non-universal IEAs and I did so through a data collection process that recorded national eligibility for nearly all original multilateral IEAs on record. I also used the full 166 years of IEA ratification from 1857 through 2022. Beyond just the scope of the research, this paper is the first to study IEA ratification from a network perspective, while also being able to incorporate within-time dependence terms as well as one mode influences on the bipartite network. The latter advancement was also a methodological contribution, which allowed for the modeling of one mode influences on two mode networks within the ERGM framework.

Beyond the study of IEAs there are also general takeaways for the field of sociology and the study of international relations. It is clear that a historical perspective can aid in sociological understandings. During the height of IEA production, both resource based, and culture-based factors exert some influence on ratification patterns, but this is not the case for much of the 120 years of IEA production. It is important to understand how patterns change over time because often, the influences of the past shape the patterns we find in the present. Additionally, a spatial understanding of sociological phenomena is crucial. While IEAs concern the management of geographically located resources, this is the first study to account for any geographic factors in the analysis of IEA ratification. Moreover, these variables were among the strongest and most consistent predictors of ratification patterns over time. Lastly, while this study is the first to account for within time dependence, only two structural factors were included in the analysis. Future studies should continue this line of work, testing for other dependencies among IEA ratification and other forms of international cooperation.

Table 3.1: Description of variable measurement for variables in final TERGMs.

| Variable | Source | Measurement |
|---|---|---|
| **World Systems** | | |
| GDP per capita | Maddison Project, World Bank | GDP/ total population (2011 international dollars) |
| Trade | COW | Smoothed total trade values between two countries in a year (millions of 2017 US dollars) |
| World systems position | Atyabi et al. (2020); Babones (2005); Chase-Dunn et al. (2000) | Which nations are in the core and which nations are in the periphery |
| **World Society** | | |
| IGO | COW | Number of international governmental organizations a country is a member of in a given year |
| Joint IGO Membership | COW | Number of international governmental organizations that two countries are both members of in a year |
| **Regionalism** | | |
| Contiguity | COW | Whether or not two countries share a land or river border |
| Distance | CEPII | The distance (km) between two countries' capitals |
| Religion | COW | Majority religious category of a country: animism, Shintoism, Judaism, Islam, Christianity, Buddhism, Hinduism, Syncretic religions, non-religious, other |
| Religious Homophily | COW | Whether or not two countries share the same majority religious group (regardless of group) |
| **Environmental Degradation** | | |
| Energy Consumption | COW | Annual national energy consumption (thousands of coal-ton equivalents) |
| Total Population | COW | Total Population (thousands) |

Table 3.2: Description of variable measurement for variables in final TERGMs continued.

| Variable | Source | Measurement |
|---|---|---|
| **Exogenous Relations** | | |
| Diplomatic Exchange | COW | Whether or not one or both countries had representation within the other (see COW codebook for full list of types of representation) |
| Militarized Interstate Disputes | COW | Whether or not two countries were involved in any militarized interstate disputes in a given year |
| Alliances | COW | Whether or not two countries had an one or more alliances in a given year |
| **Treaty Factors** | | |
| Treaty Age | IEADB | Number of years since the signing year of an agreement |
| Treaty Subject | IEADB | Main subject of an agreement: fresh water resources, nature, species, pollution, oceans, weapons (non-nuclear), habitat |
| Agreement Type | IEADB | Type of agreement: agreement, protocol, amendment |
| Agreement Type Homophily | IEADB | Whether two agreements are of the same type (regardless of type) |
| Agreement Subject Homophily | IEADB | Whether two agreements are of the same subject (regardless of subject) |
| Lineage | IEADB | Whether two agreements have the same legal lineage |

Table 3.3: Description of variables used for final models.

| Variable | Variable Type | Time Variant | Years Covered | Dyadic Dependence |
|---|---|---|---|---|
| Contiguity | binary | No | - | Yes |
| Distance | continuous | No | - | Yes |
| Energy Consumption | continuous | Yes | 1857-2012 | No |
| GDP per capita | continuous | Yes | 1857-2022 | No |
| World systems position | categorical | No | - | No |
| World systems homophily | binary | No | - | Yes |
| Total Population | continuous | Yes | 1857-2012 | No |
| IGO | count | Yes | 1857-2014 | No |
| Treaty Age | count | Yes | 1857-2022 | No |
| Treaty Subject | categorical | No | - | No |
| Agreement Type | categorical | No | - | No |
| Religion | categorical | Yes | 1857-2022 | No |
| Religious Homophily | binary | Yes | 1857-2022 | Yes |
| Agreement Type Homophily | binary | No | - | Yes |
| Agreement Subject Homophily | binary | No | - | Yes |
| Lineage | binary | No | - | Yes |
| Diplomatic Exchange | binary | Yes | 1857-2010 | Yes |
| Trade | continuous | Yes | 1870-2014 | Yes |
| Joint IGO Membership | count | Yes | 1857-2014 | Yes |
| Militarized Interstate Disputes | binary | Yes | 1857-2010 | Yes |

# Chapter 4

# Calling The Dead: Resilience In The WTC Communication Networks

## 4.1 Abstract

Organizations in emergency settings must cope with various sources of disruption, most notably personnel loss. Death, incapacitation, or isolation of individuals within an organizational communication network can impair information passing, coordination, and connectivity, and may drive maladaptive responses such as repeated attempts to contact lost personnel ("calling the dead") that themselves consume scarce resources. At the same time, organizations may respond to such disruption by reorganizing to restore function, a behavior that is fundamental to organizational resilience. Here, we use empirically calibrated models of communication for 17 groups of responders to the World Trade Center Disaster to examine the impact of exogenous removal of personnel on communication activity and network resilience. We find that removal of high-degree personnel and those in institutionally coordinative roles is particularly damaging to these organizations, with specialist responders being slower to adapt to losses. However, all organizations show adaptations to disruption, in some cases becoming better connected and making more complete use of personnel relative to control after experiencing losses.

*Keywords:* resilience, relational event models, disaster, communication, networks

## 4.2 Introduction

Individuals confronting an ongoing threat grapple with an array of challenges, needing to identify the threat, determine an appropriate response, and minimize the loss of life and property in the process. Disasters pose a significant test for human communities, often introducing additional obstacles that complicate their usual modes of organization. Such obstacles can range from the disruption of local radio communications (Kean, 2011), telephone communication failures (Mondal et al., 2021), or the loss or incapacitation of key personnel, such as those with training or managerial authority, who are relied upon in crisis situations. Our study explores what happens when an individual in such a dynamic system goes "radio silent," or becomes unable to respond. Using empirically-calibrated models of interpersonal communication during an unfolding disaster, we consider the impact of such node removal on aggregate communication networks, functionally relevant dynamics, and on the reorganization of the communication system in response to disruption.

The remainder of the paper is structured as follows. We begin in Section 4.3 by briefly reviewing relevant background on how communication systems respond to disruption, and on factors relating to maintenance or restoration of function in the face of personnel loss. Our data and methods are described in Section 4.4, with the results of our simulation study provided in Section 4.5. Discussion of additional issues is included in Section 4.6, and

Section 4.7 concludes the paper.

## 4.3 Background

Although the details vary depending on organizational type and task structure, organizational function typically requires the ability to coordinate the activities of its members (Galbraith, 1977). This generally requires the ability to disseminate information to the members of the organization; the ability of individuals with interdependent tasks to communicate with each other and/or a mutual superior who can resolve conflicts (Thompson, 1967; Krackhardt and Carley, 1998); and the ability of organizational members receiving or discovering information of broader importance to direct this to others who may need it (Cohen et al., 1972). Secondarily, communication keeps members oriented on organizational goals, directs their attention, facilitates situational awareness, and raises morale (Auf der Heide, 1989); thus, preventing individuals from becoming isolated can also be an important consideration *per se*.

In the face of disruptions such as personnel loss ("damage"), such capabilities may become threatened. Broadly, it is useful to think of changes in organizational function under disruption in terms of distinct notions of *robustness* and *resilience*.[1] Here, we use the term "robustness" to reflect the capacity of an organizational system to *maintain* function in the face of damage, while "resilience" reflects the capacity of such a system to *restore* function lost due to damage. Of these complementary concepts, robustness is the better understood, having been widely studied in the context of organizational and biological networks (see e.g. Klau and Weiskircher (2005) for an introduction). Studies of resilience, by contrast, have been hampered by the need to have access to dynamic models that can capture the reorganization of networks to damage. As we describe below, we are here able to leverage a

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[1] We note that these terms are not used consistently in the literature, and many studies of robustness (as we define it) employ the term "resilience." Here, we refer to such studies in terms of our terminology.

set of empirically calibrated models for communication dynamics (Renshaw et al., 2023) to probe such reorganization, giving us the ability to speak to resilience *per se*.

Before turning to our specific approach, it is useful to motivate our study by briefly reviewing relevant prior work on robustness and resilience in organizational communication networks. In the section that follows, we then describe the models we are using, and the simulation experiments we employ to examine the consequences of personnel loss.

## Structural Change

As noted, a considerable literature exists on network robustness. Typically, such studies begin with observed and/or simulated networks and remove nodes or edges, examining how functionally relevant properties are altered by these changes (known generically as "attacks"). Bellingeri et al. (2020) provides an overview of link and node removal studies on real networks, finding applications in diverse fields like biology, ecology, transport, infrastructure science, informatics, economics, and sociology. These studies use node and link removal to assess indicators of robustness – measures of a complex system's ability to maintain function after loss of connectedness or group members. These studies often aim to understand the types of attacks that cause the most damage, typically related to vital links or nodes (Bellingeri et al., 2020). Just as networks vary in robustness to various nodal attacks, we might expect a similar variation in resilience (a question we probe below).

Many robustness studies focus on "breaking" networks, essentially limiting their ability to function and seeing which factors most effectively lead to fragmentation, as well as which factors increase network susceptibility. Boldi et al. (2011) found that social networks tend to experience less disconnection upon node attacks than web-graphs, but the most efficient removal strategy was related to what they termed "label propagation." This technique involves iteratively labeling nodes based on their neighbors and identifying hub-structures that may or may not be high out-degree nodes. This finding resonates with other work by Qi et al. (2019) on optimal network disintegration patterns of multiplex networks. Previous research on the World Trade Center (WTC) communication network has aimed to understand its robustness under attack. Findings suggest that during the 9/11 events, the organizations involved in the 17 radio communication networks maintained connectivity through a relatively small number of coordinators. However, the reliance on these coordinators was context-dependent. As was discussed by Fitzhugh and Butts (2021), the structures found in the WTC radio communication networks are hub-dominated; while it makes them robust to random node removal, they are severely vulnerable to targeted attacks that implicate the hubs ("degree-targeted attacks" (Fitzhugh and Butts, 2021; Klau and Weiskircher, 2005)). Those who find themselves in these coordinative, hub-structural roles, are the most likely to have high degree – through disconnecting the networks via these important actors, these types of attacks tend to be fairly effective at disrupting the network and limiting the ability for information transmission to occur in the absence of subsequent reconfiguration Fitzhugh and Butts (2021).

Comparative studies have also considered networks from other complex systems (e.g., metabolic networks and infrastructure systems). These, too, exhibit varying degrees of robustness to different types of attacks. For instance, scale-free networks, like the World-Wide Web, have high tolerance for random attacks, but are extremely vulnerable to targeted high-degree node attacks (Albert et al., 2000; Callaway et al., 2000). Social networks, in contrast, are much more robust than Random Erdos-Renyi graphs (De Meo et al., 2018). A review of the literature by Bellingeri et al. (2020) concluded that many social networks are "robust yet fragile" to attacks – in that random node removal attacks do not dismantle the network, while highly targeted attacks (like malicious attacks) can often quickly and easily cripple a social network. Motivated by this observation, here test various hub attacks against random attacks to understand how the ability to reorganize is impacted by the type of nodes removed.

In related work, Lv et al. (2022) found in designing a model for cascading failure that also considers activity overload when actors are randomly removed, that the "dynamical behavior" of the complex system is also a critical factor to consider for a network's robustness. They noted that networks with "birth and death" and regulatory dynamics are much more sensitive than biochemical or epidemic dynamics to their use of a sensitivity factor (which involved the ability of nodes in the network to resist the perturbation) (Lv et al., 2022). Fitzhugh and Butts (2021) also considered a form of dynamic robustness, in which they examined the impact of failures on forward connectivity under observed dynamics (as opposed to reorganization in response to damage); they found generally similar patterns of vulnerability to those seen in time-aggregated networks, but noted that this may or may not hold when the network can adapt to damage. We will revisit that question in our study below.

While past robustness studies have yielded important insights, Bellingeri and Cassi (2018) notes that different node removal approaches can yield results that are sensitive to how both the target network and the attack are specified, potentially leading to misleading results if analyses are not prepared and interpreted carefully. For example, they found that studies focusing on individuals with "binary-topological indicators" like the largest connected component might identify "false hub-nodes," which could merely be nodes with many weak links; put another way, disruptions to network structure may or may not have equal functional significance, and it is important to consider how function is maintained in the network (e.g., for diffusive systems, what is diffusing across the network and how diffusion occurs). For instance, in an epidemiological study of vaccination inoculation, identifying individuals in hub-roles might not be the most strategic choice for inoculation, despite what traditional analyses might naively suggest. This is because false hub-nodes with higher binary connectivity might have many links that are exceedingly weak and therefore limited contact time or low probability of infecting others (Bellingeri and Cassi, 2018; Bellingeri et al., 2020). Similarly, time aggregation can exaggerate the potential for disruption due to hub removal, leading to misleading conclusions regarding the efficacy of such attacks for inhibiting diffusion (Butts, 2009). It may also be important, particularly in dynamic settings, to consider nodes with particular roles or other characteristics (e.g., in the WTC case, nodes occupying institutionalized coordinative roles), whose removal may have different consequences than the removal of other network members. Finally, it must be observed that robustness itself may not always be of primary substantive interest, in contexts where reconfiguration (and hence resilience) is possible. As noted by Butts and Carley (2007), there can exist regimes in which organizations can repair damage indefinitely, so long as the intervals between attacks are long enough relative to repair times; this constant need for damage repair imposes a *homeostasis cost,* which can affect optimal organizational structure. In such settings, the cost of adaptation may be a more important theoretical target than the potential for catastrophic failure. This motivates closer study of adaptation and resilience, a significant concern of this paper.

### Robustness in the WTC Case

The goal of this and prior papers investigating communication in the 9/11 disaster have been to understand how individuals maintain effective communication in conditions that make it extremely difficult - indeed, conditions in which the kinds of tasks with which individuals are faced are often unlike anything seen in normal circumstances. Prior work on the WTC case has attempted to characterize the emergent hub-structures seen in the communication networks (Petrescu-Prahova and Butts, 2008a; Butts et al., 2007), identify mechanisms driving responder communication (Butts, 2008), understand the dynamics of hub formation formation (i.e., what kinds of social forces create the hub-structures seen in the observed networks) (Renshaw et al., 2023), and examine the robustness of the communication networks to node removal (Fitzhugh and Butts, 2021). This study continues this line of research by using dynamic models to probe resilience of the WTC networks to personnel loss.

As noted above, Fitzhugh and Butts (2021) studied the WTC communication networks to understand their robustness to attack. Their work highlights a contrast between communication strategies that rely heavily on centralization to maintain connectivity of actors in the organization (which would thus favor efficiency and robustness to random failure) but have the added effect of relying on a small number of key players (relative to a decentralized network). Their study employed several node removal strategies using both time-aggregated and time-sequenced networks. For both, they considered random failure in uniform random order, random failure of individuals in Institutionalized Coordinative Roles (ICRs), degree-targeted failure, and degree-targeted failure of ICRs for all of the 17 WTC radio networks. In the time-aggregated case, the WTC organizations were found to be more impaired by random failure of ICRs than they were by removal of random actors; thus, individuals in institutionalized coordinative roles play a vital role maintaining connectivity. By contrast, degree-targeted failure was more effective at impairing the network than degree-targeted failure of ICRs, suggesting that ICR status, while important, is not as consequential as the degree of the actor, which is more indicative of hub structure. This follows prior work which found that while ICRs tend to be more likely to occupy hub roles, the majority of such roles emergent (Petrescu-Prahova and Butts, 2008a).

A second major part of their study, which partially motivates our approach, involved an analysis of the impact of node removal on observed event sequences, thus respecting the consequences of (observed) dynamics. Taking the observed ordering of events as given, they considered the "temporal unfolding" (Bearman et al., 2004) of the dynamic network and the potential "pathways of transmission" for information through time (Fitzhugh and Butts, 2021). They find broadly similar results to the aggregated case (e.g., the WTC networks were more robust to random failure than to random failure of ICRs, and more degraded by degree-targeted failure than degree-targeted ICR failure), though the difference between degree and degree/ICR attacks was no longer significant. Overall, their study demonstrates the ability to utilize robustness analysis to understand and detect network properties that may not be easily detected through more traditional measures (Freeman, 1979; Wasserman and Faust, 1994), but raises the question of what happens when the stricken organizations are able to dynamically reorganize their communication pattern in response to damage. For instance, one may hypothesize that hub removal will have reduced impact in this adaptive scenario, because new hubs may simply emerge to replace the old; by contrast, ICRs (which cannot be replaced) may take on greater significance in an adaptive setting. To examine these questions, we must go beyond the observed patterns of communication in the WTC disaster, to instead consider the observed *behavioral dynamics* governing the network and ask how these dynamics unfold when the network is damaged. This takes us beyond the realm of robustness, and into the realm of resilience.

### Resilience Studies

While robustness to attack has been studied in both human and non-human contexts, there have been far fewer studies on resilience in human networks. While robustness relates to functionality under attack, resilience is the idea of regaining functionality and reorganizing in response to disruption (de Bruijne et al., 2010). Social science research in this area has to date tended to focus less on understanding how systems dynamically respond to disruption, instead involving after-action case studies of how organizations and their members responded to major organizational failures. The organizational literature has had some focus on issues relating to resilience, particularly in the area of organizational learning; this includes e.g. work on the kinds of organizational structures that have been found to be more or less efficient in their ability to learn/respond to changes in their environment. Several simulation studies by Carley 1991; 1992 provide context to organizational learning within settings of communication breakdown and or crisis. This research also provides insights in the context of turnover, i.e. organizational actor loss. Research by Virany et al. (1992) found that executive turnover (leadership) may be necessary in a turbulent environment for organizations to adapt to changing circumstances – the logic being that executives do not have training in the new crisis/turbulent environment and that prior organizational scripts and routines might be counter-productive and even detrimental to organizational success. Having some turnover might allow for organizations to be more flexible overall. While node removal is generally viewed as a disruptive event, this work suggests the intriguing possibility that it may not always lead to impairment, and indeed that it could in some cases actually improve organizational performance. The idea that organizations can dynamically "build back better" in emergency settings is counterintuitive; as we show, however, some such *hormetic* or *eustretic* behavior is seen in the case of the WTC networks.

## Emergencies and Efficient Communication

Effective communication for coordination between organizational members in nominal or disrupted context is critical, with early research finding that effective patterns of communication are "a first principle of effective performance" (Bavelas, 1950, p.594). More generally, prior work has found that successful organizations and effective communication between organizational members are critical to many performance measures (Chandler, 1977; Galbraith, 1977; Malone, 1987; Minsky, 1986; Wageman, 1995; Brusoni et al., 2001), and that effective coordination in tasks enhances group performance (Tushman, 1979; Liang et al., 1995; De Dreu et al., 2016). To ensure that information can flow optimally, organizations need to utilize reliable channels to collect and disseminate their information. When these important channels fail the consequences can result in many counterproductive effects, including task delay or even failure to execute (Chandler, 1977; Galbraith, 1977; Kim and Burton, 2002; Radner, 1992; Sah and Stiglitz, 1986; Tjosvold, 1984; Krackhardt, 1996).

Thus, one of the main areas in which communication has been studied is in the context of emergency communications – events that can often lead to communication interruptions or failures in a context where information can be extremely time-sensitive. In their review of emergency communication and the use of Information and Communications Technologies (ICT) in disaster management, Mondal et al. (2021) summarizes the impact of several large-scale natural disasters over the past decade. They report that disasters such as floods, hurricanes, and earthquakes affected television and cell phone communications for a duration ranging from 3 or 4 days to more than three months, as seen in 2020 during Hurricane Maria in Puerto Rico. In scenarios where modern connectivity options failed, they observed that amateur radio, in addition to portable satellite equipment, was employed (Mondal et al., 2021). Radio communications, including amateur radio communications, has been a critical medium, particularly during the contexts of disasters – there are studies that find that as a decentralized communication medium, it can weather the impact of disasters more effectively than highly centralized communication infrastructure like cell phone towers (Gill, 2020; Nollet and Ohto, 2013; Coile, 1997).

While radio communication is a decentralized medium, centralization of communication can still occur via a process in which coordinative and organizational responsibilities become concentrated around a relatively small number of individuals. Such centralized communication structures and groups have been found to exhibit advantages in executing decomposable tasks, resulting in better performance (Hage et al., 1979; Tushman, 1979; Brusoni et al., 2001). In the classic Bavelas task-performance and structure study, it was found that task groups with high, localized centralization were capable of learning more quickly, had fewer errors in their performance, and tended to be more stable than groups with low centralization (Bavelas, 1950). However, it has also been noted that centralization, a kind of structural adaption, can have drawbacks including the inability to perform effectively in the context of non-decomposable tasks, like multilateral negotiation (Carley, 1992).

While structure has been a focus of the early literature, more recent studies have found that what is "optimal" or more "efficient" for communication is not merely determined by structure, and that for certain tasks, environments, or organizational contexts, there may be advantages or disadvantages to distinct structural forms. Despite early research pointing to "ideal-types," there is likely a menagerie of structural forms that may be ideal depending on the context (Scott, 1981; Levitt et al., 1999; Donaldson, 2001; Shenhar, 2001).

Several studies have found that organizations leverage role differentiation and task routinization through specialization that allows for coordination among interdependent roles and sets of individuals with particular skills and abilities (Hage et al., 1979; Kogut and Zander, 1996; Van De Ven et al., 1976; Brusoni et al., 2001; Crawford and Lepine, 2013). Prior research has found that specialized roles and their associated routinization of tasks can help with efficiency of task performance (Cohen, 1994; Kalleberg and Moody, 1994). Consolidating tasks to more particular, specialized, roles, has been found to enhance emergency response organizations' information flow (Comfort, 2007) – also noting that while these roles are well designed and operational in nominal/ordinary circumstances, it can often lead to rigidity, poor performance, and an inability to adapt in the face of tasks and contexts that those groups have had little experience with or preparation for (Comfort, 2007). Comfort (2007) discusses that organizations might need to design role structures, i.e., specialization of roles, with the consideration that they may need to be adapted in contexts with limited resources, time, and more novel tasks.

To this point, Carley and Harrald's (1991) overview of organizational learning in the context of actual hazard and disaster responses found that training organizational members on standard operating procedure may not necessarily degrade performance, but that leaning too much on standard operating procedure can lead to organizational rigidity where personnel follow things dogmatically – they found that newer personnel at lower organizational levels (less-specialization) tended to follow SOP unless they encountered new situations where the procedures did not cleanly apply – they then fell back on personal experiences which can fruitfully lead to creative solutions. However, mid-level, more specialized personnel tended to follow SOP to the point of rigidity, not seeing past their organizational script - which in catastrophic disaster events, due to their rare nature are difficult to train personnel for, and learning is hard to transfer. They found that teams where personnel were empowered to act on the basis of their experience tended to outperform teams that strictly followed SOP. While specialized networks are trained to respond to crises, this might actually decrease their ability to respond to changing circumstances and we might suspect resilience to vary by the specialization of our networks.

The WTC networks also vary by their level of specialization – some of the organizational units were trained to respond to crises and others were not. In the static case, Fitzhugh and Butts (2021) looked at the difference between specialist and non-specialist networks. When they teased apart the specialist/non-specialist difference, they found that random failure of ICRs was significantly more devastating to network structure connectivity than random failure, but only for specialists; non-specialists seem to be robust to random ICR removal. They explain that this may be that these institutionalized coordinator roles plays a particularly important consideration in specialist networks, where nonspecialists tend to be less reliant on these individuals.

Organizations in environments with high levels of uncertainty around tasks, or at least novelty of tasks, may be better suited for decentralized teams, which can operate more efficiently than a hierarchy could, saving cost and time (Kim and Burton, 2002; Van De Ven et al., 1976). Early theoretical work has provided some inclination that teams may in fact learn faster than hierarchies (Carley, 1992). With individuals embedded in a hierarchy, more centralized, key individuals, may be subject to more information overload in these novel, uncertain, contexts; making them less effective in these contexts (Carley, 1992). It has also been found that novel crisis situations give way to more decentralized communication patterns among organization members (Uddin et al., 2011), and that adaptation to crisis can ultimately be more efficient in the absence of centralized forms of communication (Pitt et al., 2011; Rodan, 2008).

## Functionality and Resilience

In order to understand better what mechanisms might help maintain functionality under pressure, we draw on studies related to social insects, which have used, in more recent years, a much more systematic approach to the issue of systemic resilience. Like human societies, social insects have complex social interactions that greatly influence group-level fitness, information sharing, and cooperation (Easter et al., 2022). The field of entomology has a rich history of studying these social dynamics among various social insect species (Wilson, 1971; Holldobler and Wilson, 2009). One area of social insect research involves experimental and simulation studies that manipulate some aspect of the colonies' environment or the colonies themselves to understand the resulting dynamic changes. For example, some studies have increased the temperature in beehives (Johnson, 2002; Cook and Breed, 2013) or augmented food availability (Pasteels et al., 1987; Beckers et al., 1990; Traniello and Robson, 1995) to induce changes in the colonies' behavioral dynamics. Relevant to our current study are the removal studies, where researchers study worker loss either through experimental approaches (e.g., physically removing ants) or in-silico simulations to understand how the colony dynamics adjust to the loss of workers. Several studies have shown that the workforce is usually replaced by other workers in the colony (Johnson, 2002; Mirenda and Vinson, 1981; Huang and Robinson, 1996; Gordon, 1986; Wilson, 1983,9; McDonald and Topoff, 1985; Charbonneau et al., 2017a), thereby maintaining functionality despite the removal of actors.

While broadly the idea of "social loafing," described as the tendency for individuals to lower their productivity when participating in a larger group (Ringelmann, 1913; Ingham et al., 1974; Simms and Nichols, 2014), has a negative connotation (often as a social disease (Latane et al., 1979, p. 831) some have speculated that, in social contexts, it could be an adaptive strategy relating to the conservation of resources (Williams and Karau, 1991; Bluhm, 2009). While there has not been much further engagement with the positive re-framing of "social loafing," similar contexts have found that reserves of actors and organizational slack (i.e, individuals who are not actively engaging but may be mobilized) may play an evolutionary advantageous role in certain systems. Surprisingly, in the case of social insects, it has been found that up to 50% of workers in several species of social insects are inactive at any given time (Charbonneau et al., 2017a). This has been observed in honey bees (Lindauer, 1952; Moore, 2001; Moore et al., 1998), bumble bees (Jandt et al., 2012), wasps (Gadagkar and Joshi, 1984), termites (Maistrello and Sbrenna, 1999), and ants (Charbonneau and Dornhaus, 2015; Herbers, 1983; Cole, 1986; Dornhaus, 2008). It had been commonly hypothesized that this worker "reserve" can be mobilized quickly if workload increases (Charbonneau et al., 2017b).

Charbonneau et al. (2017b) tested this hypothesis by systematically removing highly active workers, inactive ants, and randomly selected workers from a colony of *Temnothorax rugatulus* ants to see how the overall activity of the colony was affected. In support of the commonly held hypothesis, they found that the colony was able to maintain pre-removal activity levels when highly active workers were removed, supporting the idea that inactive workers serve as a pool of "reserve" labor. Interestingly, when inactive workers were removed, the level of inactivity decreased and remained lower after the removal period, suggesting a system-level ability to maintain active worker levels but not specific inactive worker levels (Charbonneau et al., 2017b).

Other social insect research has demonstrated that during heat stress, an environmental emergency, honey bees have been observed to switch tasks more frequently and prioritize specific tasks that aid in thermoregulation across all types of reserves, not just specific worker groups (Johnson, 2002). Theoretical evidence suggests that this ability to reallocate reserves and workers based on task-switching could support colony survival during major catastrophes or large-scale disturbances to worker populations (Hasegawa et al., 2016). This body of research indicates that social systems have mechanisms in place to respond to and regulate worker loss, aiming to maintain average work activity and preserve the functionality of the social group in both standard and emergency contexts.

Finally, within organizational contexts, there has been a line of work that has looked at how organizations responded to environmental shifts and to better understand which organizations tend to be most resilient/robust to these exogenous shocks/shifts through their use of "slack resources" (Cheng and Kesner, 1997). Bourgeois 1981 discussed organizational slack as "a cushion of excess resources." Researchers argued that slack provides the ability for the flexible use of resources, to be mobilized in uncertain contexts / new environments to adapt and enhance an organizations ability to respond to these new contexts (Carter, 1971; Cyert and March, 1963; Mohr, 1969). Often in this literature organizational slack is operationalized as excess financial resources that can be leveraged in a pinch, however slack could also include humans as a resource to be mobilized as well.

Charbonneau et al. (2017b) offers an overview of how other complex social contexts could benefit from a systematic approach such as that used to study social insects. They discuss the potential that human organizations might possess fewer reserves, as humans typically operate in more predictable environments than social insects, or that human organizations might not adequately account for variability and should consider more flexible workers to optimally navigate diverse environments (Charbonneau et al., 2017b, p.15). Through our current study, we hope to contribute to this larger research on social systems by providing insights into the potential flexibility of humans in situations where actor incapacitation or loss might positively or negative impact the functionality of the collective system. Our study leverages the simulation capabilities in the `relevent` R package (Butts, 2013), to mobilize a battery of simulation studies to test the impact of various forms of node removal attacks on measures of resilience, building off prior work to find in which ways these networks are resilient.

## 4.4 Data and Methods

The data we use for this study comes from coded transcripts of radio communications among specialist and non-specialist responders during the World Trade Center disaster on the morning of September 11th, 2001. This data was extracted from transcripts released by the Port Authority of New York and New Jersey; they were originally coded by (Butts et al., 2007) and were recently made publicly available (Renshaw et al., 2023; Butts et al., 2021). Specifically, these data are from seventeen organizational units associated with the Port Authority of New York and New Jersey, each of which was communicating internally using handheld radios. The data consists of the sequences of radio calls among named communicants within each group, beginning when the first plane crashed into the WTC North Tower at 8:46 am, and extending for 3 hours and 33 minutes or until communication was terminated by structural collapse (in the case of some groups who were inside the WTC complex). Further background on the data set can be found in Butts et al. (2007); Petrescu-Prahova and Butts (2008b).

In prior work, Renshaw et al. (2023) used relational event models (REMs) to examine the communication dynamics among WTC responders, with a particular eye to identifying mechanisms responsible for hub formation. They generated best-fitting relational event models (Butts, 2008) for each of the 17 radio communication networks, using AICc-based model selection criteria and validation via simulation-based model adequacy checks. We leverage these empirically calibrated models for the purposes of this simulation study. Our general approach is as follows. In each simulation replicate, we perform the following for each network:

1. We fix the first half of the observed event history (starting our simulation at the halfway mark).

2. We identify a set of nodes (chosen by an *attack mechanism,* as described below) to be incapacitated; these are "marked," and rendered incapable of sending messages.

3. Using the empirically calibrated model for the specified network (subject to the additional constrained that removed actors cannot send), we simulate 600 additional events conditional on the history in (1).

The resulting simulated sequences are then analyzed to examine the impact of the attack on communication network structure and dynamics; simulated sequences in which no individuals were incapacitated were used as controls. As described below, we analyze the ability of the WTC networks to respond to different types of personnel loss, allowing us to probe the resilience of the communication system; importantly, while the *tendencies* of agents within each network are held to their empirically calibrated values, their actual behavior is free to adapt as the network evolves. This therefore complements the traditional network robustness studies reviewed in Section 4.3, in which observed communication patterns are held fixed (net of vertex removal).

## Simulation Design

Our procedure is implemented as follows. We first take the empirically calibrated parameters for each model reported by Renshaw et al. (2023) and generate a corresponding model skeleton using the `relevent` package (Butts, 2013) in the R statistical programming language (R Core Team, 2020b). Each model skeleton includes a covariate for whether a given node occupied an ICR, as well as a binary covariate indicating the nodes to be incapacitated; a sender covariate effect was added to the calibrated model for the incapacitation covariate, with a sufficiently large (i.e., effectively numerically infinite) negative coefficient to ensure that the hazard for sending from incapacitated nodes was numerically zero. (The values of the incapacitation covariate were set using the appropriate attack mechanism, as described below, with control cases having no incapacitated nodes.) Using the `relevent` simulate function, we then simulate additional events from these models, fixing the first half of the event history to the empirical data, generating 600 new events into the future after node removal. For instance, our largest network, Lincoln Tunnel, has a total of 1146 events in the empirical network; we thus use the first 573 events as the starting point for our simulated sequences, simulating 600 events past this point for a total of 1719 events. Our study hence employs an *in silico* interrupted time series design, where we compare *treatment* histories in which nodes were incapacitated at a specific point to *control* histories in which the intervention was not performed, with both prior history and behavioral mechanisms held constant.

With this as our base framework to simulate new event sequences, we then consider network evolution under several attack mechanisms; a descriptive table of node attacks with a breakdown of the number of simulations in each condition can be found in Table 4.1. We start out by creating a comparative baseline (i.e., control) condition for each of the 17 communication networks, where no attacks were performed. In these baselines, the first $n$ events are still fixed, with $n$ being the halfway point of the empirical networks. With no nodes removed from the network, we then simulate 600 events into the future. We conducted 100 independent simulations for the control condition for each of the 17 networks. We then simulated network evolution under four different attack mechanisms: Degree Attack, ICR Attack, Combined Attack (i.e., Degree and ICR), and a Random Attack. The degree attacks were constructed by sorting the actors by their total call volume (valued Freeman degree) in the empirically observed networks and then removing the highest k% of nodes. For ICR Attack, we randomly ordered all nodes occupying ICRs, followed by a random ordering of all non-ICR nodes, and took the top k% of nodes in this sequence (i.e., selecting ICR nodes first). For the Combined network attack, we first randomly ordered our ICR actors, and then ordered the non-ICRs from highest to lowest empirical degree; we then removed the first k% of actors (i.e., first removing ICRs at random, and then removing remaining nodes in descending degree order). Finally, Random Attack was conducted by randomly selecting k% of actors to be removed regardless of degree or ICR status. We conducted each of these attacks with $k$ set to 5%, 10%, 15%, 25%, and 50%, for a total of 20 different attack mechanisms – generating a new node removal vector for each simulation within each attack. For each of these 20 attacks, we generated 100 different simulations per network, for a total of 35700 simulated event sequences (including our 1700 control simulations).

We note that, unlike traditional robustness tests that simply remove nodes from a fixed communication network, our protocol allows incapacitated nodes to remain *targets* of communication. The simulated actors in the network do not initially "know" that their alters have been removed, and indeed may spend time and resources attempting to contact them (the titular act of "calling the dead"). This is similar to how real incapacitation or death during a disaster often occurs, with radio silence from the person on the other end, and is reflective of the the environment of the WTC response in which agents typically had to infer who was present and active from observed communication activity (Butts et al., 2007). By observing the rate at which organizations are able to detect losses and reconfigure communication in response to them, we are able to probe their resilience to personnel loss. Further, by examining the variation in resilience across attack mechanisms, we are able to probe the relative dependence of each organization on high degree versus institutionally defined coordinators.

|  | Baseline | Degree | ICR | Combined (Degree & ICR) | Random | Total |
|---|---|---|---|---|---|---|
| Baseline | 1,700 | - | - | - | - | 1,700 |
| 5% | - | 1,700 | 1,700 | 1,700 | 1,700 | 6,800 |
| 10% | - | 1,700 | 1,700 | 1,700 | 1,700 | 6,800 |
| 15% | - | 1,700 | 1,700 | 1,700 | 1,700 | 6,800 |
| 25% | - | 1,700 | 1,700 | 1,700 | 1,700 | 6,800 |
| 50% | - | 1,700 | 1,700 | 1,700 | 1,700 | 6,800 |
| Total | 1,700 | 8,500 | 8,500 | 8,500 | 8,500 | 36,700 |

Table 4.1: Number of observations for different node removal strategies and removal percentages, with totals.

## Outcome Measures

In evaluating our simulated trajectories, we focus on three categories of measures: structural changes, efficiency and functionality, and the role of reserves. Within each category we test for differences in the type of attack (combined, degree, ICR, and random), the percentage of nodes removed (5%, 10%, 15%, 25%, and 50%), and the differences between specialist and non-specialist networks. In order to evaluate differences in outcomes we use a series of $t$-tests, comparing networks under node-removal conditions and under baseline (i.e., treatment vs. control).

We use the following five measures to evaluate treatment effects on aggregate network structure. The first is the Theil index of communication volume, which is used as a measure of hub formation; an inequality measure, the Theil index is higher in networks with greater hub structure (a major feature of the WTC networks). This measure replicates that used in Renshaw et al. (2023). Next we measure the Krackhardt connectedness (Krackhardt, 1994) of the aggregated network, in parallel to robustness studies that frequently focus on fragmentation as a result of node removal. Our third measure is the degree centralization of the aggregated network, employed to test how evenly distributed communication volume is across each network; centralization has also been used frequently in studies of network efficiency. We also measured aggregated graph density to understand how many potential connections were realized. Lastly, we measured the proportion of the graph consisting of isolates (nodes that do not send or receive communications) in order to get at how much of the network is involved in communicating and how much slack is present under each condition. Taken together, we can understand whether or not these networks are fragmenting after node removal, or if they display a different pattern of resilience.

To measure efficiency and functionality, we measure the number of calls directed to incapacitated nodes and the average forward reachability within each simulated network. More efficient networks will waste fewer calls on those who cannot respond and learn more quickly not to direct calls to them. Likewise, communication networks only function if they are able to disseminate information, motivating the fraction of forward-reachable pairs as a measure of functional capacity.

Finally, the literatures on network resilience, slack resources, and organizational learning all point to the role of reserves in maintaining network functionality and responding to crisis. We thus construct a measure of reserve use (i.e., mobilization of previously inactive agents) and compare this across network conditions to understand their role in the reorganization and functionality of our radio communication networks.

## 4.5 Results

### 4.5.1 Changes In Network Structure

#### Attacks Induce Coalescence

In order to capture the pattern of network resilience, we focus on the five general measures from Section 4.4: the Theil index, network connectedness (Krackhardt, 1994), degree centralization (Freeman, 1979), density, and proportion of isolates. These measures allow us to

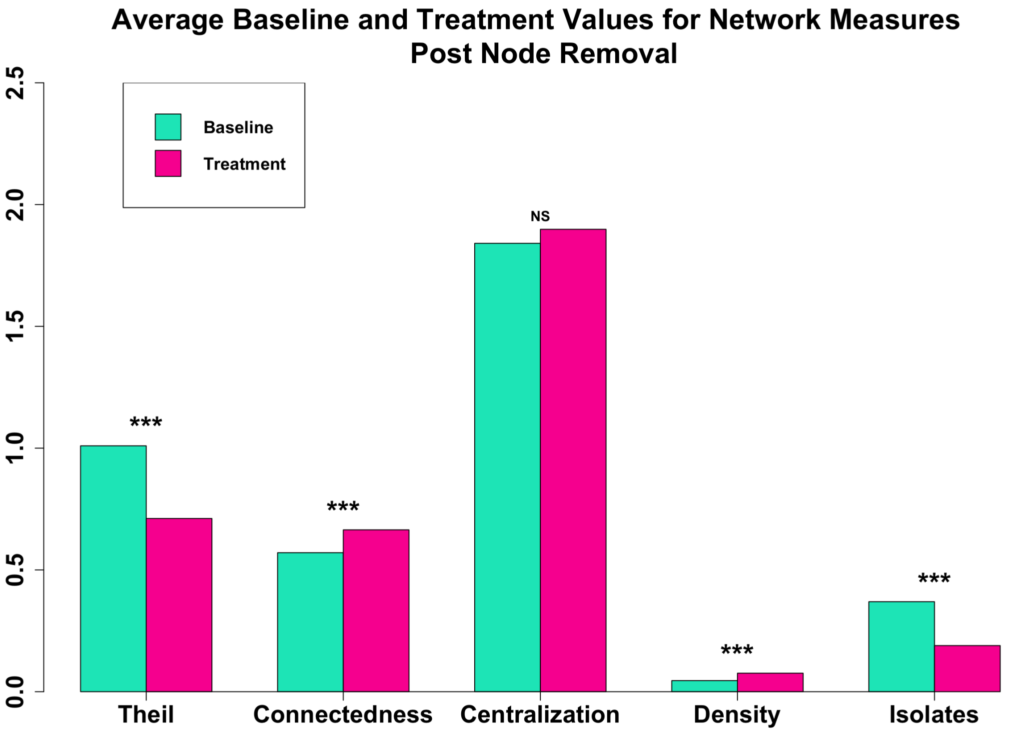

Figure 4.1: Mean values for time-aggregated network properties over all networks for treatment and control simulations ($*** = p < 0.001$). Overall, attacks lead to enhanced cohesion versus baseline simulations.

understand how the networks come together, or fragment after node removal, how much of the network is involved in communication, and how concentrated communication activity is. Figure 4.1 shows the average measure across all 17 networks after node removal compared to the average measure in the control condition, in which no nodes were removed. All measures are taken on the network over the 600 simulated events (i.e., not including the pre-history) in order to make all measures comparable. Rather than fragmenting, these communication networks appear to show a general trend of coalescence: density and connectedness are higher, while the Theil index, and the proportion of isolates are lower compared to the baseline simulations, while centralization remains unchanged. This implies that these networks have more actors involved, more connections between the actors, and are less hub-dominated following node removal.

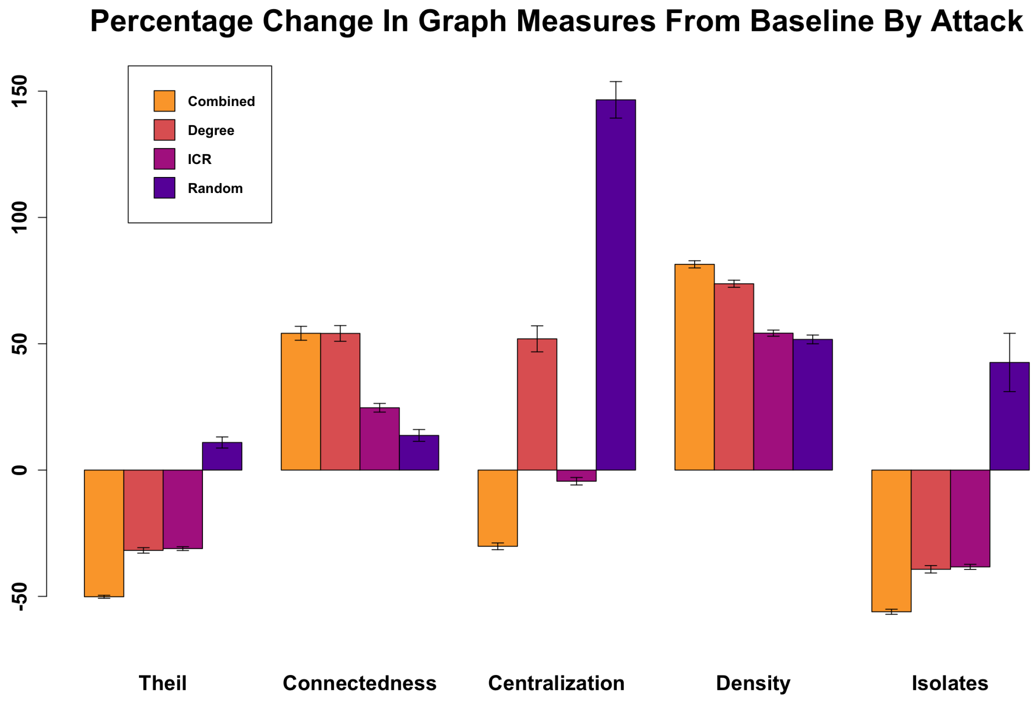

Figure 4.2: Percentage difference in time-aggregated network properties versus control over all networks, by attack mechanism. Cohesion enhancement is broadly consistent over targeted attacks, but not for random node removal.

We also tested whether or not this result varied by attack type and percentage of the network removed. Figure **??** shows mean treatment/control differences by attack mechanism. All measures of interest have statistically significant differences in means between all categories except for Theil index, where ICR and degree attacks are not statistically different, connectedness, where degree and combined attacks are not different, and proportion of isolates, where ICR and degree and not different on average. Overall, we can see that attack types do tend to vary from one another in their impacts on changes from the baseline network structure, but that all targeted attacks tend to enhance cohesion. We can also see that random attacks behave quite differently than targeted attacks, increasing Theil index, centralization, and the proportion of isolates, while increasing density and connectedness less than the targeted attack types. The only other attack type that shows a contradictory effect is degree attacks on degree centralization, but we suspect that this may be due to the nature of degree centralization – if there are many high degree nodes, targeting a fraction of them could actually result in a network of less active individuals and a smaller subset of very active nodes, thereby increasing our centralization measure.

We conducted the same test for percentage of nodes removed and found that there are more similarities in changes from baseline by percent than by attack. The only category that shows starkly different behavior is 50% node removal, likely due to the extreme nature of removing half of the network. For the other 4 categories of removal, there is a general pattern of increasing coalescence up to approximately 10% to 15%, with 25% removal producing similar changes in Theil index and isolate reduction, but producing slightly more centralized, less connected, and denser networks compared to 15%. Overall, we find that both the attack type and amount removed will impact the resulting re-structuring of the network, but in general targeted attacks that remove less than 50% of the network produce a pattern of *coalescence,* rather than the fragmentation expected from robustness studies.

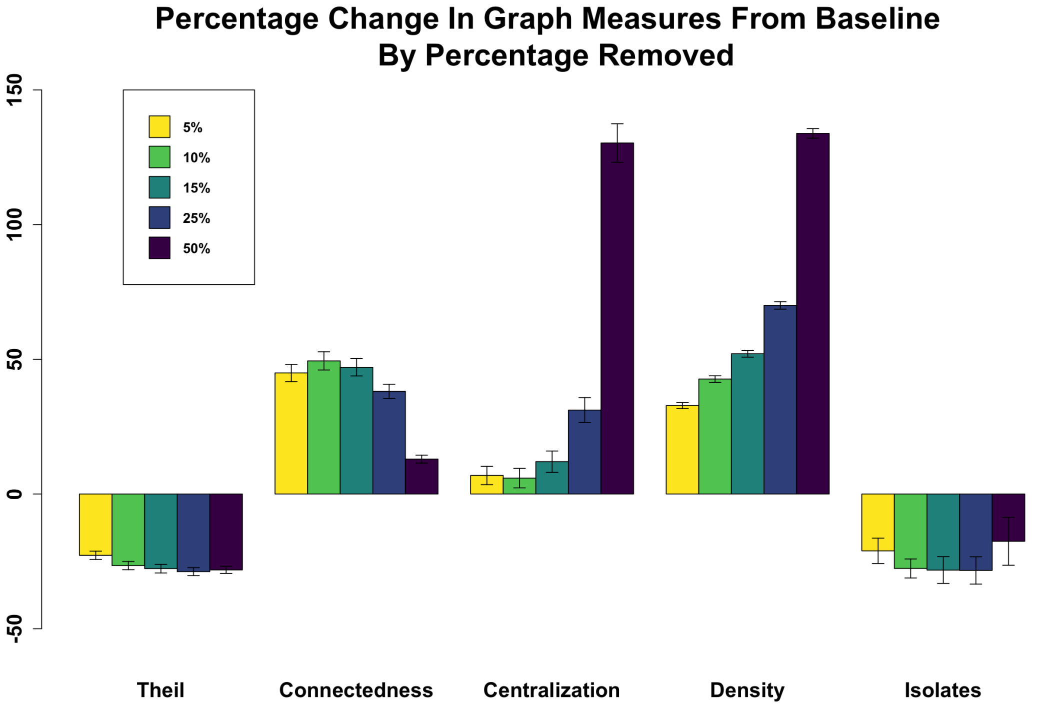

Figure 4.3: Percentage difference in time-aggregated network properties versus control over all networks, by fraction of nodes removed. Removal fraction has non-monotone effects for all outcomes other than network density, with the strongest effects observed at moderate levels of node removal.

### Specialist and Non-Specialist Networks Respond Differently

While our general findings appear in line with the literature on node removal in both insect studies and social communication networks, we also consider whether there is substantial variation in the effects of removal across different types of networks. The main grouping of interest in the WTC case is networks of specialist versus non-specialist responders, corresponding to whether the organizational unit is one that would be trained and organized to respond to emergency situations as part of their normal repertoire. The networks are divided fairly evenly between these categories, with 9 specialist networks and 8 non-specialist networks. We thus disaggregate the findings from above and test for differences between the two groups.

When we group the changes by node removal percentage, we can see higher levels of coalescence across all groups, with the only statistical difference being in isolate reduction at 50% removal. Looking at attack type, we can see that in general, non-specialist groups tend to show greater magnitudes of coalescence with higher decreases in hub structure and isolate percentage, and larger increases in density. However, when we look at ICR attacks, we see that specialists networks show the largest decrease in both hub structure and isolate percentage. This may indicate that the role of ICRs differs between the two groups. It may be that non-specialist networks have more non-ICR emergent coordinators compared to specialist networks and that the resilience behavior we observe is driven by the removal of coordinator nodes, which may also explain the distinct effect of random attacks.

| | Theil | | | Connectedness | | | Centralization | | | Density | | | Isolates | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Specialist | Non-Spec. | Diff | Specialist | Non-Spec. | Diff | Specialist | Non-Spec. | Diff | Specialist | Non-Spec. | Diff | Specialist | Non-Spec. | Diff |
| Combined | -50.30 | -49.98 | | 24.83 | 87.11 | *** | -31.36 | -28.84 | | 70.50 | 93.76 | *** | -58.56 | -53.30 | *** |
| Degree | -23.89 | -40.68 | *** | 20.73 | 91.63 | *** | 94.50 | 4.09 | *** | 58.41 | 91.03 | *** | -33.01 | -46.33 | *** |
| ICR | -43.44 | -30.82 | *** | 20.06 | 40.08 | *** | -19.16 | 9.34 | *** | 59.01 | 71.79 | *** | -52.41 | -38.84 | *** |
| Random | 29.20 | -6.92 | *** | -1.58 | 36.33 | *** | 165.38 | 96.53 | *** | 31.65 | 59.83 | *** | 87.25 | -6.61 | *** |

Table 4.2: Mean change from baseline for five structural measures by attack type and specialization. The difference between specialist networks and non-specialist networks was tested ($* * * = p < 0.001$, $** = p < 0.01$, $* = p < 0.05$). Specialist networks tend to show less coalescence across all attack types expect for ICR attacks.

| | Theil | | | Connectedness | | | Centralization | | | Density | | | Isolates | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Specialist | Non-Spec. | Diff | Specialist | Non-Spec. | Diff | Specialist | Non-Spec. | Diff | Specialist | Non-Spec. | Diff | Specialist | Non-Spec. | Diff |
| 5% | -15.97 | -30.39 | *** | 15.97 | 77.53 | *** | 17.37 | -4.91 | *** | 21.13 | 45.95 | *** | -4.7 | -39.54 | *** |
| 10% | -19.63 | -34.4 | *** | 17.79 | 84.98 | *** | 22.58 | -12.87 | *** | 31.51 | 55.24 | *** | -12.6 | -44.56 | *** |
| 15% | -22.74 | -33.3 | *** | 18.56 | 79.11 | *** | 27.09 | -4.94 | *** | 41.85 | 63.56 | *** | -17.8 | -39.98 | *** |
| 25% | -25.47 | -32.6 | *** | 17.76 | 61 | *** | 46.9 | 13.46 | *** | 59.69 | 81.61 | *** | -20.36 | -37.36 | ** |
| 50% | -26.72 | -29.8 | * | 9.98 | 16.31 | *** | 147.76 | 110.65 | *** | 120.29 | 149.15 | *** | -15.46 | -19.9 | |

Table 4.3: Mean change from baseline for five structural measures by percentage removed and specialization. The difference between specialist networks and non-specialist networks was tested ($* * * = p < 0.001$, $** = p < 0.01$, $* = p < 0.05$). Specialist networks tend to show less coalescence regardless of percentage removed.

### 4.5.2 Network Efficiency

While the networks may appear to coalesce, this does not mean that they are more or less efficient than the baseline configurations. We know that these networks experience some level of call loss, but the attack type and percentage killed may lead to more or less call loss overall. We thus begin by examining the mean lost call volume, i.e. the proportion of all communication within a simulation devoted to "calling the dead." Figure 4.4 shows the mean value over all of the communication networks for each removal strategy by percentage and attack type. First, it is evident that each of these attacks result in more calls to incapacitated nodes, on average, as we increase the number of nodes removed. We can also see that random attacks on average do not induce the same levels of call loss compared to the other attack types. Degree attacks at lower percentage of removal tend to be the most high-impact removal strategy, but this becomes slightly outpaced by the combined attack at much higher removal levels (25% and 50% removal).

This is indicative of findings we might expect to see on *a priori* grounds, especially with the behavior of random removal. As observed in prior work (Petrescu-Prahova and Butts, 2008a; Renshaw et al., 2023), the WTC networks are strongly hub-dominated. These hub-structures are composed of high degree individuals, and are frequently individuals who have been identified in pre-disaster contexts as being in an Institutionalized Coordinative Roles (ICR). When such individuals are removed, the same social mechanisms that fostered the initial emergence of hub roles (conversational inertia, preferential attachment, and ICR-directed communications) encourage persistence of attempts to contact them; by contrast, randomly selected responders are unlikely to occupy hub roles, and hence less likely to be persistent targets. While non-response from incapacitated nodes will eventually reduce or extinguish this behavior, it takes time for this to occur (as we show below).

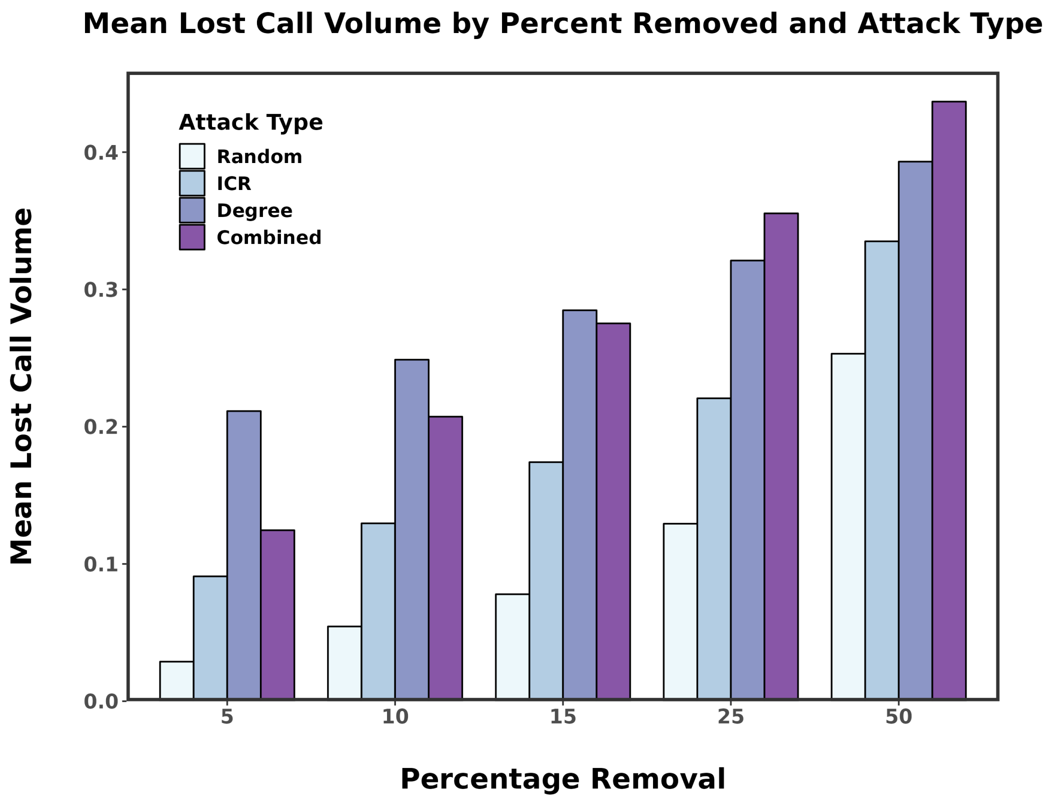

Figure 4.4: Mean fraction of all calls directed to incapacitated nodes, by attack mechanism and removal fraction. Targeted attacks lead to substantially greater loss of call volume than random attacks at all levels of removal, with removal of high-degree nodes generating greater losses than removal of ICRs per se.

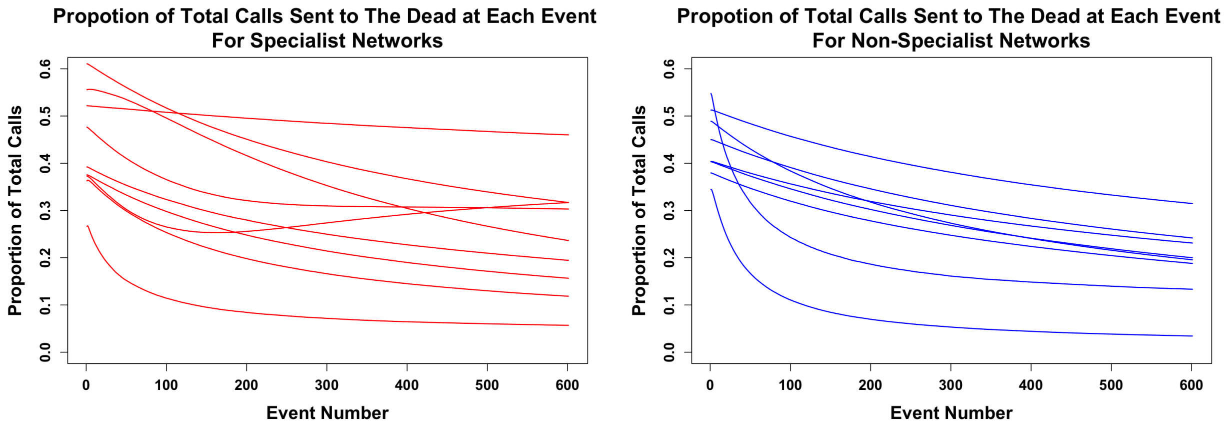

Figure 4.5: Average call loss curves for specialist (left) and non-specialist (right) networks across all attacks. While rates of calls to incapacitated nodes fall in nearly all networks, learning is faster on average in non-specialist networks (with some specialist networks showing high persistence in attempting to contact incapacitated nodes).

### Specialists Waste More Calls on The Dead

As was found in prior work relating to the WTC radio networks – particularly in the recent work by Fitzhugh and Butts (2021), there are differences in efficiency between specialist and non-specialist groups. First, we test the mean differences in call loss percentage between the specialist and non-specialist networks, which can be seen in Table 4.4. Results here show that there are statistically significant differences between the mean call volume loss between specialist and non-specialists, indicating that specialists across all attack mechanisms are more likely to contact inactive nodes.

| | $t$-value | $p$-value | Mean Spec | Mean Non-Spec | Difference |
|---|---|---|---|---|---|
| Combined | 10.13 | $p < 0.001$ | 0.30 | 0.26 | 0.04 |
| Degree | 11.88 | $p < 0.001$ | 0.31 | 0.27 | 0.04 |
| ICR | 24.46 | $p < 0.001$ | 0.23 | 0.14 | 0.09 |
| Random | 4.52 | $p < 0.001$ | 0.12 | 0.10 | 0.01 |

Table 4.4: Mean percent call loss (proportion of calls sent to removed/incapacitated alters) compared between Specialist and Non-Specialist networks.

On average, specialists expend anywhere from 1% to 9% more call volume on trying to reach incapacitated nodes than their non-specialist counterpart networks. We also can see that

ICR attacks are particularly disruptive to the normal functioning of the specialist networks, with specialists spending nearly 10% more call volume on incapacitated nodes than non-specialists.

We also tested for differences by fraction of nodes removed. In Table 4.5, we can see that all of percentages are significantly different between the specialist and non-specialist networks, affirming that specialist waste more calls across all percentages of node removal. Looking at table 4.5, we find that in the lower attack percentages there is less of a gap between groups, with 3 percentage points in both the 5% and 10% removal cases. As the amount of nodes removed increases, the gap between specialists and non-specialists widens with a difference of 5, 7, and 6 percentage points for the 15%, 25%, and 50% removal cases, respectively.

|  | $t$-value | $p$-value | Mean Spec | Mean Non-Spec | Difference |
|---|---|---|---|---|---|
| 5% | 10.97 | $p < 0.001$ | 0.13 | 0.10 | 0.03 |
| 10% | 9.19 | $p < 0.001$ | 0.17 | 0.14 | 0.03 |
| 15% | 12.36 | $p < 0.001$ | 0.23 | 0.18 | 0.05 |
| 25% | 14.24 | $p < 0.001$ | 0.29 | 0.22 | 0.07 |
| 50% | 12.46 | $p < 0.001$ | 0.38 | 0.32 | 0.06 |

Table 4.5: Mean percent call loss (proportion of calls sent to removed/incapacitated alters) compared between Specialist and Non-Specialist networks within each percentage removed.

### 4.5.3 Functionality

#### Forward Reachability Increases After Node Removal

While the ability of the of the WTC networks to reduce lost communication effort after attack can be determined by calls wasted on the dead, a general measure of functionality should capture the ability of nodes to pass information to others. Here, we assess this via a measure of forward reachability. We calculated forward reachability for each living node after the time of attack using the `networkDynamic` (Butts et al., 2023) and `tsna` (Bender-deMoll and Morris, 2021) packages for R. In particular, we measured what fraction of the network

Figure 4.6: Static versus forward reachability in a relational event system. Node A sends to node B and then node C sends to node A. In a time-aggregated network, C can reach B because there is a directed path from C to B, via A. However, in the dynamic structure, C cannot reach B because it sent to A after A had already sent to B.

could be reached by a randomly chosen node, accounting for the time ordering of edges. While the time-aggregated network may be more connected after node removal (as was seen in our above analyses), this does not necessarily mean that nodes can actually reach each other in the dynamic network, as relational events are directed and ordered. This difference between a static reachability measure and forward reachability is illustrated in Figure 4.6

This measure more accurately captures the functionality of the dynamic communication networks, and we can use it to assess the extent to which information passing potential is impaired by attack. Forward reachabilty was calculated for each node as the fraction of other "living" nodes it could reach and then averaged across all nodes in the network.

Testing for differences between all simulations and baseline, we find that reachability is not only sustained post node removal, it almost doubles, with a given node being able to reach 11.2% of the network on average in control versus 21.8% when averaging over all treatments. When looking at how this varies by attack type, we find that combined and degree attacks are not statistically different and increase reachability the most compared to baseline. ICR attacks appear to cause a larger increase in reachability than random attacks, indicating that targeted attacks increase reachability more than non-targeted ones. More specifically, Combined and Degree attacks increase the forward reachability measure by 104.62% and 107.22% above baseline, respectively, ICR attacks increase forward reachability by 83.46%, and finally random attacks cause an average increase of 77.91%.

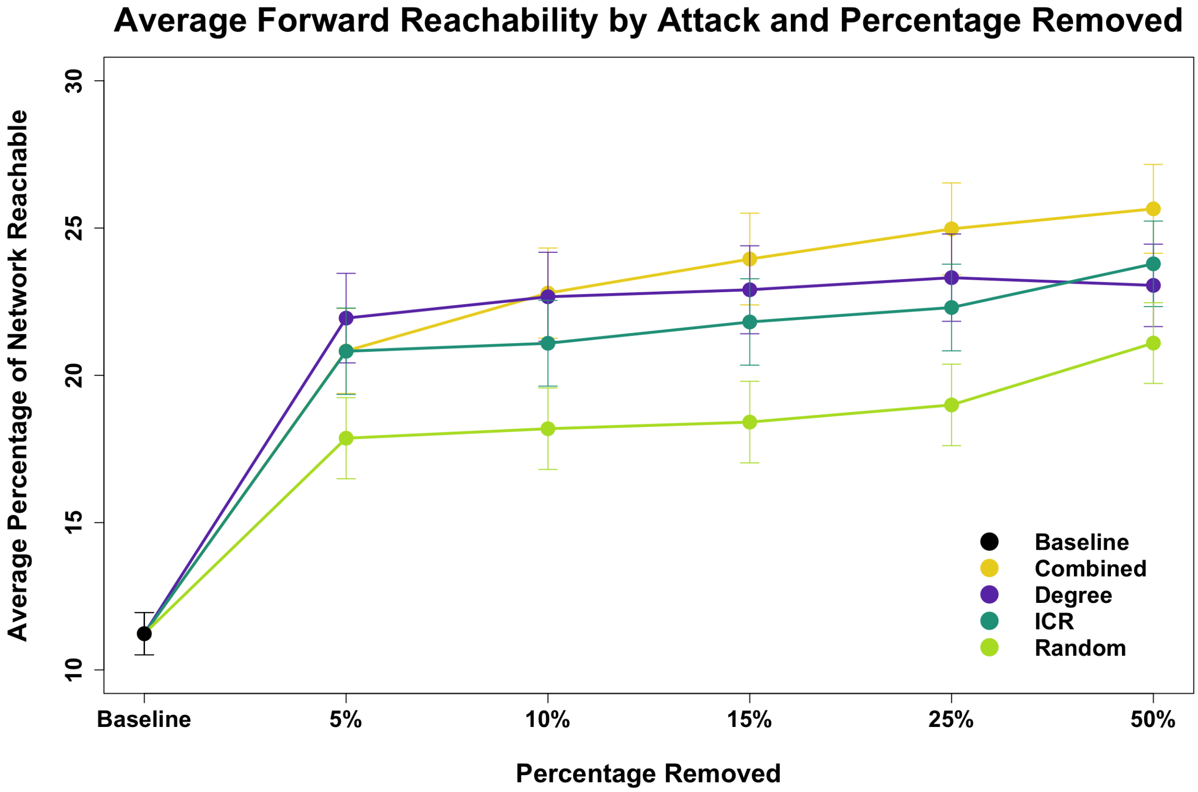

Figure 4.7: Mean forward reachability by both attack type and percentage removed. Forward reachability tends to increase with the percentage of nodes removed, but at varying rates per each attack type.

| Attack Type | Special. Average | Non-Spec. Average | lower CI | upper CI |
|---|---|---|---|---|
| Combined | 103.21 | 111.73 | -12.43 | -4.61 |
| Degree | 97.53 | 112.62 | -19.04 | -11.13 |
| ICR | 85.89 | 80.73 | 1.46 | 8.86 |
| Random | 74.70 | 81.51 | -11.09 | -2.54 |
| % Removed | Special. Average | Non-Spec. Average | lower CI | upper CI |
| 5% | 67.55 | 70.57 | -6.86 | 0.81 |
| 10% | 77.46 | 78.10 | -4.73 | 3.45 |
| 15% | 87.33 | 84.37 | -1.28 | 7.20 |
| 25% | 98.66 | 100.28 | -6.05 | 2.80 |
| 50% | 120.67 | 149.92 | -34.22 | -24.27 |

Table 4.6: Change in mean forward reachability as a percentage of baseline compared between Specialist and Non-Specialist networks by percentage removed and attack type.

In terms of the percent of actors removed, we find that all percentages removed are significantly different from one another. It appears that the increase to reachability scales positively with the number of actors removed, from 68.97, 77.76, 85.93, 99.42, and 134.44 for 5%, 10%, 15%, 25%, and 50% respectively. As this effect is likely partially influenced by size, we also tested for differences in the average count of actors reachable by a given node. Despite the networks shrinking after node removal, reachability still demonstrates a statistically significant increase compared to baseline, with the differences between attack type and percentage removed remaining consistent.

Finally, when we compare the specialist and non-specialist networks, we find that specialist networks see a smaller increase in reachability compared to non-specialist networks. Combined attacks increased forward reachability, with specialists seeing a 103.21% increase to their forward reachability (relative to control) and non-specialists seeing an increase of 111.73%. For Degree-targeted attacks, the mean increase in reachability was 97.53% for specialists, and 112.62% for non-specialists. Random attacks increased baseline reachability by 74.7% and 81.51% respectively, and ICR attacks impacted specialists slightly more at 86% compared to 80.7% for non-specialists.

When we break out the information for difference in reachability by the percentage removed, we find few statistically significant differences, with the exception being 50% removal; non-specialists increase reachability 150% above baseline compared to 120.67% for specialist networks. The differences between specialist and non-specialist networks were also confirmed in our test of the reachability count measure.

### Reserve Use Increases After Node Removal

Prior literature on resilience in social insect colonies points to the use of reserves to maintain functionality and respond to crises. Knowing that our networks appeared similarly resilient in the case of node removal, we tested for the use of reserves as well. We defined reserves as those individuals who had not sent communications at the time of node removal, and who were not removed from the network. We then measured the proportion of these specific nodes that sent communications by the end of the simulation process, and defined this as the rate of *reserve use*. We compare this measure to baseline to see how the removal strategy types and percent of actors removed affects the involvement of reserves.

Overall, networks under node removal conditions use an average of 80% of their reserves, compared to only 40.57% in baseline. Broken down by attack type, combined and degree attacks are not statistically different from each other, with reserve use increasing at 114% and 113% of baseline respectively. ICR attacks show an increase of 99.5% above baseline compared to only 88.5% for random attacks, indicating that targeted attacks are better for mobilizing reserves than random attacks, but that any node removal increases reserve use.

When broken out by the percentage removed, we find that 10% and 15% removal are the only groups that are not statistically different and that reserve use increases from 109% in the 5 percent removal case to 111.8% for both 10 and 15 percent removal cases. Reserve use then shrinks to 104.6% and 82.46% in the 25 and 50 percent removal cases, respectively.

Finally, for our specialized versus non-specialized tests, we find that non-specialized networks

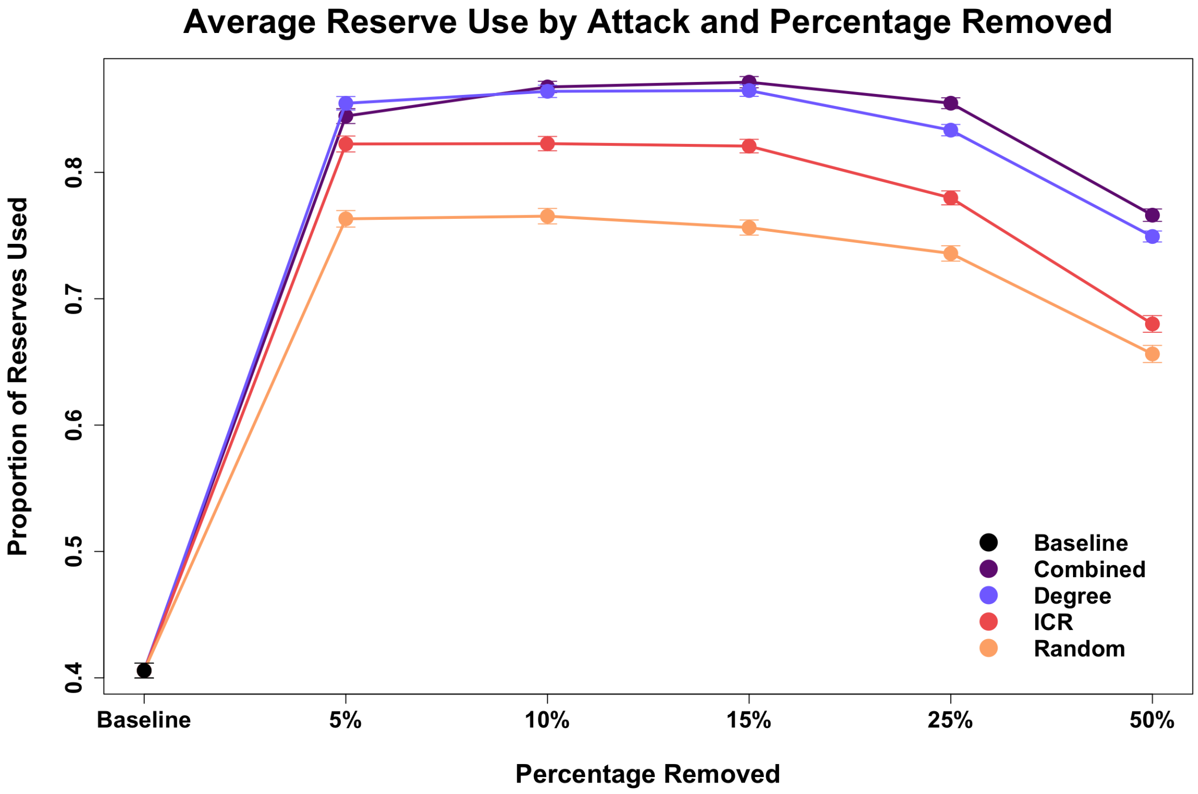

Figure 4.8: Mean reserve use by both attack type and percentage removed. Reserve use is higher for all percentages removed, compared to baseline, but decreases at higher rates of node removal compared to 5%-15% removal. This pattern holds for all attack types, but at varying magnitudes.

| Attack Type | Special. Average | Non-Spec. Average | lower CI | upper CI |
|---|---|---|---|---|
| Combined | 102.57 | 127.38 | -26.71 | -22.89 |
| Degree | 103.48 | 124.66 | -23.38 | -18.97 |
| ICR | 92.18 | 107.78 | -17.58 | -13.61 |
| Random | 76.56 | 102.00 | -27.61 | -23.27 |
| % Removed | Special. Average | Non-Spec. Average | lower CI | upper CI |
| 5% | 98.06 | 121.38 | -25.53 | -21.10 |
| 10% | 102.74 | 122.05 | -21.63 | -16.98 |
| 15% | 102.05 | 122.63 | -22.98 | -18.18 |
| 25% | 91.52 | 119.35 | -30.11 | -25.55 |
| 50% | 74.11 | 91.85 | -20.06 | -15.42 |

Table 4.7: Mean reserve use as a percentage of baseline compared between Specialist and Non-Specialist networks within each percentage removed and attack type.

utilize reserves about 15 to 30 percentage points more under all node removal conditions. While reserve use clearly increases, there is a possibility that this is simply due to swapping places with active nodes, which is not quite consistent with how reserve use is conceptualized in the literature. In order to understand whether or not this increase was attributable to a decrease in non-reserve activity, we measured the fraction of inactive nodes that become active and compared it to the fraction of formerly active nodes that become inactive. This measure ranges from -1 to 1, with -1 indicating that no reserves were activated, while all formerly active nodes became inactive and 1 indicating that all reserves became active and no formerly active nodes became inactive. The results are shown in Figure 4.9 and indicate a positive measure for all attack types and node removal percentages. The baseline simulations are the only ones with a negative value indicating that more formerly active nodes are becoming inactive compared to the number of reserves that are becoming active. This measure is also positively associated with the percentage of node removal and all targeted attacks result in a lager measure than random attacks across percentages. Overall, this indicates that the increase in reserve activity is not attributable to formerly active nodes becoming inactive.

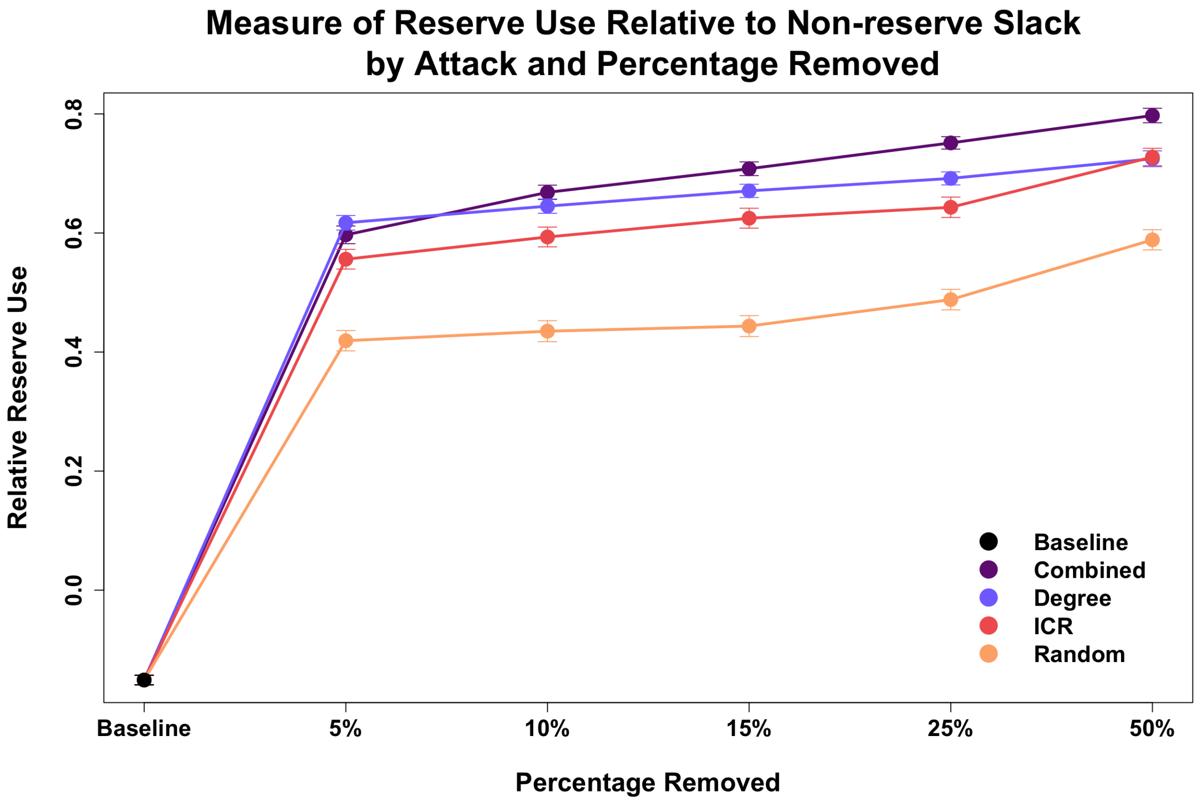

Figure 4.9: The mean difference between the fraction of inactive nodes that become active, and the fraction of formerly active nodes that become inactive. If $n_a$ is the count of previously active nodes, of which $s_a$ are later inactive, and if $n_i$ is the count of previously inactive nodes, of which $s_i$ are later active, this measure is then $\frac{s_i}{n_i} - \frac{s_a}{n_a}$. All attack types and percentages of nodes removed result in a positive measure, indicating that more reserves are being activated compared to the number of non-reserve nodes that are becoming inactive. We find the opposite pattern in our baseline simulations.

## 4.6 Discussion

Our study provides novel insights into the resilience of human networks in the context of 17 radio communication networks during the unfolding World Trade Center disaster. We examined how these networks – both specialist and non-specialist – were able to cope with the incapacitation or death of key communicators, thereby providing valuable insights into their ability for dynamic response and resilience.

Arguably, the most striking finding of our simulation study is the observed tendency of the WTC networks towards increased coalescence after suffering personnel loss (particularly the loss of coordinators). While prior research within the network robustness paradigm has emphasized the potential for node removal to lead to fragmentation, our study suggests that human social networks may be more resilient to disruption than previously understood. Across the board, our networks demonstrate a higher rate of connectedness and involvement from actors in networks attacked by node removal. This tendency also coincides with not only a maintenance of functionality, but an *increase* in it as measured by forward reachability. Such effects could not have been seen in robustness studies (including prior robustness studies on the WTC networks), since by definition such studies do not allow for adaptation of the social system to disruption. Although we note that our findings do not undermine those studies – they are measuring different things – they do suggest that care may be needed when *interpreting* robustness studies in settings where adaptation to damage is likely.

Our approach also allowed us to identify notable differences in how two types of organizations would be expected to respond to death or incapacitation of members during a disaster event. Specialist networks displayed a greater difficulty in adapting to the loss of key actors by spending more time contacting the dead than their non-specialist counterparts, while also coalescing less and demonstrating a lower increase in forward reachability. This relative lack of adaptation appears to be a result of their dependence on Institutionalized Coordinator

Roles (ICRs), potentially due to more rigid reliance on organizational standard operating procedures – a factor identified in prior research as a potential constraint on flexibility in hazard and disaster contexts (Carley, 1992). In contrast, non-specialist networks demonstrated superior resilience and flexibility in response to the attacks, with their adaptability involving a greater mobilization of reserves as well as a greater increase in their network functionality with respect to forward reachability.

Drawing parallels with social insects, organizational slack management, and engineering studies of node removal, this research highlights the critical role that reserve mobilization plays in the context of network resilience – observing a general tendency across the board that previously non-participating individuals had increased activation post-removal. Not only did we note a decrease in the percentage of isolates in the networks when compared to baseline, but we find that the sending activity of those who are isolates directly following node removal increased more than in baseline networks. While pressures for efficiency often suggest elimination of slack resources, our study reinforces the potential value of such resources in times of disruption.

### 4.6.1 Future Research

Compared to most node removal studies conducted to date, we find that our networks do not have a tendency to fragment and disconnect upon death or incapacitation. Instead, we find that there is a general tendency towards what we call "coalescence." Rather than fragmenting, coalescence is the ability for the network to restructure itself in a way that increases overall participation and connectivity while more evenly distributing the communication across actors; in our study this occurs in response to the removal of key communicators in targeted attacks. While this suggests the potential for higher levels of resilience in human social networks than has been implied by robustness studies, we observe that one should not conclude that such resilience is always optimal; for instance, the same adaptations that make specialist networks in the WTC less resilient in our study may make them more efficient when not experiencing personnel loss. Likewise, desirability of network resilience is obviously in the eye of the beholder: resilience in criminal networks, networks of proliferating cells in a tumor, or the like may pose obstacles to social or health intervention. Regardless, our findings suggest that researchers may need to give more consideration to network adaptation in interpreting node and edge removal studies. Probing the behavior of dynamic models to edge or node removal can account for potential temporal variability in how networks respond, resulting in considerably different outcomes than would be suggested by removal of elements from a static network.

An obvious benefit of robustness studies is that they are simpler to perform than resilience studies, as one needs only a single empirical observation; a perhaps less obvious benefit is the lack of a need for assumptions about how a network will respond to damage. This is an inherent tradeoff, since resilience is *per se* a dynamic phenomenon. To that end, it should be observed that an increasingly wide range of approaches (including but not limited to relational event models, temporal exponential family random graph models, and stochastic actor-oriented models) are available for developing and validating empirically calibrated models of network dynamics. Such models offer considerable opportunity to broaden our understanding of resilience, not only in communication networks but in other types of systems.

It should also be observed that there are many other kinds of resilience studies that could be carried out. Here, we held the behavioral mechanisms governing the networks fixed, and saw how the networks responded to disruption. In some settings, attacks may trigger changes to network dynamics themselves. While this is something that we cannot examine here (since we have no data to use for calibration), this would seem to be a fruitful area for future empirical and theoretical research. One could also consider other types of interventions beyond those conducted here, including alternative removal schedules, testing the impacts of intermittent failures, or focusing on edge removal, or even edge “scrambling” so that the intended recipient is unaware of the targeted nature of the communication, as prior work has found that conversational norms like turn-taking are critical for phenomena such as hub formation (Gibson et al., 2019).

Finally, we highlight some practical implications of our findings for enhancing resilience in emergency management contexts. While we cannot speak directly to effectiveness of the resulting networks in terms of how they reorganize after being attacked, from a purely structural standpoint – where individuals are capable of maintaining connectivity and reducing loss post-removal – we find that there are some obvious gains to not being too dependent on specialized roles and actors in communication networks (such as ICRs in our case). Further, training that emphasizes the need to adapt to apparent losses (when an agent “goes silent”) and switch to communications with other available agents, may expedite communication adaptation when loss occurs. This, of course, must be balanced against the gains in efficiency and communicative memory that is obtained by focusing coordination costs on a small number of (ideally trained and institutionally identified) individuals. We cannot speak to where this balance is, but we do show that there are costs to resilience from this strategy.

## 4.7 Conclusion

To conclude, our study provides insights into the dynamics and resilience of both specialized and non-specialized networks in response to personnel loss, allowing us to see into the potential behavioral responses to a real-world context in an unfolding emergency. The observed shift toward coalescence following network disruptions as well as the potential rigidity of reliance on institutionalized coordinators highlights an intricate interplay between structural and behavioral factors in the dynamic resilience of the WTC networks.

Crucially, our findings suggest a need for a more nuanced interpretation of traditional approaches to studies of network robustness – particularly as it applies to understanding network fragmentation. While robustness studies are unquestionably valuable from a purely structural standpoint (i.e., in showing e.g. how connectivity is maintained within particular networks), their utility in predicting responses to damage in real systems depends on the often tacit assumption that damage will not be restored on the relevant timescale. While this is often viewed as a convenient but reasonable approximation, this may always be accurate: in the case of the WTC networks, we see rapid and dramatic adaptation to personnel loss that results in *enhancement* of connectivity, something that could not be seen from a robustness study. Particularly where robustness studies are employed to inform policy or network design, it is important to rule out or otherwise account for such effects. Relatedly, our findings suggest that factors that do not contribute to robustness (most prominently, the presence of minimally connected or even disconnected nodes in the original network) may contribute to resilience, as when previously uninvolved personnel become mobilized when demands escalate. The utilization of reserves in the WTC networks suggests that the presence of "social loafers" or "slack" should to be considered in future studies as a potentially adaptive feature for resilience to personnel loss, as has been found in the social insect literature.

Finally, our study highlights the value of recent advances in statistical network analysis for theoretical studies of social process, and for the ability to approach questions relating to the resilience of social networks in an empirically informed manner while still working within the often severe limits of available data. Not mere hypothesis-testing tools, generative models for social process constitute formal theories for how the world unfolds, and can be employed for a wide range of purposes.

# Chapter 5

# Conclusion

The goal of this thesis was to explore and analyze the factors of successful coordination in two distinct contexts. These two settings occupy opposite extremes of a spectrum with regard to the scale of actors and their social contexts. One occurs at the global scale between nearly every country in the world over a time span of 166 years and the other took place over 3 and a half hours between 17 groups of people communicating during a disaster. While vastly different in content, both were studied as evolving systems across time with the broad goals of coordination and cooperation.

The second chapter takes a more zoomed out look at the patterns of homophily and heterophily within the international environmental agreement (IEA) co-ratification network. The goal of this chapter was to explore previously tested theories and their implications for patterns of mixing, based on categories of national characteristics. Additionally, this analysis included a control for prior co-ratification in order to disentangle the historical forces from those presently shaping cooperation.

The third chapter expands on the work of the first and analyzes the full bipartite IEA network over time. This analysis is the first to be able to take into account the eligibility of countries to ratify a given IEA and uses this new data to analyze all multilateral IEAs to date. This chapter tested prior theories with new dependence terms, including new model terms created for this dissertation, that had yet to be explored.

The fourth chapter shifts from the macro context of IEAs to the micro communications of first responders during the 2001 World Trade Center Disaster. This chapter uses a simulation study and best fitting relational event models to explore resilience within these networks. More specifically, we conducted a node removal study and allowed the networks to reorganize post removal. We explored measures of structure, efficiency, and functionality and looked at the differences in these measures between specialist and non-specialist networks.

This dissertation contributes to the field of sociology in the following ways:

- Chapter 2 is the first study to test IEA co-ratification rather than individual ratification. This study provides a first understanding of the factors shaping the strength of IEA co-ratifying relationships and invites future studies on the topic.
- The data collection for chapter 3 provides crucial information for studying IEAs in a systematic manner. This data can answer even basic descriptive questions that we have not been able to explore until now and will hopefully spur many future studies.
- The model terms constructed for chapter 3 are general terms that allow for the study of one mode effects on bipartite networks within the ERGM framework. These terms will allow future researchers to understand new complex relationships within two mode social networks.
- The results from chapter 4 open the door to possibilities outside of fragmentation within the context of network disruption. Not only are the findings themselves interesting and new, but the methodological framework can and should be leveraged to better understand the evolution of human social systems.

While the findings presented here are innovative and informative, there are a few limitations to highlight:

- The second chapter does not disentangle eligibility within the co-ratification patterns. This study was conducted before the data availability of chapter 3, so this was not feasible at the time. However, it does highlight the usefulness of the data collection conducted for chapter 3.
- In chapter 2 and chapter 3, I combined historically distinct regimes in order to treat countries as single entities. This was done due to data availability; while the IEADB distinguishes between countries at different time periods (e.g., "India (pre-1947)" and "India"), my covariate data does not make such distinctions. I chose to combine states in a way that allowed for more interpretable models as well as the best variable coverage, but greater data availability could lend itself to more nuanced and historically accurate results.
- Chapter 4 is a highly descriptive paper, utilizing a series of exploratory analyses. While we hint at mechanisms for differences in outcomes, post node removal, we do not conduct a formal analysis of the factors that lead to variation in outcomes. This type of analysis, while informative, seemed beyond the scope of the current paper, but should be considered for future work.

These studies not only move the field forward, but they suggest directions for future research as well:

- For both chapter 2 and chapter 3, time periods were constructed to overlap with typical decades, but were not situated in the specific historical patterns of IEAs themselves. Future work should adjust these time periods in various ways to verify that the findings do in fact hold and to give a more historical understand of the changes in IEA ratification over time.

- Future studies should re-analyze co-ratification using the newly coded eligibility information from chapter 3 in order to understand how the opportunity to co-ratify plays into the patterns of cooperation.
- The greatest challenge I see facing the study of IEA ratification is the lack of generalizable analyses of success. Often the number of ratifying countries is treated as a measure of success, but this fails to account for the real world impacts of these agreements and the factors that influence success in reference to achieving the goals laid out in the agreement text. This question of on the ground success must be addressed in future research in order to have the most substantial impact on future policy making.
- As suggested above, future research should work to understand what influences differences in post-node removal outcomes. Understanding this could help shape disaster responses and ultimately minimize the impacts of future disasters.
- Finally, the framework from chapter 3 should be extended to other social networks. There is a large literature on node removal studies, many of which could be better understood with the use of simulation methods.

Regardless of context, coordination is a dependent process and often one used to achieve a shared goal. It is through these cooperative actions at every scale that society functions and moves forward as one evolving system. In this dissertation, I have added to our understanding of coordination through new and unusual findings, richer data collection, and useful methodological tools. I hope that future scholars may use these to advance our understanding of environmental policy, disaster response, and social systems, both big and small.

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