Theorizing conditions and incentives that lead actors to develop resilient management strategies in complex environmental governance settings

THESIS

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ABSTRACT

Modern environmental problems pose unique management challenges since they are usually interdependent in myriad, complex ways. Climate change is the ultimate example of a problem that forces environmental managers to confront highly interdependent challenges, such as invasive species, rising temperatures, and habitat loss. A growing area of interest in understanding complex, polycentric governance systems has been to analyze the engagement of stakeholders in policy issues and the participation of stakeholders in policy forums. In this thesis, I focus on climate change adaptation governance in Ohio, USA as a model study system to evaluate conditions and incentives that drive actors to manage for interdependent issues or to participate in forums in ways that are collectively beneficial. To answer questions about actor management strategies in complex, polycentric governance arrangements, I analyze climate change governance as a three-mode network of interrelations among actors, forums, and policy issues related to climate change adaption in Ohio.

I draw upon the Ecology of Games Theory (EGT) and an Institutional Fitness framework to formulate hypotheses that uncover the conditions, incentive structures, and attributes that prompt actors to engage with issues and participate in forums in ways that promote adaptive capacity. Chapter 2 tests whether actors are likely to simultaneously manage environmental policy issues that are highly interdependent (such as nutrient management and water quality, which are connected through the process of eutrophication). Then, Chapter 3 tests for how different types of theorized

closure structures (i.e., unique situations of actor benefits) – lead actors to participate in decision-making forums. To tackle the questions at hand, both chapters utilize Exponential Random Graph Models (ERGMs), which is a tool for inferential network analysis.

The results indicate that actors are more likely to manage for pairs of interdependent policy issues when they are more strongly interdependent and are highly popular among the public. Interestingly, the results also suggest that the simultaneous management of interdependent issues is associated with issues for which there has been more progress. Furthermore, the results show that the incentive structures that guide forum participation do not necessarily promote optimal governance arrangements or optimal environmental outcomes.

Together, these findings advance theoretical understanding of institutional fitness and resilience in social-ecological systems by revealing how actors navigate highly interdependent environmental governance settings. Additionally, I highlight the benefits of examining complexity in polycentric governance systems through the more nuanced approach allowed by the analysis of three-mode networks.

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CHAPTER 1

Approaching complexity in climate change adaptation governance

Introduction

Climate change adaptation as a social-ecological system

In the Anthropocene, the changing climate creates numerous issues for stakeholders. Each issue can be considered as a separate "wicked problem" (Rittel and Webber 1973) or even a "super wicked problem" because there is a need to adapt quickly, because those who contribute to the problem (e.g., contribute to emissions) also seek to solve it, and because policy solutions irrationally discount the future in favor of the present (Levin et al. 2012). Climate change adaptation can be defined as "actions taken to cope with or respond to circumstances that have been altered as a result of a changing or more variable climate" (Popke et al. 2016: 72) and has become a focus in the contemporary politics of climate change (Adger et al. 2009).

Since 1990, the U.S. Global Change Research Program (USGCRP) is required by the Global Change Research Act (1990) to create and deliver a National Climate Assessment every four years to the U.S. Congress; the most recent version is the Fourth National Climate Assessment (NCA4), which includes an entire volume on current climate risks and adaptation in the U.S. (Reidmiller et al. 2018). Across the world, the impacts of the changing climate are experienced unevenly (IPCC 2014); the prominent issues on coastlines differ dramatically from issues facing inland regions. NCA4 includes region-specific chapters because of the differential impacts across the country (Roesch-McNally et al. 2020), including one for the U.S. Midwest (Angel et al.

2018). The Midwest report, as well as all other regional reports, engaged diverse stakeholders in the drafting of the document, and primarily exist to provide digestible, up-to-date climate research to practitioners, including decision-makers (Roesch-McNally et al. 2020).

In the state of Ohio specifically, there are many issues posed by the changing climate that are important adaptation priorities for stakeholders. These issues include changes to warm season weather conditions, rising temperatures, impacts on storm water management, land use, water quality, human health, and vulnerable human populations, to name a few. There is no perfect way to separate climate change adaptation issues into discrete and non-overlapping categories, and the issues listed above present multiple collective action problems that can disrupt human systems (Angel et al. 2018).

Using social-ecological networks to capture complex interdependencies

Climate change and its impacts on society can aptly be viewed as a system of interrelated parts (i.e., systems thinking; Meadows 2008). Climate change adaptation can also be considered as a social-ecological system, which, true to its name, consists of social entities, ecological entities, and their interactions (Janssen et al. 2006, Ostrom 2009). These perspectives emphasize the interactions between system components, such as resource sharing or policy learning between stakeholders (Ansell and Gash 2008) and the ecological feedbacks between different issues (Le Blanc 2015, Bergsten et al. 2019, Reyers and Selig 2020). For example, changing weather conditions create storm water issues, which exacerbates soil erosion, which then contributes to poor water quality, aquatic habitat loss, and drinking water contamination (i.e., human health). Given the complexity and sheer volume of interconnections between components in the climate

change adaptation system, network approaches are used by researchers as a tool to operationalize concepts of social-ecological systems and their interdependencies, capturing fundamental relationships between sets of nodes (Bodin 2017, Bodin et al. 2019, Sayles et al. 2019, Kluger et al. 2020).

Social-ecological networks consist of multiple types of nodes (entities in a network) and multiple types of edges (relationships between the entities), including social and ecological nodes, and social-social, social-ecological, and ecological-ecological edges (Sayles et al. 2019). In practice, most social-ecological network analyses operationalize social nodes as individuals, organizations, or policies; the connections between social nodes often represent co-attendance at meetings or collaborative partnerships (Bodin and Tengö 2012, Treml et al. 2015, Bodin 2017, Angst 2019, Bergsten et al. 2019, Metz et al. 2020, Hedlund et al. 2021). Ecological nodes can represent sustainability issues (Bergsten et al. 2019), ecosystem services (Alonso Roldán et al. 2015), or habitat patches (Bodin and Tengö 2012); the connections between ecological nodes (i.e., ecological-ecological edges) often represent biophysical or ecological feedbacks, pathways, and connectivity (Bodin and Tengö 2012, Dakos et al. 2015, Le Blanc 2015, Treml et al. 2015). Social-ecological edges can represent actors managing sustainability issues (Bergsten et al. 2019, Hedlund et al. 2021) or the reflection of ecological topics in existing policies or regulations (Ekstrom and Young 2009, Treml et al. 2015).

Beyond organizations and issues, a third type of node is relevant in environmental governance: policy forums (Lubell 2013, Fischer and Leifeld 2015, Nohrstedt 2018, Mewhirter at al. 2019, Lubell et al. 2020, Olivier and Berardo 2021). Forums are decision-making or information

sharing venues that provide a space for coordination and multiple types of interactions between stakeholders (Bogason and Musso 2006, Fischer and Leifeld 2015). In the Ohio climate change adaptation system, forums take the form of meetings, workshops, working groups, seminars, or conferences, among other decision-making and resource-sharing venues. Actors attend forums to gain resources (e.g., social, financial, political capital), technical information, and to impact the governance of issues (Fischer and Leifeld 2015). In a three-mode network of actors, forums, and issues, actor-forum linkages represent organizations participating in forums; forum-issue linkages represent forums focusing on policy issues. Within the literature on social-ecological networks there is a lack of studies that go beyond two modes (e.g., only actors and forums, or only actors and issues).

Many researchers use network analyses to extend theories of environmental governance and social-ecological systems, including the Ecology of Games Theory (EGT) and Institutional Fitness. These two frameworks to study social-ecological systems form the conceptual approach for this thesis research and are discussed in greater detail in the following section.

Conceptual framework

This thesis draws heavily upon the EGT, which is a theoretical framework that considers policy processes and environmental governance as complex adaptive systems (Levin 1998, Levin et al. 2013, Lubell 2013). First introduced by Norton Long (1958), the EGT is a metaphor to describe complex policy systems as comprised of interlinked policy games that are played by actors (Long 1958). This metaphor has been updated in recent years in applications to modern social-ecological systems, where policy games consist of sets of actors who seek to impact the game

and who operate within the formal and informal rules that govern decision-making processes (i.e., policy institutions; Lubell 2013, Berardo and Lubell 2019). The EGT is a theory of polycentricity, which is a feature of most governance systems in which there are many autonomous units or decision-making processes that are formally independent but are functionally interdependent (V. Ostrom 1961, E. Ostrom 2010, Carlisle and Gruby 2017). The research questions and hypotheses in this thesis have been formed in part to explain how polycentric systems are shaped and how they function, for example through actors choosing policy games to play in (e.g., engaging with issues – Chapter 2, or participating in forums – Chapter 3).

One key tenet of the EGT is that policy games are interlinked with one another; however, there are no EGT-based empirical studies that explicitly analyze the interconnections between policy games. This lack of empirical analysis on interlinked policy games constitutes a gap in the EGT literature. There is a growing research interest using network analyses to understand environmental interdependencies (Bodin et al. 2019, Bergsten et al. 2019, Hedlund et al. 2021), but not in the context of the EGT. The research presented in this thesis highlights the importance of interdependent policy issues in polycentric governance systems, specifically in the context of climate change adaptation.

Institutional fitness, or social-ecological fitness, is an additional framework to unpack complexity in social-ecological systems; it describes the degree to which social systems reflect the environmental systems in which they are embedded (e.g., through management actions or policies; Young 2002, Folke et al. 2007, Lebel et al. 2013, Epstein et al. 2015). Although it is not

a certainty, the institutional fitness literature generally assumes that good fitness is associated with improved environmental outcomes (Janssen et al. 2006, Borowski et al. 2008, Bodin et al. 2014, Barnes et al. 2019, Wang et al. 2021). As an example, institutions can be more 'fit' when an actor (e.g., an organization) manages for interdependencies between ecological issues or collaborates with another actor who works on an interdependent issue (Bergsten et al. 2019, Hedlund et al. 2021). Additionally, 'fitness' increases when two actors who work on the same policy issue collaborate and share resources with each other (Bergsten et al. 2019). Despite an understanding of which governance arrangements are 'fit' and which are 'unfit', there is a dearth of existing empirical research that tests for the conditions that lead to 'fit' governance arrangements in the first place. This gap in the literature is the motivation for the analyses conducted in Chapter 2.

This thesis aims to address the gaps in the literature described above by pursuing the following objectives:

1. To uncover the conditions that lead actors to manage for environmental interdependencies.
2. To understand the incentive structures that lead actors to participate in forums.
3. To illustrate the advantages of multi-modal network analyses in research on complex environmental governance settings.

Overview

A mutual objective of Chapter 2 and Chapter 3 is to understand the conditions that lead actors to engage in sustainable or unsustainable management decisions when surrounded by hundreds of

other stakeholders, hundreds of decision-making forums, and dozens of collective action problems. Specifically, Chapter 2 aims to uncover the conditions under which actors choose issues to manage in ways that contribute to 'institutional fitness', while Chapter 3 attempts to identify the incentive structures that guide actor participation in forums in ways that can either be collectively optimal or suboptimal. In meeting these objectives, Chapters 2 and 3 provide evidence on conditions associated with sustainable management in governance systems characterized by complexity.

Both Chapters 2 and 3 utilize different parts of the same data set, which focuses on climate change adaptation in Ohio. This state-wide climate change adaptation governance system provides a prime setting to test our hypotheses because it is comprised of many actors, forums, and issues that interact with each other across multiple scales and boundaries (e.g., geographical, jurisdictional, organizational). In total, we identified 659 actors, 391 forums, and 19 issues. There is a great diversity of actors involved in Ohio-based climate change adaptation, including environmental interest groups (N=268), special districts (N=113), local government departments (N=43), state government departments (N=33), federal government departments (N=26), university departments (N=63), coalition groups (N=43), and industry groups (N=70). Moreover, these actors operate at different spatial scales, including at the local- (N=102), county- (N=189), regional- (N=108), state- (N=153), and national-level (N=107). Beyond actor attribute data for "organization type" and "organization scope", we also collected data on the attributes of forums and issues. Forum attributes include "sponsored by government" and "sponsored by university"; issue attributes include "progress" and "popularity." The measurement of each of these attribute variables will be defined in the following chapters. This diversity in actor type and scope, in

addition to a diversity in forum and issue attributes, positions the Ohio-based climate change adaptation system as an ideal study system to uncover conditions that lead actors to engage with issues (Chapter 2) or participate in forums (Chapter 3) in ways that are institutionally 'fit' (Chapter 2) or collectively optimal (Chapter 3).

Both empirical chapters use network analyses to answer the main research questions. Chapter 2, which focuses on the conditions that lead actors to manage for interdependent issues, analyzes a two-mode network of organizations and policy issues. Chapter 3 focuses on actor participation in forums and includes three-mode data: organizations, issues, and decision-making forums. In its use of a three-mode network analysis, Chapter 3 provides the first empirical study that applies the EGT to understand how dynamics among actors, forums, and issues shape polycentric governance systems.

The two empirical chapters in this thesis (Chapters 2 and 3) focus on two relatively under-researched components of the EGT, respectively: issues and forums. In devoting a chapter to each of these levels fundamental to modern ecologies of games, this thesis adds to our understanding of how actors operate in complex, polycentric arrangements. On another note, although it is commonly understood that social systems 'fit' to their underlying ecological context are associated with positive environmental outcomes, there is little research to uncover the conditions that lead to 'fit' institutions in the first place. Similarly, although it is generally accepted that the make-up of participants in decision-making forums has an immense impact on policy outcomes and environmental outcomes, there is more work to be done to understand the incentive structures that guide actors to participate in forums. Therefore, the main contribution of

this thesis is to discover the conditions and incentives that lead actors to choose issues to work on and forums to attend in ways that promote positive environmental outcomes. Given the immediate need to address the worsening impacts of climate change, this research is particularly important because it identifies features that promote environmentally 'fit' management (Chapter 2) and effective participatory governance arrangements (Chapter 3).

CHAPTER 2

Closing Integrative Gaps in Complex Environmental Governance Systems

Introduction

Individual environmental problems rarely exist in isolation. Ecological dynamics and feedbacks cause individual issues to become interwoven with other issues in complex ways. For instance, the spread of an invasive plant in a forest is triggered by warming micro-climate temperatures; the warming temperatures are exacerbated by increased economic activity both locally and beyond. The issue of invasive plants might also be caused by improper wildlife management, or by transportation-related seed dispersal. Such linkages exemplify one of the key challenges facing environmental decision-makers – stakeholders with a vested interest in improving environmental outcomes are confronted with a constellation of issues and are tasked with managing the interconnections and evolving dynamics between them. The lack of well-defined definitions, rules, and the nested nature of modern environmental dilemmas qualifies them as wicked problems that are uniquely difficult to manage (Rittel and Webber 1973).

Despite the many interdependencies between environmental issues (i.e., the change in one issue affects the outcome in another, or two issues have overlapping management activities; Pham-Truffert et al. 2020, Hedlund et al. 2021), stakeholders do not always address these interdependencies in a holistic manner (Le Blanc 2015, Munsch et al. 2020). In complex governance systems, actors may operate more efficiently when they focus their limited capacity on a subset of interrelated issues because this, for example, can lower the environmental externalities that result from managing problems in a fragmented way. Since environmental externalities can cause shocks and perturbations across an entire system, actors who manage for environmental interdependencies – opposed to those who manage an assortment of random, unrelated issues – improve system-level efficiency by internalizing the costs associated with integrative gap closure (Bergsten et al. 2019). From the standpoint of the entire system, appropriate management responses should ideally cover entire groups of interconnected environmental issues. A stakeholder with an ideal management approach would oversee an entire group of forest patches that are ecologically linked by seed dispersal, or collaborate with the managers of linked patches, instead of managing isolated patches (Bodin and Tengö 2012). Similarly, an ideal stakeholder would focus their efforts on a set of sustainability issues that are all influenced by each other, creating virtuous cycles of synergistic management (Folke et al. 2005, Pham-Truffert et al. 2020). Inappropriate or non-ideal management responses are those that address an issue without first attending to its potential feedbacks and interconnections.

The term “integrative gap” is used in the institutional fitness and environmental governance literatures (Young 2002, Folke et al. 2007, Epstein et al. 2015) to describe instances when a stakeholder fails to account for biophysical interdependencies in their management approach

(Bergsten et al. 2019). Integrative gaps have implications for how well governing institutions reflect the biophysical system in which they are embedded, a key tenet of institutional and social-ecological fitness (Folke et al. 2007, Galaz et al. 2008, Lebel et al. 2013, Kininmonth et al. 2015). A great number of integrative gaps across a system may lead to fragmented management practices and ineffective environmental governance systems (Lubell 2013, Bodin 2017, Cejudo and Michel 2017). The closure of integrative gaps is desirable in that it is likely associated with improved sustainability outcomes (Bodin et al. 2014, Bergsten et al. 2019). Despite the increasingly recognized importance of policy issue integration for improving governance outcomes and efficiencies (Trein et al. 2019, Pham-Truffert et al. 2020), actors do not always close integrative gaps (Metz et al. 2020). We aim to understand the reasons why an actor is more or less likely to manage environmental interdependencies by formulating and testing our main research question: under what conditions do stakeholders close integrative gaps?

To answer our research question, we investigate integrative gaps in the climate change adaptation governance system of Ohio (Midwest USA). Climate change is a prominent example of an issue that is associated with multiple, distinct sub-issues related to specific adaptation challenges. Each issue poses unique challenges for local environmental managers. In Ohio specifically, managers must adapt to rising temperatures, heightened pest and pathogen pressures, and non-native species invasions, among other issues (Angel et al. 2018).

We operationalize climate change governance in Ohio as a multilevel network that is composed of over 600 stakeholders, 19 climate change adaptation issues, and their interconnections. This network can be categorized as a partially articulated social-ecological network ("Type II";

Kluger et al. 2020). Social-ecological networks capture complex interdependencies between social and ecological components (Sayles et al. 2019) and are increasingly turning into a dominant analytical focus for scholars interested in the study of environmental governance systems and their institutional fitness (Janssen et al. 2006, Treml et al. 2015, Ekstrom and Crona 2017, Bodin et al. 2017, Angst 2019, Bodin et al. 2019, Barnes et al. 2019, Cinner and Barnes 2019, Metz et al. 2020, Hedlund et al. 2021). We test a series of hypotheses about the conditions under which an actor closes integrative gaps. Our results are important in that they extend existing literature on policy issue integration to uncover factors associated with actor-based integrative gap closure, which can improve social-ecological efficiencies and environmental outcomes.

Environmental interdependencies, integrative gaps, and institutional fitness

Integrative gaps occur when actors fail to account for environmental interdependencies by working on a topic without paying attention to how it interacts with other topics (e.g., working on water quality without considering how increasingly common extreme weather events can impact said quality; Bergsten et al. 2019). In highly interdependent environmental systems, there are many pairs of connected issues, meaning that there are many possibilities for integrative gaps to occur. To make matters difficult for environmental actors, governance systems with many interdependent environmental issues are the rule, not the exception. What's more, the interdependencies become increasingly complex and relevant in governance contexts as the world becomes more globalized: the outcomes in one social-ecological system are invariably tied to outcomes in others (Kissinger et al. 2011, Centeno et al. 2015).

Examples of interdependent issue systems abound. In transcontinental aquatic systems, ecological interdependencies exist between the distinct issues of habitat restoration, water flow, and fisheries management (Munsch et al. 2020). In lake governance systems, interdependencies exist between the issues of pollution, water quality, and human health. There is also recognition that interdependencies occur across geographical boundaries, such as the linkages between rural and urban environmental issues (Buttel and Flinn 1977). In wildfire-prone regions, such as much of the Western U.S., high ecological connectivity facilitates the spread of fire across jurisdictions and can link actors together based on shared wildfire risk (Hamilton et al. 2019). These examples speak to the fact that environmental interdependencies, which occur across spatial and temporal scales, should be a fundamental consideration in an actors' management strategy (Cumming et al. 2006, Cash et al. 2006).

At a global level of integrative gap closure, Reyers and Selig (2020) have proposed that future Sustainable Development Goals (SDGs) create targets that emphasize social-ecological feedbacks and interdependencies that occur between the issues of biodiversity, ecosystem services, and sustainable development. They propose that future targets should fundamentally reject the "silo mentality" of separation between sustainability sectors and between scales of management (Griggs et al. 2014, Stafford-Smith et al. 2017, Reyers and Selig 2020). To promote the integrative gap closure of interconnected issues, SDG targets and similar policies themselves should reflect biophysical processes and feedbacks, emphasizing the tight interconnections that exist between issues (Le Blanc 2015). The holistic management of key relationships between

SDGs has been identified as an entry point to replace "vicious cycles" of negative environmental feedbacks with synergistic "virtuous cycles" (Pham-Truffert et al. 2020).

In environmental governance contexts with many interdependent issues, the dynamics and feedbacks of an entire social-ecological system are greater than the sum of its parts. This means that complexity is derived from the relationships between issues and not merely because there are many issues (Levin 1999). In the same sense, the concept of ecosystem-based management has gained support over the past few decades and includes management approaches that consider entire systems and not separate components or sectors (Leslie and McLeod 2007, Levin et al. 2009). It is therefore counterproductive for managers to approach singular environmental issues without first attending to the roles they play in other domains. This is the challenge for environmental stakeholders: the high degree of complexity in navigating environmental interdependencies makes sustainable management a difficult feat.

How well a set of actors in a governance system reflect ecosystem dynamics has implications for how "fit" the social system is to its ecological context (Young 2002, Folke et al. 2007) – a high prevalence of integrative gaps is an indicator of poor institutional fitness (Lebel et al. 2013, Bergsten et al. 2019). Conceptually, the fitness of institutions is analogous to the fitness of organisms: the most "fit" organisms and institutions are those that are best adapted to their environmental setting. In governance systems, adverse environmental outcomes occur when actors fail to match their management approaches to the underlying realities of the social-ecological systems in which they operate (Epstein et al. 2015), similar to how a plant species that

cannot withstand changing weather conditions will eventually be outcompeted by another species, with implications for the overall ecosystem.

Integrative gap closure improves institutional fitness since actors who manage interrelated issues are better able to holistically account for system feedbacks. Highly interconnected ecological systems can both facilitate the spread of disturbances and recovery across a landscape (Dakos et al. 2015), meaning that actors who close integrative gaps can oversee – and thus manage for – fundamental ecological processes. These biophysical interconnections are otherwise more difficult to observe and account for when approaching an issue in isolation (Armitage et al. 2009). Actors who extend their resources to manage multiple interconnected issues can improve their understanding of environmental interdependencies and use their newfound knowledge to guide their individual management decisions; an accumulation of enhanced management strategies across many actors can ultimately improve overall system governance.

Systems where actors largely fail to account for biophysical interdependencies in their management approaches (i.e., systems with a high prevalence of integrative gaps) could more easily be pushed past "tipping points" into undesirable, irreversible pathways toward degraded states (Galaz et al. 2008). Resultingly, integrative gaps contribute to a decline in system resilience and an increase in vulnerability. We argue that integrative gaps are ecologically uninformed management approaches because they fundamentally fail to account for essential ecological processes. In a case study of agricultural systems in Australia, ecologically uninformed policies have led to a loss of social-ecological resilience and increased vulnerability (Anderies et al. 2006). Furthermore, one study found the largest contributor to institutional misfit

in an estuary system was the lack of reflection of ecosystem relationships in policy documents (e.g., the co-occurrence of ecosystem components in the same sentence of a policy document), emphasizing the need for ecologically informed management as a means to improve system resilience (Ekstrom and Young 2009).

To establish the importance of being fit, we must first unpack how fitness shapes environmental outcomes, although there are few studies that do so (Bodin et al. 2019, Wang et al. 2021). There is no clear-cut, simple relationship between network structure and ecological outcomes or resilience (Janssen et al. 2006). However, the general assumption is that fit institutions lead to improved conservation success through enhanced management (Borowski et al. 2008, Guerrero et al. 2015, Ingold et al. 2018). This notion has been supported in an agricultural system case study (Bodin et al. 2014) and in Kenyan coral reef communities, where good social-ecological alignment was associated with improved reef ecosystem conditions (Barnes et al. 2019). Good fitness does not necessarily improve environmental outcomes, though; an empirical case of strong spatial fitness did not encourage effective drinking water regulations in the Rhine River catchment (Ingold et al. 2018). In the transcontinental aquatic system example, the simultaneous management of fisheries, water flow, and habitat restoration was found to benefit diadromous fish species like Pacific salmon (*Oncorhynchus* spp.) that migrate between rivers and oceans (Munsch et al. 2020). The closure of an integrative gap in this system, for instance, might occur when an actor utilizes water discharge and habitat quality data to decide the environmentally optimal location to open a new fishery.

Understanding when integrative gaps are closed

Given the importance of well-aligned social-ecological systems for sustainable governance arrangements (Bodin 2017), we devise a series of hypotheses that investigate the conditions and attributes that could enable an actor to close integrative gaps. We argue that the conditions associated with integrative gap closure can be leveraged to improve social-ecological fitness and thereby foster system sustainability. We study integrative gap closure at the level of the actor, not the system, although the closure of integrative gaps is efficient both for individual actors who have limited resources, and for entire governance systems when individual actors internalize the externalities stemming from between-issue dynamics (Kininmonth et al. 2015). An integrative gap (Figure 2.1A) is closed when an actor manages both of a pair of related issues (Figure 2.1B), requiring both potential social-ecological edges to be fulfilled. We test for the conditions and attributes that lead actors to form social-ecological edges that close integrative gaps.

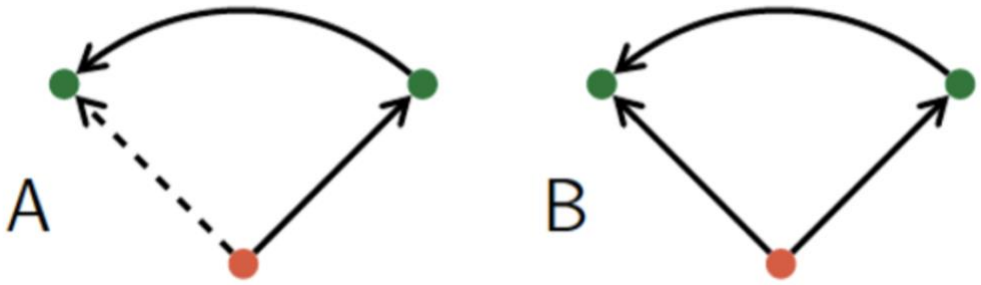

Figure 2.1. A visualization of integrative misfit (A) and integrative fit (B) depending on the absence (dashed) or presence (solid) of a tie between an actor (red circle) and two biophysically related issues (green circles), regardless of the direction of the relationship between the two issues.

Not all pairs of issues are made equally; instead, they vary in strength and importance based on several factors. What this means for stakeholders is that some pairs of interrelated issues are more essential to manage than others. Actors should ideally choose to work on issues that are the

most closely related to the other issues they work on. For example, an actor who manages water quality should also consider the issue of soil erosion, since the latter can increase turbidity – often directly associated with water pollution (Lal and Stewart 1994). On the other hand, an actor who manages water quality and air quality simultaneously would be closing a less important integrative gap, because although water quality and air quality indeed are interrelated (e.g., via CO2 emissions that indirectly stimulate algal biomass growth; Chen et al. 2019), this interrelation is more subtle compared to others. From an efficiency standpoint, loosely related issue pairs do not warrant the same priority of integrative gap closure as do closely connected topics, and so we should expect to see fewer efforts to jointly work on loosely related issues. Accordingly, our first hypothesis is related to the closure of integrative gaps based on the strength of ecological interdependencies.

> H_1: Actors are more likely to close integrative gaps for pairs of topics that are more strongly interdependent.

Issue Attributes

Beyond the strength of interconnections between issues, an actor's propensity to close integrative gaps may be impacted by certain relevant attributes of the issues themselves. One prominent attribute of issues that we believe to explain integrative gap closure tendencies is public attention. Certainly, some issues receive more public attention than others, such as media attention (Angst 2019). Select issues may demand the public's attention, including the attention of key actors (Kingdon 1984, Berardo et al. 2015). Stakeholders may be more likely to recognize

high-attention issues as more important to manage (Wlezien 2005), which could be a precursor for integrative gaps to be closed for high-attention issues. The interdependencies between popular issues are likely popular themselves, such as the interdependency between water quality and human health that receives high levels of attention during toxic algal blooms events. We expect that because popular issues are connected to each other via popular interdependencies, they are management priorities for environmental stakeholders. Accordingly, we propose H_2:

> H_2: Actors are more likely to close integrative gaps between issues for which there are higher levels of public attention.

Additionally, we posit that integrative gap closure is associated with higher levels of progress made on resolving issues. We define progress as the amount of headway made on resolving or adapting to an issue, which we gauge based on a series of interviews with experts who indicated their perception of issue progress. We use perceived issue progress as a proxy measurement for environmental outcomes and expect that integrative gap closure leads to high levels of progress. This is because social-ecological alignment is generally assumed to lead to conservation success (Bodin et al. 2014). In testing for an association between integrative gap closure and issue progress, we must also recognize the possibility that high levels of progress could make integrative gap closure more likely. For instance, issue pairs with high progress levels likely have higher levels of scientific certainty, which in turn should reduce the transaction costs that actors bear when managing for uncertain and complex ecological interdependencies. Our expectation is that integrative gap closure leads to higher levels of issue progress and improved environmental outcomes, and therefore propose H_3.

H_3: There is a higher level of progress solving issues for which fewer integrative gaps exist.

Actor Attributes

We expect that the ability of actors to work on multiple issues (and therefore be able to close integrative gaps) varies with an actor's organizational type and organizational scope. To manage a single issue (i.e., work on projects, programs, and advocacy), an actor must expend resources such as time, money, and human capital. Then to manage multiple issues, or a great number of issues, actors must spend an even greater sum of resources. We predict that because different types of organizations (e.g., NGOs, governmental agencies, universities, etc.) are differentially equipped with resources, organizational type plays a key role in actor-issue engagement, and therefore in integrative gap closure. Government actors are heavily solicited as collaborative partners in management efforts because they often occupy the role of a broker – government actors utilize their financial, human and political resources to connect otherwise unconnected actors, leading to the exchange of nonredundant resources (Berardo 2009, Henry 2011). Furthermore, government actors tend to have more experience, authority, and participate in decision-making forums more often than other types of actors (Lubell et al. 2014, 2017). Beyond these factors, government actors are often mandated or are implicitly expected to perform functions that protect the public good (i.e., social contract theory; Locke 1965, Rosseau 1973, O'Brien et al. 2009), which can potentially be completed through integrative gap closure. We expect that these advantages and responsibilities of government actors position them to better manage for environmental interdependencies than non-government actors.

H_4: Government actors are more likely to close integrative gaps when compared to non-government actors.

Furthermore, the ability for an actor to overcome the transaction costs associated with working on multiple issues may be a challenge for small-scale stakeholders because they would need to spend major resources to gain technical, social, and political capital for the management of each issue (Angst 2019). As such, an actor's geographic scope (e.g., local, regional, state) may dictate whether it should specialize on a single issue or a subset of interrelated issues. In addition to impacting the issues an actor engages in, geographic scope impacts the forums that an actor participates in. Actors are less likely to participate in forums that do not match their own organizational level (Hamilton et al. 2018). Geographic scope is an important consideration in matching management to ecosystem dynamics at different spatial scales: social-ecological mismatches can occur in cases when social actors responsible for managing some part of the environment operate at a geographic scale inconsistent with the scale of environmental processes (Cumming et al. 2006). Because there often are spatial incongruencies between patterns of ecosystem services and the policies meant to sustain them (Qiu et al. 2017), the scope of organizations involved in the governance of biophysical issues plays an essential role in social-ecological alignment. We posit that actors who operate at wider management scales are better able to account for jurisdiction-crossing issue interdependencies and resultingly are more likely to manage for them. Therefore, we propose one final hypothesis related to geographic scope:

H_5: The greater an actor's geographic scope, the greater the likelihood that it will close integrative gaps.

Methods

To test our hypotheses, we collected social-ecological network data on climate change adaptation governance in Ohio. In any given policy system, there are likely many issues occurring simultaneously (Lubell 2013), so we constructed a network that includes social-ecological and ecological-ecological ties, which can be categorized as a 'Type II' network (see Kluger et al. 2020, Sayles et al. 2019). Figure 2.2 depicts a theoretical social-ecological system where several stakeholders manage a subset of climate change issues, closing some, but not all, integrative gaps.

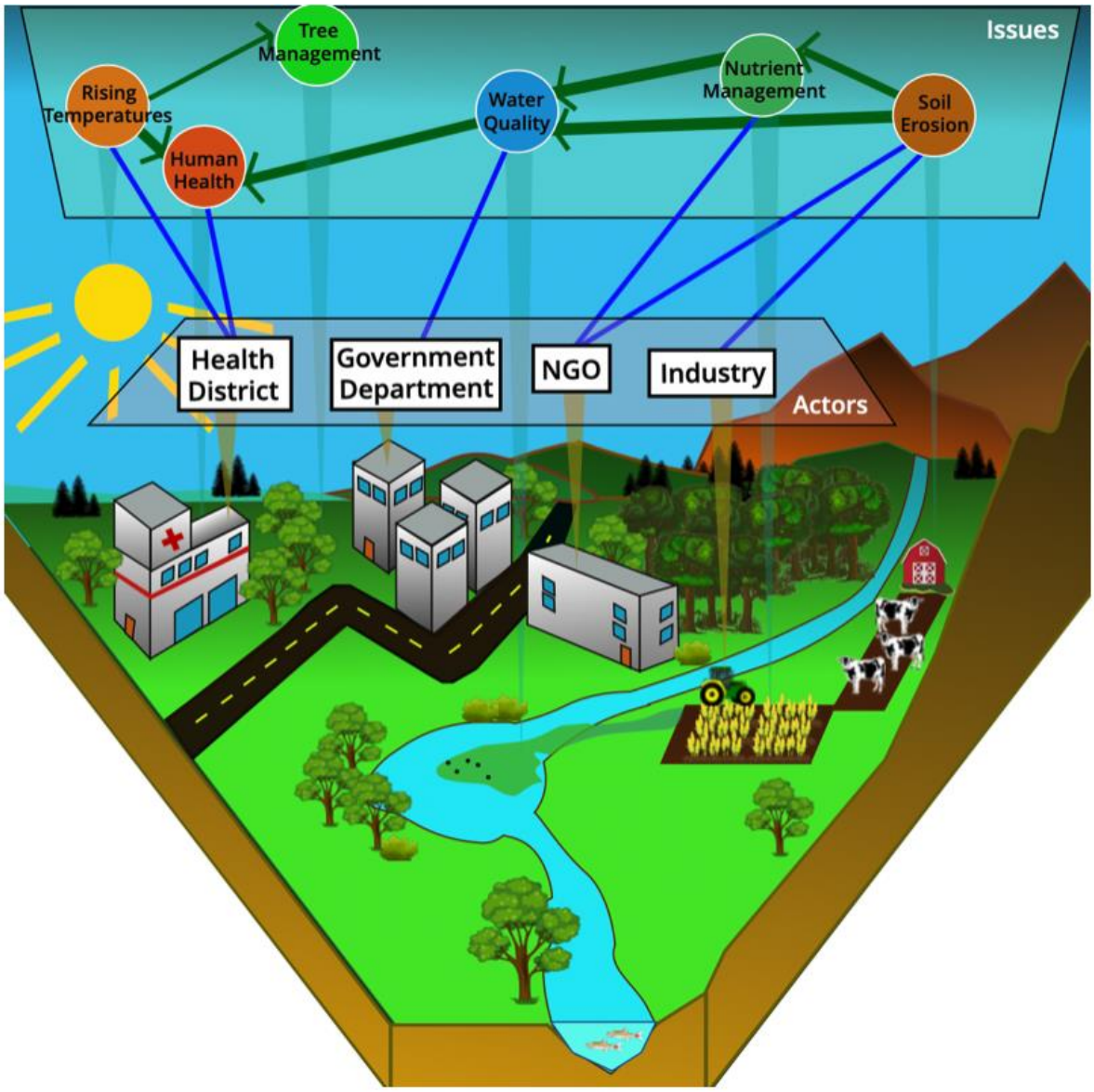

Figure 2.2. A drawing of a social-ecological system consisting of interdependent climate change issues and four actors. The green arrows represent issue interdependencies that occur across the landscape, which are directed and weighted. The blue lines indicate the issues that the actor manages. Integrative gaps occur when actors manages only one issue of a related pair of issues.

Our social-ecological network included 19 climate change-related adaptation issues relevant to Ohio, the actors who work on these issues, and the relationships that occur between them. Social-ecological network studies emphasize the relationships between two sets of system components (social and ecological) rather than just social-social ties or ecological-ecological ties (Bodin et al. 2019, Sayles et al. 2019). In the social-ecological network, we focus on the ties between issues and the ties between actors and issues (typically referred to as affiliation ties). We utilize issue interdependencies as edge covariates to explain social-ecological edge formation.

Issue interdependency network

The issues in our two-mode network are themselves intertwined and we aim to explore these interrelationships. We first identified the issues as described in the US Global Climate Research Program's (USGCRP) Fourth National Climate Assessment (FNCA), which is a comprehensive report that provides the state of the science on climate change in the US. Because climate change affects regions in unique ways, some effects are heightened in various locations (Roesch-McNally et al. 2020). To make regional climate change effects more salient for local stakeholders, the USGCRP provides regional summary reports of the FNCA and includes key messages that describe the most pressing issues for each region (Angel et al. 2018). A diverse array of participants and voices contributed to each regional FNCA chapter, meaning that each chapter identifies problems from a multidisciplinary perspective (Roesch-McNally et al. 2020). The Midwest chapter, which we use in this analysis, outlines six key messages that are important from an adaptation standpoint in the region. These key messages focus on agriculture, forestry, biodiversity and ecosystems, human health, transportation and infrastructure, and community vulnerability. In May of 2019, each of this paper's authors read through the key messages to

identify specific collective action problems, then met to reconcile differences in individual lists, resulting in a total of 19 specific adaptation issues relevant in Ohio, shown in Table 2.1. These adaptation issues are the ecological nodes in the network.

Table 2.1. Climate change adaptation issues and the adaptation activities that correspond to them. The issue list and their associated activities were derived through a text analysis of the Midwest Report of the Fourth National Climate Assessment (Angel et al. 2018).

Issue	Activities
Air Quality	Air quality monitoring, permitting, and enforcement
Forests	Forest protection, forest biodiversity management
Green Infrastructure	Rain barrels, green roofs, backyard homesteading
Green Spaces	Park management and trail-way development
Habitat Loss	Habitat preservation, habitat creation, buffer zones
Human Health	Climate-related health advocacy and care
Invasive Species	Invasive species removals, invasive species education
Land Use	Conservation easements, sub-urban sprawl, research
Natural System Restoration	Dam removal, habitat restoration or enhancement
Nutrients	Nutrient diversion, fertilizer management practices
Pests and Pathogens	Crop pest and pathogen research, management plans
Rising Temperatures	Temperature adaptation, air conditioning
Soil Erosion	Cover crops, conservation tillage, filter strips
Storm Water	Installation of runoff diversion infrastructure
Transportation	Sustainable transportation systems and clean fuels
Tree Management	Tree planting, urban tree canopy assessments
Vulnerable Communities	Promoting food access and resilience to hazards
Warm Season	Weather pattern adaptation and management
Water Quality	Water pollution abatement and clean-up

A classic use of ecological networks has been to set habitat patches, specific locations, or ecosystem types as ecological nodes (Sayles et al. 2019). Pittman and Armitage (2017) use types of habitat as ecological nodes, including seagrass and reef habitat, to investigate social-ecological fitness across a land-sea interface. Alternative types of ecological nodes have been utilized by some authors, including sustainability issues like “human-wildlife conflict”, “food

access", and "agricultural expansion" (Bergsten et al. 2019). Specific ecosystem services have been used as ecological nodes as well (Alonso Roldán et al. 2015).

We then measured connections among the 19 issues based on their approximated biophysical relationships according to the opinions of 57 experts who we interviewed for this project. From May to August 2020, we conducted a series of semi-structured interviews with local experts to understand how each issue affects and is affected by every other issue, generating a score and description for every possible issue-issue pair. Interviewees were told to identify relationships between issues that existed at the time of the interview. We identified experts for each of the 19 issues through online searches and interviewed three experts for each issue. For example, a water quality expert answered questions about how water quality affects all other issues, and how all other issues affect water quality. Each interview produced a cognitive map of issue-issue relationships and we combined all 57 cognitive maps to construct the issue interdependency network. The issue network thus captures the interdependencies between issues as assessed by the experts, thereby synthesizing multiple (academic and non-academic) forms of knowledge (Dray et al. 2007, Jones et al. 2011, Pittman and Armitage 2017). We interviewed relevant faculty members from local universities in addition to field technicians who work in Ohio. Of the 57 experts who were interviewed, 18 were faculty members from universities, 20 were scientists from government departments, and 19 were scientists from NGOs and other organizations.

Table 2.2 shows three issue pairs and their bidirectional connections, scores, and descriptions: the pairs included in the table were specifically chosen to demonstrate variability in issue interdependencies. Scores range from 0 (no interdependency) to 1 (strongest interdependency). The strength for each directed edge (X_{ij}) is the average of six expert responses, three experts from each topic (*i* and *j*). Then, we took the average of the directed edge weights (X_{ij} and X_{ji}) to

produce undirected edge weight scores for each issue-issue dyad. For example, the undirected edge weight for the interdependency between "Air Quality" and "Forests" is 0.575, the mean of 0.50 (impact of "Air Quality" on "Forests") and 0.65 (impact of "Forests" on "Air Quality" – see Table 2.2).

Table 2.2. Sample bidirectional linkages, strengths, and descriptions for three pairs of issues. For each issue-issue pair, tie strength is calculated as the average strength of both directions (A to B and B to A). For instance, the edge strength between Air Quality and Forests is 0.575. The data displayed is the aggregate score and description of issue interdependencies based on expert interviews, where the edge strength between Air Quality and Forests is the average response of three Air Quality experts and three Forest experts.

Issue A	Impact On	Issue B	Strength	Description of Impact
Nutrients	->	Soil Erosion	0.67	Soil nutrients promote plant growth and root cover, which stabilizes soil erosion
Soil Erosion	->	Nutrients	0.83	Eroded soil particles carry attached nutrients along with them, resulting in nutrient influxes in water bodies
Air Quality	->	Forests	0.50	Forests may be impacted by particulate matter and sulfates, although healthy forests are generally resilient to these impacts
Forests	->	Air Quality	0.65	Forests filter out some air contaminants and they capture carbon dioxide, leading to improved air quality
Water Quality	->	Human Health	1.00	Drinking water is essential to life; water pollutants can be deadly and lead to chronic health problems if ingested
Human Health	->	Water Quality	0.27	People in poor health have a limited ability to lessen their personal impact on water quality; poor environmental health can spur water quality improvement initiatives

To assess the level of public attention that each issue commanded (information needed to test H_2), we used "Google Trends", which provides the relative popularity of unique search terms during a controllable time range and location. We obtained the relative search popularity in Ohio for each of the 19 climate adaptation issues for each week from October of 2016 to November of 2019, then averaged these scores to produce a single public attention score for each issue. To obtain perceived progress scores, we asked the same experts to indicate their agreement (along a five-point Likert scale) with the following statement: "Over the past 50 years, there has been a significant amount of progress made toward addressing this issue." Response scores were averaged for each issue, producing a perceived progress score for every issue, which we use to test H_3.

Actor-issue linkages

The social nodes in our analysis are organizations involved in management efforts in Ohio of at least one of the 19 issues we identified. From June through August of 2019, we identified organizations using an internet-based snowball approach (Hileman and Lubell 2018). We started by identifying a group of seed actors who work on climate adaptation in Ohio, which included several large environmental organizations near our home institution, the Ohio State University. Then, we conducted a hyperlink analysis from seed actor websites to identify the organizations with whom they work on climate change adaptation activities with; these additional actors were often listed as partners. The snowball process was repeated until no new actors were revealed, resulting in a network of 659 actors. We coded several organizational attributes for each actor, including organization type (e.g., NGO, state government) and organization scope (e.g., local, sub-state regional, state, national).

We measured actor-issue linkages based on the information displayed on organizations' websites; most common were strategic plans, project descriptions, or Annual Reports. Specific activities listed on individual actor websites were used to substantiate actor-issue linkages. For instance, a mention that the organization is active in promoting the use of rain barrels would create a tie linking the actor to the issue "green infrastructure." Table 2.1 displays a list of adaptation activities that are associated with each adaptation issue.

Bipartite exponential random graph models

To test our hypotheses, we use bipartite Exponential Random Graph Models (ERGMs), which are statistical models used to determine whether theoretically-important network configurations appear more frequently in an empirical network than what would be expected from a large distribution of randomly-generated networks of the same size (Robins et al. 2007, Lusher et al. 2013). ERGMs simulate large numbers of randomly generated networks with the same number of nodes and linkages (i.e., density) as an empirical network and then compare the distribution of structures of interest in the randomly generated networks to the number of such structures that are present in the observed networks. This exercise allows the researcher to gauge the extent to which the observed structures in the real network depart from what would be expected from a purely random process of tie formation.

For each parameter included in an ERGM, the model generates an estimate and standard errors. The likelihood of a certain configuration occurring because of emergent dynamics in the empirical network is expressed by the parameter estimate coefficient, where a non-zero and significant coefficient indicates that the structure is either enhanced (positive) or suppressed

(negative) in the empirical network. It is common to start with simple models, then refine them in additional models by continually adding new parameters that are thought to explain the empirical network structure (Robins et al. 2011, Bodin et al. 2016).

To estimate our models, we employ the package "ERGM" (Hunter et al. 2008) in R (R Core Team 2019) and construct four models that successively build from each other. We test the propensity for actors to close integrative gaps for pairs of issues that are strongly biophysically interconnected (H_1) using issue interconnection scores as an edge covariate. We include additional edge covariate terms that test for integrative gap closure tendencies based on public attention to the issues and perceived progress made on them (H_2 and H_3). To test H_4 and H_5, we use two different effects, including: (1) baseline *issue engagement* (*nodefactor*) and (2) *integrative gap closure* likelihood (*edgecov*) for each actor type and scope level, where *Federal Government* and *National* are used as reference categories, respectively. Figure 2.3 displays the network configurations for each of the hypotheses. We differentiate issue engagement from integrative gap closure, where issue engagement is interpreted as the propensity for a given actor to work on a given issue, while integrative gap closure is the likelihood that an actor closes an integrative gap.

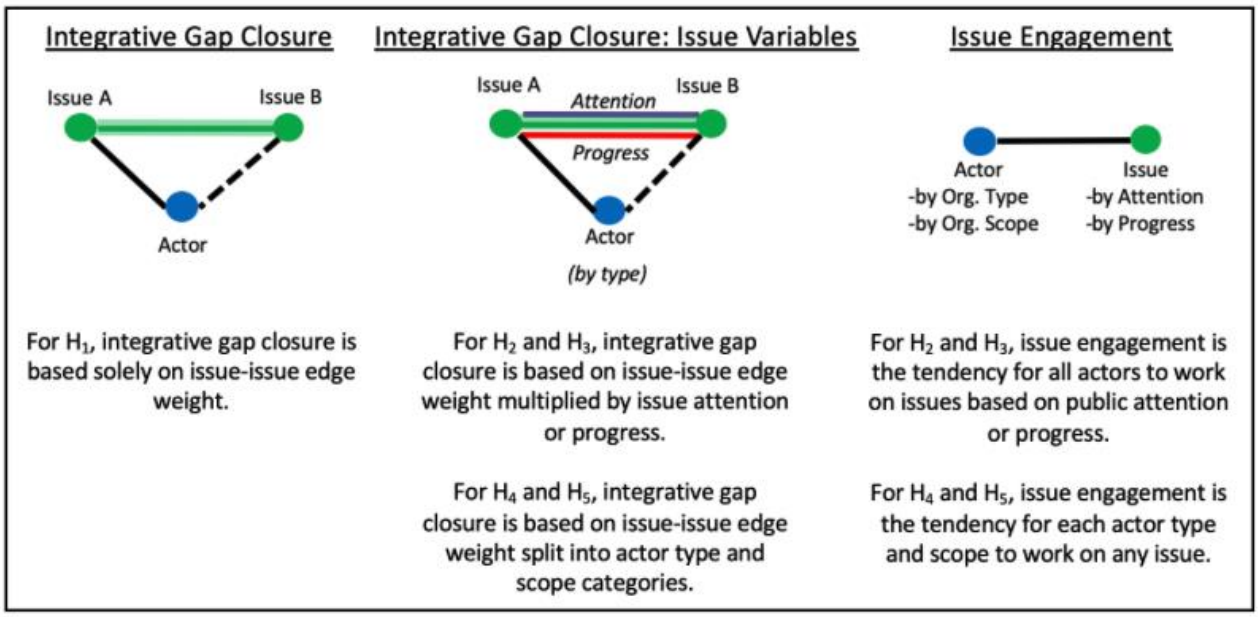

Figure 2.3. Network configurations and descriptions used in the Bipartite Exponential Random Graph Models.

Finally, we include several endogenous parameters that test network tendencies for social-ecological edge formation (*edges*) and actor-level degree distribution (the number of issues a given actor works on; *gwb1deg*), which are explained in greater detail in Appendix 1. We also include baseline tendencies for actors engaging in issues based on attention and progress as exogenous control parameters.

The first model shows baseline results and additional models add parameters that test hypotheses related to integrative gap closure. We include actor type and scope parameters in their own models because collinearity problems cause the model to not converge when they are included together. There were consistent parameter estimates and standard errors for the terms that were used in multiple models, indicating the robustness of our findings. Appendix B includes a table

that displays the R code and data source for each of the "ERGM-terms" in the models. Goodness of fit diagnostics revealed that the models were well-fit to the data (Appendix C).

Results

Table 2.3 presents the parameter estimates and standard errors for the four bipartite ERGMs. The first hypothesis, which expects that actors close integrative gaps for pairs of issues that are closely interdependent, was supported by the positive and significant parameter estimate for the *integrative gap closure* term. Likewise, there were positive and significant parameter estimates for the *public attention* integrative gap closure terms, signifying that actors are more likely to close integrative gaps for pairs of issues that receive high levels of public attention. This finding provides support for H_2. We also find support for H_3, since the *issue progress* effect indicates that actors tend to close integrative gaps for pairs of issues with high progress. The parameter estimates for the *public attention* and *issue progress* terms are based on edge covariate matrices that also account for issue interdependency strengths from H_1, so they should be interpreted as the added effect (i.e., the bonus likelihood of integrative gap closure) for *public attention* and *issue progress*, respectively.

Table 2.3. Table showing ERGM results from the four models. The "Integrative Gap Closure - Edge Weight" parameter is not included in the Actor Type and Actor Scope models because it is collinear with the integrative gap closure parameters for actor type and actor scope. "Federal Government" and "National" are used as reference categories for actor type and actor scope, respectively.

H#		Null Model	Main Effects	Actor Type	Actor Scope
		Estimate (*SE*)	Estimate (*SE*)	Estimate (*SE*)	Estimate (*SE*)
	Hypotheses				
H1	Integrative Gap Closure	0.72 (0.10)***	0.74 (0.11)***		
H2	Issue Concern / Int. Gap Closure		0.08 (0.03)**	0.07 (0.03)*	0.07 (0.03)*
H3	Issue Progress / Int. Gap Closure		0.06 (0.01)***	0.06 (0.01)***	0.06 (0.01)***
H4	**Actor Type** *(Federal Gov = Reference)*				
	State Government - **Int. Gap Closure**			-0.06 (0.44)	
	State Government - *Issue Engagement*			-0.10 (0.30)	
	Local Government - **Int. Gap Closure**			0.85 (0.41)*	
	Local Government - *Issue Engagement*			-0.77 (0.29)**	
	Special District - **Int. Gap Closure**			1.97 (0.27)***	
	Special District - *Issue Engagement*			-1.52 (0.21)***	
	Environmental NGO - **Int. Gap Closure**			0.62 (0.18)***	
	Environmental NGO - *Issue Engagement*			-0.75 (0.16)***	
	Industry Organization - **Int. Gap Closure**			0.23 (0.32)	
	Industry Organization - *Issue Engagement*			-0.78 (0.22)***	
	Education/Outreach - **Int. Gap Closure**			0.20 (0.30)	
	Education/Outreach - *Issue Engagement*			-0.32 (0.21)	
	Coalition Group - **Int. Gap Closure**			1.05 (0.40)**	
	Coalition Group - *Issue Engagement*			-0.79 (0.28)**	
H5	**Actor Scope** *(National = Reference)*				
	Local - **Int. Gap Closure**				0.63 (0.27)*
	Local - *Issue Engagement*				-0.66 (0.19)***
	County - **Int. Gap Closure**				1.42 (0.21)***
	County - *Issue Engagement*				-1.14 (0.15)***
	Regional - **Int. Gap Closure**				1.66 (0.29)***
	Regional - *Issue Engagement*				-1.27 (0.21)***
	State - **Int. Gap Closure**				-0.04 (0.21)
	State - *Issue Engagement*				-0.26 (0.14)
	Control Parameters				
	Edges	-0.75 (0.11)***	-1.43 (0.15)***	-0.80 (0.17)***	0.85 (0.14)***
	gwb1deg.fixed.2	-1.87 (0.14)***	-1.04 (0.17)***	-0.83 (0.19)***	-0.91 (0.18)***
	Issue Concern - *Issue Engagement*		0.01 (0.00)***	0.01 (0.00)***	0.01 (0.00)***
	Issue Progress - *Issue Engagement*		-0.16 (0.04)***	-0.17 (0.03)***	-0.17 (0.03)***
	Fit				
	AIC	11982.42	11497.85	11451.82	11449.6
	BIC	12004.73	11549.90	11600.53	11553.69
	Log Likelihood	-5988.21	-5741.93	-5705.91	-5710.80

***p < 0.001; **p < 0.01; *p < 0.05

We did not find support for H_4, as government actors were no more likely to close integrative gaps than other types of actors. We expected *State Government* actors to be among the most likely actor types to close integrative gaps and our results show the opposite. However, *Special District* actors – which are indeed a type of government actor, and mostly include Soil and Water Conservation Districts and Storm Water Management Districts – were the most likely to close integrative gaps. The *Special District* actors closed integrative gaps at high rates despite engaging in fewer issues, suggesting that they specialize on subsets of highly interdependent issues. Thus, the distinction between government and non-government organizations does not explain integrative gap closure; instead, the results show that specialized actors (except for industry actors) tend to close integrative gaps.

Furthermore, we found that the likelihood of integrative gap closure increased with actor geographic scope but only up to the regional level; state-level actors were not more likely to close gaps than federal-level actors (the reference category). Therefore, we reject H_5 because integrative gap closure does not increase linearly with scope. We discuss the practical and theoretical implications of our results in the following section.

Discussion

We modeled a climate change adaptation network to test expectations about the factors that lead actors to manage for environmental interdependencies, which is a critical task in achieving effective environmental governance. To understand why some interdependencies are targeted for management more than others, we must first recognize that it is unrealistic for actors to manage all interdependencies in dynamic, evolving, and complex systems (Galaz et al. 2008, Imperial et

al. 2016) especially because they have limited resources, environmental knowledge, and organizational capacity (McCann 2013).

The results from our models indicate that actors are more likely to manage for environmental interdependencies that are strongly connected, receive more public attention, and have had more progress made on them. We also found that integrative gap closure likelihood varies with actor type and geographical scope of operation. The attributes that we tested begin to explain why some environmental interdependencies are managed more than others, with crucial implications linking environmental governance structure and outcomes. Throughout the rest of this section, we discuss plausible explanations and implications for each of the conditions that impact integrative gap closure.

Closing integrative gaps

In this study, we are interested in examining how issue interdependencies are managed by single actors or organizations. We do not consider formal collaborative processes as a form of integrative gap closure, although we acknowledge that there is an extensive body of work that does (see, for instance, Guerrero et al. 2015, Bodin 2017, Tosun and Lang 2017, Widmer et al. 2019, Hedlund et al. 2021). Our approach rests on the assumption that an important step of successful environmental management is for individual actors to understand the complex interconnections that exist among the myriad issues that deserve attention. Without this awareness, institutional fitness is likely to be lower, which would lead to the exacerbation of environmental problems (Bodin et al. 2014, Bergsten et al. 2019, Angst 2019).

Our findings show that actors tend to close integrative gaps for pairs of issues that are more closely interdependent. This suggests that climate adaptation actors in Ohio recognize important biophysical processes and manage for them, improving system-wide institutional fitness and adaptive capacity. Our findings suggest that actors can craft their portfolio of issues to manage for crucial interdependencies, a desirable feature in social-ecological systems that are highly dynamic (Metz et al. 2020). From a practitioner's standpoint, we believe these results should be seen with optimism, since they suggest that there is a good amount of integration between climate adaptation initiatives in Ohio and the issues emphasized in the FNCA report. Since we collected issue interconnection data based on expert responses, it is also encouraging that actors tended to close integrative gaps for the pairs of issues that experts indicated were closely interdependent. In other words, actor-issue linkages across the network tended to reflect the expert-elicited cognitive map of issue interconnections.

According to our results, actors tend to close integrative gaps for pairs of issues that collectively receive high levels of public attention. We suspect that the interdependency between two high-attention issues would receive high attention itself. For example, two issues that garner high levels of public attention are transportation and air quality, which are interdependent because transportation-related emissions release many pollutants into the air. Because the public is comparatively highly attentive to both of the issues in this relationship, it would follow that the interdependencies between them are also well-known or are at least well-known to environmental managers. Our findings on integrative gap closure based on public attention match those of Brandenberger et al. (2020), who found that policy issue popularity was a key factor in an actor's involvement in multiple issues in the same issue subsystem.

We also explored the association between integrative gap closure and perceived issue progress to better understand the connection between social-ecological alignment and environmental outcomes. Because our data is cross-sectional, we are unable to establish causality and consequently there are two plausible interpretations for the relationship between perceived issue progress and integrative gap closure. The first interpretation is that high levels of progress improve the likelihood of integrative gap closure. There are likely more potential partners and better resource-sharing opportunities for pairs of issues with high collective progress, lowering the transaction costs associated with integrative gap closure. The alternative interpretation is that the closure of integrative gaps leads to improvements in governance outcomes, which translates into high levels of reported progress made on these issues. This version is far more interesting because it has major implications for environmental governance and sustainability outcomes. To make this interpretation we are required to use perceived issue progress as a proxy measurement of environmental outcomes, equating high issue progress with positive environmental gains. In this interpretation, our model results provide evidence of the benefits of good social-ecological alignment on conservation outcomes, substantiating a growing literature of work to correlate social-ecological fit to on-the-ground environmental improvements (Bodin et al. 2014). Future work can utilize longitudinal data to better understand the ways in which closed integrative gaps lead to changes in environmental conditions.

Integrative gap closure likelihood varied with organization type and scope, although not in the ways we expected. From our results, we learn that certain types of actors are more likely than others to close integrative gaps and thereby contribute more to institutional fitness, based on the

difference between the number of issues an actor works on (*issue engagement*) and the number of integrative gaps an actor closes. Put differently, certain actor types more efficiently devote their resources towards the management of environmental interdependencies and contribute more to institutional fitness, perhaps based on their freedom in choosing issues to manage. Ultimately, our model results point to an important conclusion on the effects of actor type on integrative gap closure: specialized and non-industry actors outperformed non-specialized actors.

Specialized and non-industry actors are organizations who focus on few issues and are not primarily profit-driven enterprises. This categorization includes *Special Districts*, *NGOs*, *Coalition Groups*, and *Local Government* actors. Since these actors are either interest groups (*NGOs* and *Coalition Groups*) or small-scale government bodies (*Special Districts* and *Local Government*), they are each motivated to protect the public good and therefore should be inclined to close integrative gaps. Additionally, knowledge advantages could play a role in actor-type differences in integrative gap closure. Specialized and non-industry actors could have greater technical information about fundamental ecological pathways than other actors. Also, different types of actors could have differential freedoms in choosing issues to work on – actors with less freedom to choose issues may be less likely to close integrative gaps. We expect that freedom in choosing issues varies with actor type – for example, codified laws might restrict government agencies to managing just one issue. Since we lack additional data on actor capacities and characteristics – such as organization size, perceptions of responsibility in protecting the public good, funding, or leadership skills (i.e., Olsson et al. 2007) – we cannot examine how other actor attributes are associated with gap closure and emphasize the need for future studies to tease apart

these differences. However, we emphasize that specialized and non-industry actors tend to improve institutional fitness by closing integrative gaps.

The geographic scope at which organizations operate also plays a major role in integrative gap closure. Notably, regional actors closed integrative gaps at the highest rate when compared to the baseline comparison category of national-level organizations, despite working on the fewest number of issues. This means that the regional level could operate as a "goldilocks" position in which management actions could be particularly effective. Unlike local actors, regional stakeholders are better positioned to observe and act on ecological processes whose scales exceed the merely local levels of municipal jurisdictions, which might give them the chance to reduce scale mismatches (Cumming et al. 2006). In such cases, regional stakeholders may be better equipped to reduce the high transaction costs associated with obtaining key scientific information, searching for collaborative partners, or resolving jurisdictional disputes – all of which may be difficult for city government departments or local NGOs (McCann 2013). In regional climate change adaptation governance, where conditions vary with location, our findings suggest the importance of regional actors in managing important contextual ecological feedbacks (Morrison 2007, Termeer et al. 2011).

Local and county actors also closed integrative gaps at a greater rate than national-level actors while working on comparatively few issues. Considered holistically with the finding discussed in the previous paragraph, this result suggests that management actions that are limited in scope (i.e., bottom-up) can play an important role in adaptation to climate change and may in fact lead

to enhanced institutional fitness, adaptive capacity, and the mitigation of environmental risk (Ostrom 2005, Guerrero et al. 2015, Carlisle and Gruby 2019).

Conclusion

In this paper, we aimed to understand when and why actors bridge integrative gaps, which are inefficiencies that occur in the absence of joint management of interdependent environmental issues. To this end, we performed analyses on a climate change adaptation network and uncovered several key attributes of actors and issues that are associated with improved social-ecological fitness, likely leading to improved environmental outcomes. We argue that at their core, integrative gaps indicate poor management practices that lead to fragmented governance systems, and that the closure of integrative gaps promotes positive environmental outcomes. Our results show that actors are more likely to close integrative gaps when pairs of issues are strongly interdependent, receive high levels of public attention, and have had more progress made on them, and that this likelihood is especially high for regional-scale, specialized, non-industry actors. Policymakers, practitioners, and stakeholders alike should prioritize management initiatives that operate under these conditions associated with closing integrative gaps. In cases where actors have less freedom to choose issues to manage, collaboration can be used as an alternative strategy to address issue interdependencies, where management is integrated through cooperation of actors from different sectors (Tosun and Lang 2017, Widmer et al. 2019). Actors may have greater freedom to choose their partners than to choose the issues they manage. Also, integrative misfit can be identified in order to pinpoint areas where management capacity could be strengthened to improve joint consideration for social and ecological concerns (Sayles and Baggio 2017). The practical contribution of this paper is to discover conditions that improve

institutional fitness, adding to the ongoing discussion of how to improve environmental conditions in complex governance systems. Our findings suggest that to achieve more effective environmental governance, individual practitioners should reflect on whether their management activities account for environmental interdependencies.

Our findings provide empirical evidence supporting the theorized relationship between strong social-ecological fitness and positive environmental outcomes. Because our results show an association between integrative gap closure and high levels of issue progress, we bolster the argument that social-ecological alignment (or at least, integrative gap closure) leads to positive environmental gains. Separately, our study complements prior work that uses mental models of experts to systematically create environmental networks for higher-order ecological units that typically lack available data (Hamilton et al. 2019, Hedlund et al. 2021).

There are some limitations from our methodology that should be acknowledged. The first limitation arises from the web-based actor identification process because it inherently omits actors that lack websites, likely underestimating the number of small-scale actors in the network. Future research could utilize Annual Reports found on actor webpages as evidence of an actor's financial capital, because financial resources could impact integrative gap closure likelihood. A second limitation arises because we assumed that the issue interdependency network applies uniformly across the state. We likely overemphasized the importance of certain issue interdependencies in some regions. For instance, the interdependency between "nutrients" and "water quality" is especially important in Northwestern Ohio, which is dominated by agriculture, and less relevant to Southeastern Ohio, which is mostly forested. To this end, a direction for

future research could be to systematically map issues to specific locations, then use this map as a backdrop from which to measure location-based social-ecological fitness.

Although it is important for researchers to continue to identify leverage points for improving institutional fitness, understanding when integrative gaps are closed is just a first step towards enhancing environmental governance across multiple contexts. Future research efforts would benefit from working closely with communities to develop research questions and goals that both advance theory and have practical use for practitioners, especially in the context of social systems and climate change (Baker et al. 2020, Jasny et al. 2021). Similarly, future research should address the qualitative aspects of gap closure and social-ecological fit. While it is certainly worthwhile to use network analyses to draw inferences about social-ecological alignment, it is critical to understand the perspectives of practitioners as they make decisions that are more or less "fit". Ultimately, we believe that this paper has helped to explain the conditions that lead to improved social-ecological fitness and has highlighted the importance of matching governance systems to their underlying biophysical systems.

CHAPTER 3

Theorizing incentive structures for actor participation in forums

Introduction

Climate change adaptation is an example of a "wicked" problem that attracts the attention of myriad actors simultaneously working on different policy forums where a variety of issues can be discussed that are directly (or tangentially) linked to the main topic of interest – how to adapt to a changing climate. As such, this topic is an example of the complex ecologies of games that define polycentric systems (Bogason and Musso 2006, Lubell 2013). Stakeholders in climate change adaptation contexts participate in forums, which are decision-making venues that facilitate and coordinate interactions between interest groups, authorities, and experts across a system (Bogason and Musso 2006, Fischer and Leifeld 2015). Policy forums involve repeated interaction between a diverse set of stakeholders according to a set of informal or formalized rules, and they include workshops, conferences, meetings, steering committees, or working groups, among other types (Fischer and Leifeld 2015). In environmental systems with distinct policy problems – of which climate change adaptation is an archetypal example – individual forums typically are formed to address specific policy issues, such as the effects of rising

temperatures on infrastructure and natural resources, the resilience of vulnerable communities, or the effects of a changing climate on water quality, to name a few.

The aggregate impact of decisions made in policy forums shape policy responses to the problem, and in turn, the environmental outcomes that they create (Baumgartner and Jones 1991, Berardo et al. 2015). For example, in Columbus, Ohio, decisions and discussions across multiple governance forums contributed to the development of a climate change adaptation plan for the city, which will guide city-wide adaptation actions for years to come. A focal challenge in the public management and policy literature has been to understand the dynamics of engagement in forums because governance outcomes, which can provide benefits for some stakeholders but not others, can be shaped by who participates in governance processes (Berardo 2014, Scott and Thomas 2017, Mewhirter et al. 2019).

The overall objective of this paper is to understand the specific conditions that lead actors to participate in governance forums in complex social-ecological systems, which we expect to depend on incentive structures (Turner and Weninger 2005). Forum participation strategies are essential to understand because more diverse forum participants can lead to equitable outcomes, and because participation of powerful participants can lead to more effective outcomes. On the other hand, incentive structures can encourage actors to participate in forums in ways that are collectively suboptimal.

In this paper, we study the climate change adaptation system in Ohio (U.S. Midwest). Modern climate change adaptation in Ohio is a well-suited study system to understand actor-forum

participation dynamics because it is influenced by many interacting and overlapping stakeholder organizations, decision-making forums, and policy issues. We operationalize climate change adaptation governance as a network of actors, forums, and issues, and their interconnections. To understand the conditions that lead actors to participate in forums, we identify four unique forms of closure – collaborative closure, issue-based closure, forum sector closure, and interdependency closure – that each convey unique benefits and costs for actors to participate in forums. We test for the importance of each closure type in guiding forum participation in the Ohio climate change adaptation network by employing Exponential Random Graph Modeling, an inferential network analysis technique. We then discuss the implications of our findings on the conditions that facilitate forum participation and make the case that the incentive structures inherent to different types of closure do not necessarily promote collectively optimal participatory governance arrangements.

Understanding forum participation in an ecology of games

The Ecology of Games Theory (EGT) is a theoretical framework designed to guide analyses of institutional complexity by considering social-ecological systems to be comprised of a constellation of 'policy actors' who participate in 'policy games' to achieve 'policy outcomes' (Lubell 2013). The EGT provides a set of working expectations about forum participation; it specifically assumes that boundedly-rational actors participate in forums that help them maximize their net benefits. Following Berardo and Lubell (2019) we regard the Ecology of Games Theory (Lubell 2013, Lubell et al. 2014) as a theory of polycentricity. Accordingly, actors involved in the governance of climate change adaptation are nested within a constellation

of other actors and decision-making arenas and forums, which focus on policy issues (Lubell 2013). Fundamentally, polycentric perspectives on governance emphasize the potential for functional interdependence among elements in the system, which can include social actors, policy forums, and policy issues (McGinnis 2011). In polycentric governance systems, actors are interdependent across sectors, hierarchies, and geographic scales, which further complicates collective action (Emerson et al. 2012, Scott and Thomas 2017, Hamilton et al. 2018). Policy games in the EGT are defined as the collective set of decisions made by policy actors that affect system governance, and in complex governance settings, the EGT expects that many such policy games are played simultaneously (Lubell 2013).

To capture complex interdependencies, polycentricity scholars often represent governance systems as social-ecological networks that are built upon fundamental relationships between social and ecological entities (Bodin 2017, Sayles et al. 2019). Social-ecological networks representing environmental governance systems are composed of separate social and ecological layers. Researchers most commonly use social nodes to represent individual actors (e.g., individual people or organizations). There is a wide range of potential ecological node types, including specific habitat patches (Bodin and Tengö 2012, Bodin et al. 2014), ecosystem services (Alonso Roldán et al. 2015), or sustainability issues (Bergsten et al. 2019). We adopt a social-ecological network approach to analyze actor-forum participation dynamics by constructing an empirical network of a climate change governance system as having three separate levels: actors, forums, and issues. Many EGT studies and explorations of actor-level benefits from forum participation use two-mode network analyses (i.e., bipartite affiliation networks; Scott and Thomas 2017, Leifeld and Schneider 2012), but we suggest that three-mode networks can offer

newfound potential for testing governance theory without sacrificing analytical tractability. Three-mode versions of social-ecological networks are rarely used despite their ability to provide more detail in network analyses, and an additional goal of this paper is to show the value of collecting and analyzing three-mode network data to study social-ecological systems. Other than Cornwell et al. (2003), which provides an early application of three-mode networks to study processes of community affairs related to the construction of a sports stadium, there are few instances of three-mode network analyses in the extant literature.

Network motifs are used to capture important governance processes between a set of a small number of nodes and are based in theory to explain the overall network structure (i.e., the tie formation process; Milo et al. 2002, Bodin and Tengo 2012). We identify and describe four such motifs that consist of actor, forum, and issue nodes, each conveying unique incentive structures as forms of closure: 1) collaborative closure, 2) issue-based closure, 3) forum sector closure, and 4) interdependency closure. The predominance of these motifs in complex polycentric governance systems may inform our understanding of what drives actors' decisions regarding their participation in the system, the first step to gauging whether solutions to the problems at hand are attainable or not. For each of the motifs, the unit of analysis is the presence or absence of an edge between the focal actor and forum. Figure 3.1 displays each of the network motifs we focus on in this paper. Collaborative closure is represented in Figure 3.1A, where an actor decides to participate in the same forum that its partner participates in. Issue-based closure is represented in Figure 3.1B, where an actor participates in a forum that focuses on an issue that matters to them. Forum sector closure is shown in Figure 3.1C, where an actor participates in forums of similar issue focus. Lastly, interdependency closure is shown in Figure 3.1D. This type

of closure occurs when an actor gains access to a forum in which multiple interdependent issues are discussed.

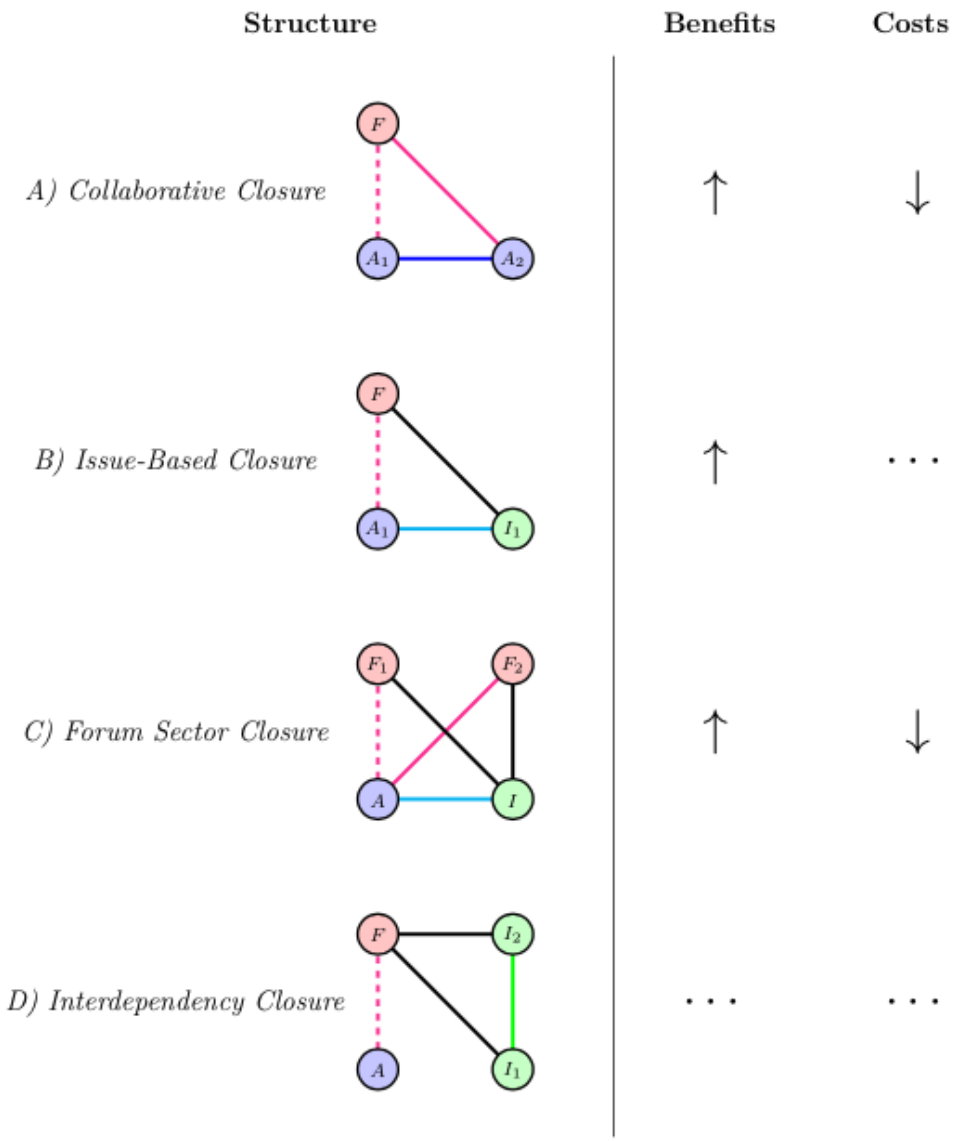

Figure 3.1. Network configurations representing (a) collaborative closure, (b) issue-based closure, (c) forum sector closure, and (d) interdependency closure, and their connoted benefits and transaction costs.

Incentive structures for forum participation

In complex environmental governance settings, actors with limited resources must make decisions about how to participate in forums where they receive the highest return on their investment. Because actors are typically not required to participate in forums, they must decide which forums give them the highest benefits with the lowest attached transaction costs. By participating in a forum, actors can gain social capital, political capital, or technical information, which typically are derived from policy learning and resource sharing. Since policy forums are institutions created to perform governance functions; their continued existence depends on their value to participants (i.e., the degree to which they help actors achieve their goals) compared to other forums, through a continued process of competitive selection (Hall et al. 1996, Fischer and Leifeld 2015). Extending from a rational choice perspective and drawing upon theories of collaboration and collective action (Ansell and Gash 2008, Yi et al. 2018) and transaction cost theory, we describe forum transaction costs throughout this paper as the costs an actor incurs to attend a forum, which can stem from information considerations, negotiation limitations, external decision autonomy, and enforcement ability (Williamson 1981, North 1990, Ostrom 2010). In maximizing the attainment of their own policy preferences as a function of perceived forum benefits minus perceived forum transaction costs, actors might participate in forums in patterns that are individually optimal but collectively sub-optimal (Hall et al. 1996). From a governance standpoint, it is essential to understand the conditions under which actors participate in forums that optimize both individual and collective gains.

To understand actor forum participation strategies, we lay out a series of hypotheses that explore how transaction costs (Williamson 1981, North 1990) and the prospective benefits of network closure (Coleman 1988) affect how actors navigate polycentric governance systems (Ostrom et

al. 1961, Ostrom 2010, McGinnis 2011). In this paper, we test how each of the four identified types of closure (i.e., collaborative closure, issue-based closure, forum sector closure, and interdependency closure) impact forum participation because each convey unique transaction costs and benefits. Because actors boundedly-rational (Simon 1956, Gigerenzer and Goldstein 1996), are faced with limited resources, and must choose between forums to attend based on incentive structures (Lubell et al. 2010, Scott et al. 2015), we expect the network motifs with reduced transaction costs and high individual benefits to occur prominently in an empirical governance network.

Actors participating in forums to achieve closure

Collaborative closure

For actors with stakes in polycentric governance systems, in general we expect collaborative closure as illustrated in Figure 3.1A to be common, particularly since participation in forums where existing partners already participate reduces the transaction costs inherent in building new partnerships. Collaborative closure is built upon pre-existing bonding social capital between actors, which is known to facilitate collective action by preventing uncooperative behavior (Adger 2003, Berardo and Lubell 2016). At its core, bonding social capital describes the strong relationships between actors that are characterized by trust and reciprocity, and that is built through repeated interaction in collaborative spaces (Berardo and Lubell 2016, Olivier and Berardo 2021). All else equal, an actor is more likely to participate in governance forums in which their partners because they can leverage their bonding social capital (i.e., their preexisting norms of trust and reciprocity) to reduce conflict and transaction costs in participating in a forum and expect credible commitment (Woolcock and Narayan 2000, Lyon 2000, Berardo and Scholz

2010). Hamilton et al. (2018) show that collaborative closure encourages joint forum participation by actors who collaborate at local levels. The reverse, where forum co-participation facilitates collaboration between actors, has also been shown to occur (Fischer and Sciarini 2016).

Furthermore, collaborative closure structures connote individual benefits for actors who can monitor the behavior of their partners and enforce outside agreements in a policy forum (Coleman 1988). Another benefit of collaborative closure is the prevention of principal-agent problems: collaborating pairs of actors could face principal-agent problems when just one of the actors participates in a forum and gains crucial technical information advantages over the other (Miller 2005). By participating in the same policy forums as their partners, information-based power asymmetries can be prevented, which can be especially important for small-scale, resource-poor actors. Following our argument that collaborative closure creates an incentive structure by reducing transaction costs and increasing individual benefits, we expect to observe more of these structures in the network we analyze.

> *H_1: Collaborative Closure – Actors are more likely to participate in forums in which their partners also participate in.*

Issue-based closure

Although the EGT outlines policy games as the constellation of "policy actors, policy institutions, and policy issues" (Lubell 2013, p. 540) – which can be readily translated into a three-mode network of actors, forums, and issues – no study has considered all three modes in one analysis. The network configuration that represents issue-based closure (Figure 3.1B) is a

three-mode network structure that captures all three components of the system. We expect that issue-based closure occurs because actors can maximize their benefits even though transaction costs are not necessarily lower.

Issue-based closure provides several benefits for actors. First, through issue-based closure, actors can gain technical information and policy alternatives for the collective action issues that matter to them (Mewhirter et al. 2019). As such, any actor – regardless of their connections to other actors, or lack thereof – can benefit from forum participation through policy learning (Newig et al. 2010, Scott and Thomas 2017). Second, issue-based closure provides actors the ability to monitor the behavior of other actors who participate in their focal policy games. Third, when an actor participates in a forum that focuses on issues that are important to them, said actor can grant visibility to that issue and use the forum as an opportunity for agenda setting (Baumgartner and Jones 1991, Fischer and Leifeld 2015). Fourth, and perhaps most importantly, issue-based forum participation encourages coordination and cooperation between actors who focus on the same issue, as co-participation in forums often leads to out-of-forum partnerships (Fischer and Sciarini 2016, Berardo and Lubell 2019). Thus, by participating in forums based on issue focus, actors can develop a portfolio of both bridging social capital (weak ties) or bonding social capital (strong ties) with other stakeholders who work on the same issues. Such social capital can help actors to navigate complex governance contexts by facilitating coordination in low-risk dilemmas and cooperation in high-risk dilemmas (Berardo and Scholz 2010, Lubell and Morrison 2021). In essence, issue-based closure can spur the closure of 'collaborative gaps' – institutional inefficiencies that occur when two actors working on the same issue fail to collaborate with each other (Bergsten et al. 2019) – by facilitating repeated interaction between

like-minded actors (Herzog and Ingold 2019). For example, an organization focused on providing equitable transportation options for vulnerable communities would benefit from partnerships that come out of an environmental justice-oriented conference. We anticipate that issue-based closure does not lower transaction costs of attending forums as the network motif does not imply lowered search costs nor lowered costs of enforcement. Following our argument that issue-based closure increases direct actor benefits and therefore creates an incentive structure for actors, we propose our second hypothesis:

> *H_2: Issue-based Closure – Actors tend to participate in forums whose issue focus matches their own.*

Forum sector closure

Network configurations that represent forum sector closure should occur prominently in environmental governance systems because they are opportunity structures that connote reduced transaction costs and high benefits for actors. By participating in many forums in the same issue sector – for example by hosting a series of workshops on the prevention of soil erosion in the presence of more extreme weather events – an actor can become a central participant and therefore gain structural power in the sector (Jasny and Lubell 2015, Ingold and Leifeld 2016, Morrison 2019). Actors who can accrue symbolic authority in a certain policy area (i.e., political capital) benefit from the ability to monitor and guide discourse across policy forums of the same sector, exert a larger influence over governance processes, and become a major source of information for peripheral actors (Ansell and Gash 2008, Ingold and Leifeld 2016, Scott and Thomas 2017). Additionally, prominent actors in each sector are best positioned to accumulate bridging social capital by connecting other relevant players 'in the game', creating social ties

through which resources such as technical expertise can flow (Berardo and Scholz 2010, Berardo 2014).

The EGT assumption that actors face transaction costs to attend forums implies that these transaction costs can accumulate substantially when actors attend multiple forums. However, in this case, we expect the consistent issue orientation of multiple forums to mitigate transaction costs, especially those related to acquiring policy-relevant information. Likewise, the social capital gained from repeated interactions between actors in multiple forums can lower forum transaction costs by limiting prospects of conflict and ensuring norms of trust and reciprocity (Lubell et al. 2020). Thus, we expect to observe a tendency for actors to engage in forum sector closure (Figure 3.1C).

> *H_3: An actor is more likely to participate in a given forum if it also participates in other forums that focus on the same issue.*

Interdependency closure

A top priority for many environmental stakeholders is to improve environmental conditions. Sustainable environmental conditions are sometimes thought to hinge upon the 'fitness' of governing institutions, which refers to how well social systems reflect their underlying ecological systems. A 'fit' institution is one where the important interconnections between environmental policy issues are managed by policy actors (Young 2002, Folke et al. 2007, Lebel et al. 2013). Integrative gaps are instances when an actor works on only one of a set of two interrelated issues; for example, an actor in the transportation industry who does not also consider vulnerable communities essentially misses the mark because the two issues are

interconnected (Bergsten et al. 2019). To manage the interconnections between issues, an actor could strategically participate in select forums that focus on a set of interdependent issues, which we operationalize as interdependency closure (Figure 3.1D). In the previous example, an actor could attend a conference focused on the intersection between 'transportation' and 'vulnerable communities' to arrive at improved governance outcomes through the simultaneous consideration of interconnected issues (Galaz et al. 2008, Epstein et al. 2015).

We expect that participating in a forum as a strategy to manage issue interdependencies implies collective governance benefits (i.e., improved institutional fitness) – akin to policy solutions (Ostrom 1990) – but not direct benefits for actors. Actors sometimes participate in forums to assert their own policy positions, and therefore they can receive individual benefits without necessarily facilitating equitable governance solutions (Lubell et al. 2010). Although an actor indeed could gain technical information by participating in a forum that specializes on interdependent issues, we argue that this benefit mostly serves to improve governance outcomes, and therefore is heavily discounted by actors during their (boundedly-rational) calculation of forum net benefits. Thus, we define forum participation to manage ecological interdependencies as an altruistic act, because it increases group payoffs at the expense of the individual who bears all associated transaction costs (Bowles and Gintis 2002). This payoff structure renders interdependency closure as a non-dominant strategy for actors. We distinguish forums that specialize on a set of interdependent issues from 'issue diversity' (Mewhirter et al. 2019), which describes forums that focus on multiple issues without regard to their interdependencies. We do not expect actors to experience reduced transaction costs when they contribute to interdependency closure because they face the same logistical challenges and expectations of

conflict when participating in forums independent of the forum focusing on interdependent issues. Accordingly, we introduce hypothesis four:

> *H_4: Actors are no more likely to participate in forums that specialize on interdependent issues than forums that do not specialize on interdependent issues*.

Methods

Climate change adaptation in Ohio

Climate change adaptation governance in Ohio is an ideal system to test our expectations related to forum participation because it is composed of hundreds of policy actors, hundreds of policy forums and nearly twenty policy issues. Climate change adaptation encompasses a host of distinct environmental issues, such as rising temperatures, nutrient pollution, and land use, and these issues vary in relative importance by location (Angel et al. 2018). A diverse array of stakeholders manages these issues, including non-governmental organizations (NGOs), government agencies, local city departments, and others, characteristic of the diversity found in modern social-ecological systems (Lubell 2013). These stakeholders 'play in the game' by participating in a diverse set of governance forums that occur across the state. The result is a highly polycentric governance system that includes complex interactions among hundreds of actors, forums, and issues, shown in Figure 3.2. Correspondingly, underlying processes that shape the network have implications for participatory governance arrangements and outcomes.

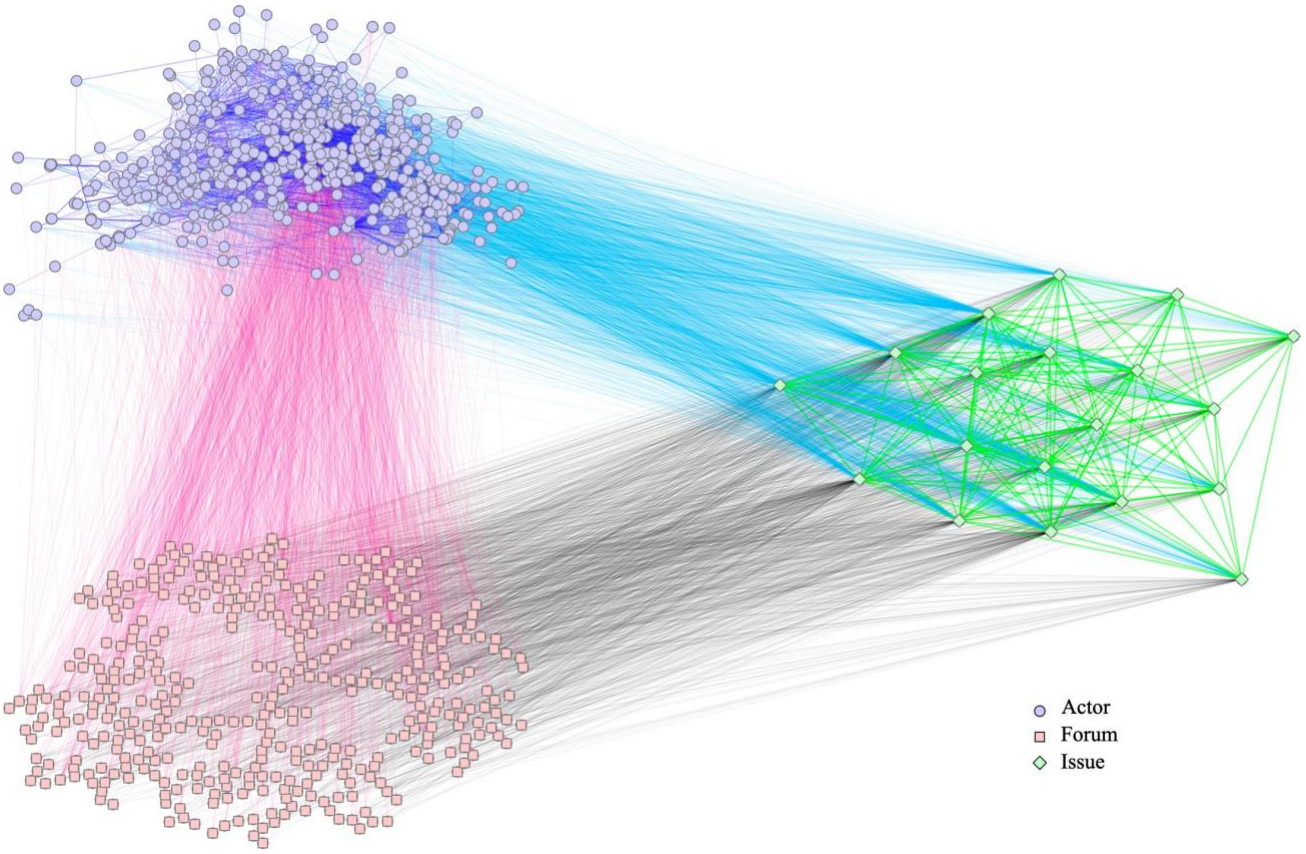

Figure 3.2. Three-mode network representation of climate change adaptation in Ohio.

Data

The Fourth National Climate Assessment (FNCA), compiled by the United States Global Change Research Program (USGCRP), provides region-specific climate change adaptation reports. We used the Midwest report (Angel et al. 2018) to identify climate change adaptation policy issues in Ohio. These issues comprise the set of policy issues in our three-mode network. Then, we conducted a snowball-style internet sampling approach (Hileman and Lubell 2018) to obtain a list of relevant actors that began with a seed group of popular stakeholders from which we followed extensions to partner websites. Lastly, to obtain a list of relevant forums, we formulated

a series of internet searches to find website hits for each type of forum (e.g., workshops, conferences, seminars, etc.) that focus on each type of issue (e.g., water quality, rising temperatures, land use, etc.). In total, we identified 642 actors, 391 forums, and 19 issues. Roughly half of all actors (315, 49%) participated in at least one forum.

Additionally, we collected data to represent five types of edges (actor-actor, actor- forum, actor-issue, forum-issue, and issue-issue). First, actor-actor partnership edge data was identified based on the partnership information found on actor webpages, where actors list the organizations with whom they collaborate. To identify the forums that actors participated in, we analyzed all available material for each forum website, which took the form of meeting minutes, event descriptions, or attendance lists. To identify the issues that actors work on, we similarly analyzed information available on actor websites, focusing on mission statements and current project descriptions. We also searched through information found on forum websites to identify the issues that forums focus on. To obtain issue-issue interdependency data, we interviewed three experts on every issue, for a total of 57 interviews. For each issue, three corresponding experts were asked to identify and explain the relationship between that issue and all other issues, thus the issue-issue edges are simply the compilation of each expert's responses. Beyond basic network descriptive statistics, we turn to inferential network analyses and modeling to test our hypotheses.

Exponential random graph modeling

In our analysis, our dependent variable are linkages from actors to forums. To evaluate the likelihood of each of the closure network configurations on actor-forum participation, we estimate an exponential random graph model (ERGM) of the actor-forum bipartite network. The

general purpose of modeling a network is to construct a probability distribution of structural features of interest in an empirically observed network (Cranmer and Desmarais 2011, Cranmer et al. 2021) – which in our case is the probability of closure motifs appearing in the climate change adaptation governance network. ERGMs are a useful inferential tool for testing the extent to which network models capture the essential generative features that produced an empirical network (Cranmer et al. 2021). When specifying an ERGM, an analyst identifies the suite of endogenous (structural) and exogenous (attribute-based) effects that they believe to be responsible for the structure of the empirical network. The ERGM uses a Markov chain Monte Carlo (MCMC) simulation process to generate a series of networks based on the model specifications and then records initial parameter values for each effect (Wang et al. 2013). As the estimation process moves along the Markov chain, the model converges upon a maximum likelihood estimate for each parameter. In interpreting the results of an ERGM, a positive and significant coefficient would suggest that the model effect occurs more prominently than would be expected by random chance in the observed network. To test the conditions that lead actors to participate in forums, we specify a bipartite ERGM and include parameters for each type of closure in addition to several control parameters. All our analyses were conducted in R (R Core Team 2020) using the "statnet" suite of packages (Handcock et al. 2008).

Building the model

In this paper, our main expectation is that policy actors tend to join forums based upon closure incentive structures. Using actor-forum edges as our unit of analysis, we specify four edge covariate terms in our model, one for each closure type. Edge covariates are exogenous effects (information external to the network itself) theorized to affect the structure of the observed network (Cranmer et al. 2021). For a bipartite network N, edge covariate values are in a separate

covariate matrix X with dimensions equal to N, where the covariate value for X_{ij} corresponds to the N_{ij} dyad. Each network configuration in Figure 3.1 is accounted for in the model as a separate edge covariate, with continuous edge covariate values for each closure type, described in more detail below. According to our central expectation that actors are more likely to participate in forums that increase individual benefits and have lowered transaction costs, we should anticipate positive and significant parameter estimates for collaborative closure and forum sector closure, a slightly smaller and significant parameter estimate for issue-based closure, and a non-significant estimate for interdependency closure.

Our first hypothesis expects collaborative closure, shown in Figure 3.1A, to occur prominently in the network, because it implies increased benefits and lowered transaction costs. We include collaborative closure in the ERGM as an edge covariate term, where the covariate value for every possible actor-forum dyad is equal to the number of partners of the actor who participate in the forum (Figure 3.3A). For example, an actor-forum dyad would receive a covariate value of '3' for collaborative closure if the focal actor has three partners who participate in that forum. We expect that higher covariate values for collaborative closure should be associated with increased forum participation.

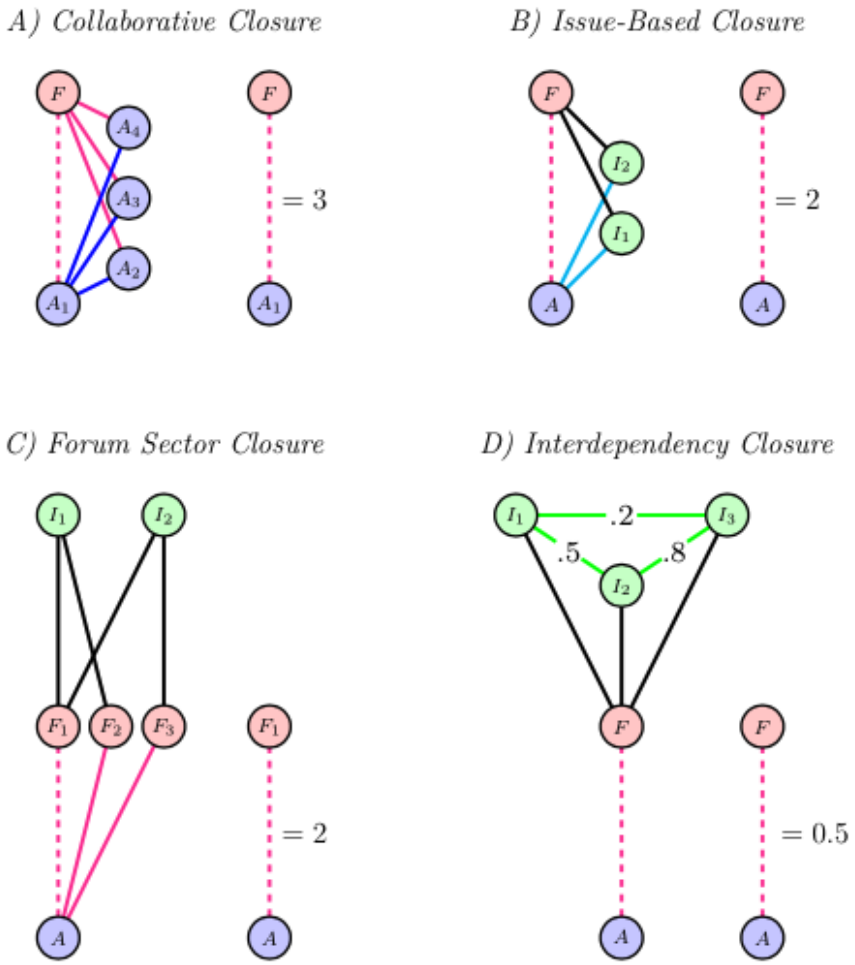

Figure 3.3. Examples of the calculation of edge covariate values in the ERGM for (a) collaborative closure, which is based on the number of an actor's partners who participate in a forum, (b) issue-based closure, which is based on the number of matched issues between an actor and a forum, (c) forum sector closure, which is based on the number of forums an actor works in that focus on the same issues as a focal forum, and (d) interdependency closure, which is based on the average edge weight between the issues a forum focuses on.

Our second hypothesis focuses on how issue-based closure (Figure 3.1B) impacts actor- forum participation. Issue-based closure is a three-mode network structure that we project onto the actor-forum bipartite as an edge covariate value equal to the number of issues in common that an actor and forum focus on (Figure 3.3B). For example, an actor-forum dyad where the actor and forum both focus on the issues 'Water Quality' and 'Soil Erosion', the covariate value is '2'. Our

expectation is as follows: actors are more likely to participate in a forum when there is a higher issue-based closure covariate value.

The third hypothesis focuses on forum sector closure (Figure 3.1C), which implies increased benefits and decreased transaction costs. Forum sector closure is also a three-mode structure that must be projected onto the actor-forum bipartite network as an edge covariate. We calculate the covariate values for forum sector closure as the total number of forums that a focal actor participates in that work on the same issues as the focal forum (Figure 3.3C). To provide an example of the covariate value calculation for forum sector closure, consider an actor-forum dyad where the forum works on 'Land Use' and 'Tree Management'. If the actor participates in three other forums that focus on 'Land Use' and four other forums that focus on 'Tree Management', the covariate value for this dyad would be '7', the sum of issue overlap across all forums the actor participates in. In accordance with H_3, actors should be more likely to participate in a forum when there are higher covariate values for forum sector closure.

Our fourth and final hypothesis focuses on interdependency closure, which we expect to imply system-level benefits and not individual benefits for actors, nor lowered transaction costs. The network configuration representing interdependency closure is in three modes (Figure 3.1D), thus we project it onto the bipartite actor-forum network as an edge covariate. The covariate value for interdependency closure for a given actor-forum dyad is simply calculated as the average edge weight between all issues the forum focuses on (Figure 3.3D). For example, if a forum focuses on 'Nutrients', 'Soil Erosion', and 'Water Quality', its interdependency closure value is equal to the average edge weight of 'Nutrients and Soil Erosion', 'Nutrients and Water

Quality', and 'Soil Erosion and Water Quality.' Accordingly, actors should not be more likely to participate in forums when they have a higher covariate value for interdependency closure.

Several additional parameters were included in the model to control for structural characteristics of the network and specific nodal attributes. Because public administration and university actors often play crucial roles as brokers in governance networks (Fischer and Leifeld 2015, Fischer et al. 2019), and because they are often seen as legitimate and powerful by other actors (Fischer and Sciarini 2015, Ingold and Leifeld 2016), we controlled for forum sponsorship by adding two node covariate terms to the model, one for government actor-sponsored forums, and one for university actor-sponsored forums. We also include more complex endogenous parameters GW (ACTOR) DEGREE and GW (FORUM) DEGREE to control for the degree distribution of actors (i.e., the number of forums actors participate in) and forums (i.e., the number of actors who participate in a forum), respectively. Similarly, we included several endogenous parameters to control for the number of ties in the network (density; Wang et al. 2009), the number of issues each forum works on, the number of partners each actor has, and the number of issues each actor works on. Appendix 1 includes a more detailed description of these control parameters, and Appendix 2 describes and presents the results of the goodness of fit and diagnostic tests conducted to confirm the fit of the model.

Results

The results of the ERGM are shown in Table 3.1. ERGM results can be interpreted in a similar manner to logistic regression coefficients, where the parameter estimates reflect the conditional log odds likelihood of observing that parameter relative to all other effects in the model, meaning that positive and significant coefficients are prominent in the observed network while negative

coefficients indicate that parameters are underrepresented. Our main expectation that actors are more likely to participate in forums that imply high benefits and low transaction costs is supported by the results, because the closure structures that convey increased benefits and reduced transaction costs are prominent in the network.

Table 3.1. The results from the ERGM.

Parameter	Estimate (SE)
Parameters for Closure Hypotheses	
Collaborative Closure	2.10 (0.09)***
Issue-Based Closure	1.09 (0.08)***
Forum Sector Closure	1.16 (0.06)***
Interdependency Closure	0.24 (0.20)
Forum Attributes	
Sponsored by Government Actor	0.05 (0.05)
Sponsored by University Actor	-0.09 (0.06)
Parameters for Network Density and Centralization	
Edges	-4.89 (0.17)***
Isolated Edges	2.32 (0.40)***
GW (actor) degree ($\theta_s = 0.4$)	-4.05 (0.12)***
GW (forum) degree ($\theta_s = 0.5$)	-0.70 (0.19)***
Forum working on Issues	0.08 (0.18)
Forum working on 1 Issue	0.14 (0.16)
Actor making Partners	0.68 (1.41)
Actor working on Issues	-0.19 (0.13)
AIC	17181.98
BIC	17328.12
Log Likelihood	-8576.99
Significance code: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$	

Results support our first hypothesis, which expects that actors are more likely to participate in forums that provide collaborative closure. The positive and significant coefficient for the network configuration representing collaborative closure suggests that actors seek to join forums that their partners also participate in. Results also support our second hypothesis: that actors are more likely to participate in forums that provide issue-based closure. The issue-based closure parameter coefficient was positive and significant, indicating that actors tend to participate in forums that work on the issues that matter to them. Next, the results support our third hypothesis: that actors are more likely to participate in forums that provide forum sector closure. The positive and significant parameter estimate for the forum sector closure parameter signals that actors tend to participate in multiple forums in the same sector. Finally, the non-significant parameter estimate for interdependency closure implies that actors are no more likely to participate in forums that address ecologically interdependent issues than they are to participate in forums that do not address interdependent issues.

Importantly, the parameter estimates for the controls used in the model provide useful information about actor-forum linkages. The government- and university-sponsored parameter estimates were insignificant, indicating that actors are not more likely to participate in forums sponsored by the government or a university. The negative and significant GW (ACTOR) DEGREE and GW (FORUM) DEGREE parameter estimates indicate a tendency for centralization around actors (i.e., a small number of actors participate in many forums, while many actors participate in few forums) as well as around forums (i.e., a small number of forums attract a large number of participants, while many forums attract a small number of actors),

respectively. Appendix 1 describes the interpretation and results of control parameters in greater detail.

Discussion

In this paper, we evaluated patterns of actors' participation in climate change adaptation policy forums to understand how stakeholders navigate complex social-ecological governance contexts by weighing expected costs and benefits of attending forums (i.e., following incentive structures). The results support our main expectation, that actors tend to participate in the forums that offer the greatest net benefits, which are forums that provide higher direct (i.e., actor-level) benefits and that have reduced transaction costs. In the discussion that follows, we highlight the implications of our results for environmental governance theory and sustainability outcomes.

Our analysis helps to demonstrate the impact of collaborative closure – which is a function of transactions costs and benefits – on an actor's decision to participate in a forum. In line with our expectation for H_1, actors are indeed more likely to participate in the same forums as their partners. In their analysis of cross-level linkages between actors and forums operating at different geographic scales in the Lake Victoria region of East Africa, Hamilton et al. (2018) also found that actors tend to participate in forums that their collaborators jointly participate in. Our results, taken together with those of Hamilton et al. (2018), highlight that collaborative closure drives actors to participate in forums across unique governance contexts (Ohio and East Africa). In a polycentric governance system with many governance forums, our findings suggest that actors rely upon their collaborators and social ties to help them navigate through complexity (Lubell and Morrison 2021). This is perhaps because collaborative closure implies lowered transaction costs. Actors expect less conflict (i.e., lower risk) in forums with their partners

because they can lean on preexisting trust and norms of reciprocity (Woolcock and Narayan 2000). Moreover, collaborative closure drives forum participation because it allows an actor to monitor their collaborators in an open governance context, enforce agreements, and reconcile dyadic information asymmetries that otherwise could lead to power imbalances between themselves and their collaborators. Collaborative closure could additionally impact environmental governance systems when actors leverage their existing bonding social capital with their collaborators to join a forum where they can create bridging social capital with new actors, which can ultimately facilitate the spread of information across networks and improve cooperative efforts. Less optimally, echo chambers can be the result of collaborative closure when the same collaborating actors continue to interact with each other in multiple venues (Olivier and Berardo, 2021). For instance, if three collaborating actors jointly participate in a working group focused on sustainable transportation, they could dominate forum discourse, leading to the regurgitation of non-innovative, potentially redundant governance actions. Therefore, the incentive structure behind collaborative closure can promote both beneficial and detrimental participatory governance arrangements.

Our results show that in complex governance settings with multiple interdependent collective action problems, actors attend forums that impact the games they play in. In other words, in an ecology of climate change games, issue-based closure is a driving force of forum participation, where actors prioritize the forums that focus on the issues that matter to them. We believe issue-based closure is a driver of forum participation because it connotes direct benefits for actors. By participating in forums that focus on the issues they work on, an actor can receive relevant technical information and create social capital with like-minded organizations. Ultimately, the

direct benefits of issue-based closure for actors can lead to improved governance outcomes in cases where learning technical information leads to informed management actions that improve sustainability (Bodin et al. 2014, Bergsten et al. 2019). Furthermore, because issue-based closure in forums allows actors to interact with others in a collaborative space, forum co-participation can trigger partnerships between otherwise unconnected actors who care about the same issues (Herzog and Ingold 2019). By participating in a soil erosion workshop, a sustainable farming NGO can meet and form partnerships with workshop co-participants, which improves institutional fit by closing collaborative gaps.

Also, our results show that forum sector closure entices actors to participate in multiple forums that address the same issue(s). These findings support Turner and Weninger (2005), who found that influential firms were the most likely to attend regulatory meetings for Mid-Atlantic fisheries. Forum sector closure implies both increased benefits and lowered transaction costs, and therefore its prominence in the climate change adaptation network is unsurprising. A key benefit of forum sector closure is the ability interact with and influence all other 'players in a game' and become a broker or gatekeeper by connecting actors and shaping discourse across governance forums (Jasny and Lubell 2015, Nohrstedt 2018, Fischer et al. 2019). While forum sector closure could lead to an efficient diffusion of information across a system through a small number of prominent actors, dominance could limit the benefits of polycentric governance, such as innovative and context-specific management approaches (Lebel et al. 2006, Carlisle and Gruby 2019). Power imbalances can arise when one voice rises above all others and fails to incorporate traditionally underserved stakeholders (Scott and Thomas 2015, Morrison et al. 2019). Actors that are prominent within a sustainability issue sector likely have both 'pragmatic power' (i.e.,

practical authority to institutionalize rules-in-use) and 'framing power' (i.e., power to influence discourse and norms) without necessarily having 'power by design' (i.e., legislated authority; Morrison et al. 2019). The incentive structure that encourages forum sector closure can be responsible for several actors to accrue both pragmatic power and framing power, which can lead to a governance arrangement much like a technocracy, dominated by technical solutions and biased towards the whims of a few central experts (Fischer and Leifeld 2015). As such, forum sector closure could bring about collectively suboptimal governance arrangements when the relative power of some actors prevents innovation. For example, prominent actors that guide discourse could uniformly recommend nutrient reduction practices to all landowners across a state, irrespective of unique contextual factors.

Despite important theoretical and empirical work to advance our understanding of actor management dynamics in complex ecologies of games, there is little understanding of the strategies that actors use to manage the interconnections between collective action problems (McGinnis 2011, Lubell 2013). The EGT assumes interconnections between policy games but lacks empirical studies that explicitly test hypotheses about how actors consider these interconnections in their management. We address these deficiencies by testing for the effect of interdependency closure on actor-forum participation and find that actors tend to not participate in forums as a strategy to manage the ecological interdependencies between issues. Because interdependency closure implies improved governance outcomes through the simultaneous management of interconnected issues, but not necessarily increased direct benefits for actors, our results suggest that in complex governance systems, actors inherently ascribe less value to governance outcomes than direct, capital-driven benefits. Resource-constrained stakeholders

who are ‘in the business of remaining a business’ must prioritize the forums that provide the greatest net benefits and forego the altruistic act of donating their resources to the common good (Bowles and Gintis 2002). Such aversion toward interdependency closure is a sign of ‘unfit’ institutions and inefficient participatory governance (Bergsten et al. 2019).

Taken together, our results have implications for environmental outcomes in participatory governance arrangements. While it should be unsurprising that actors are motivated to participate in forums based on underlying incentive structures, our results highlight the potential for incentive structures to create maladaptive governance arrangements, such as the case of issue sector dominance or the lack of interdependency management in forums. Also, our results show that actors are no more likely to participate in forums sponsored by government- or university-actors, which stands in contrast to other studies that relay the importance of governmental access for information exchange and linking policy forums (Leifeld and Schneider 2012, Fischer et al. 2019). Additionally, of the 642 actors in the network, only 315 actors (49%) participated in a forum. This suggests that in addition to potentially promoting suboptimal governance arrangements, existing incentive structures also fail to motivate many actors to contribute to participatory governance, limiting diversity in decision-making.

Conclusion

In this paper, we have identified and tested for the presence of four closure motifs, not for the purpose of creating a typology of closure types, but instead to illustrate that incentive structures help actors to navigate through complex polycentric systems, and that these incentive structures do not necessarily promote optimal governance arrangements. Each closure motif represented a

unique small-scale network configuration that conveyed unique benefits and transaction costs for an actor to participate in a forum. Our findings highlight the conditions that shape participatory modes of governance and importantly introduce theory about incentive structures that stakeholders encounter in systems with multiple, interconnected collective action problems. In an institutionalized setting with many actors, many forums, and where actors are generally free to participate in forums as they please, we have shown how incentive structures – based on an individual actor's ties in the larger governance network - prompt actors to participate in a forum when they receive high direct benefits and reduced transaction costs. Our results also suggest that two actors can experience markedly different benefits and costs in the same forum, based entirely on their positions in the larger governance network.

Although participation in forums has traditionally been thought to produce more sustainable and more innovative outcomes, we have illustrated how closure incentive structures can lead to poor governance arrangements, especially in the case of forum sector closure, which fosters governance arrangements dominated by a small number of central and resource-rich actors. Therefore, incentive structures that guide forum participation can contribute to better or worse environmental outcomes (Newig et al. 2018). For example, ecological spillover effects and environmental externalities can go unmanaged when there are no direct incentives in place for interdependency closure.

Practitioners who manage governance forums and who intend to improve the equity, legitimacy, or effectiveness of their forum should enhance incentive structures for target participants, including actors from diverse backgrounds (equity), actors with legislated power (legitimacy), or

actors known for their previous success (effectiveness) (Fischer and Leifeld 2015). To this end, EGT scholarship has found a positive effect on forum participant diversity and beneficial forum externalities across forums (Mewhirter et al. 2019). Such restructuring of incentives to target powerful and successful stakeholders can increase forum effectiveness and ultimately increase system-level and individual-level benefits alike (McCann et al. 2005, McCann 2013, Olivier and Berardo 2021). On another note, practitioners who attend forums should reflect on the incentive structures that guide their participation and ensure that their participation does not squash innovation or sustain echo chambers.

In testing our expectations about the conditions that lead actors to participate in forums, we hope we have shown how a multi-modal network perspective can provide an analytical toolkit needed to advance theoretical understanding of complex environmental governance systems (Bodin 2017). To our knowledge, our study provides the first analysis of a modern ecology of games that unpacks the complexity of 'players and policy games' as three modes: actors, forums, and issues.

An important limitation in our study is that we do not distinguish between forum founders and participants, even though these two categories of stakeholders have differential incentives and that forum founders can set the agenda and determine institutional rules that shape outcomes (Fischer and Leifeld 2015, Morrison et al. 2019). However, we do control for forum sponsorship in the ERGM, and found that actors do not preferentially attend forums that are either government- or university-sponsored. Future studies would benefit from a specific analysis of the differential incentives of forum participation and governance for general participants and

forum founders, and how these incentives shape forum outcomes. Furthermore, in accordance with the EGT assumption of interconnected collective action problems in a policy system, and although we do specifically incorporate interdependencies between sustainability issues into our analysis, future research would benefit from defining and measuring interdependencies between policy forums themselves, where decisions in one forum can have externalities on collaborative processes in another (Mewhirter et al. 2019).

We echo the call of similar papers in the environmental governance and public administration literatures and emphasize the need for longitudinal data from which causal dynamics can be explored in governance networks. Although we expect that forums are created to serve governance functions, and that forums can dissolve if they do not continue to provide positive incentive structures for participating actors, we know much less about the life cycle of governance forums and its implications for governance outcomes (Hall et al. 1996, Fischer and Leifeld 2015). Longitudinal analyses are especially interesting for interlinked collective action problems where the nature of the interconnections between policy issues changes over time, often by becoming increasingly intertwined through processes related to globalization. Furthermore, without contextualized ecological data to correlate outcomes to forum arrangements, we are unable to answer many crucial questions related to the impacts of forum participation dynamics on environmental outcomes. Future studies should adopt an interdisciplinary approach that explicitly incorporates the correlation of ecological data to participatory governance dynamics (Scott 2015, Newig et al. 2018).

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Appendix A - Description and interpretation of control parameters from exponential random graph models, from 'Chapter 2 - Closing integrative gaps in complex environmental governance systems.'

We utilized the "statnet" (Handcock et al. 2008) and "ERGM" (Hunter et al. 2008) packages in R (R Core Team 2020) to perform all our analyses. The burn-in for our models was set to 500,000, the sample size and interval were both set to 10,000, and the seed was set to 123.

We included two parameters in the model to control for structural characteristics of the network. First, the *edges* parameter shows the general tendency for actors to work on issues (i.e., the likelihood of actors to form social-ecological linkages). As such, the *edges* parameter essentially measures the density of the network – it represents how many social-ecological linkages are present versus how many are possible. Second, the geometrically weighted degree distribution for the actor level (*gwb1degree*) term measures the distribution of actors' ties to climate adaptation issues (i.e., the number of issues that each actor is linked to). Degree refers to the total number of ties attached to a node; the actor-level degree distribution measures the number of issues that are tied to each actor. The parameter for the actor-level degree distribution (*gwb1degree*) term indicates the extent to which a tie decreases the likelihood of an additional tie, according to a decay parameter, θ_s (Hunter 2007). To optimize and ensure model convergence, we set the decay parameter (θ_s) to 2.

Parameter estimates for control terms are included in all four models and are displayed in Table 2.3. The negative parameter estimate for *edges* is unsurprising, indicating that the network is sparsely connected through social-ecological linkages. The negative and significant parameter

estimate for the actor-level degree distribution term (*gwb1degree*) indicates that it is more likely for a given issue to be managed by actors who manage many additional issues, as opposed to actors who work on only a few issues.

Appendix B - ERGM-terms, data type, and R objects for each parameter from exponential random graph models, from 'Chapter 2 - Closing integrative gaps in complex environmental governance systems.'

Table B.1 displays information pertaining to each parameter included in the exponential random graph models. Included in this table for each parameter are the specific ERGM-term used, the type of data it employs, and the named R object the authors used in the model. The R code used in this analysis are available at https://doi.org/10.6084/m9.figshare.c.5294758.v1.

Table B.1. Terms included in exponential random graph models are shown with the corresponding ERGM-term used in the R package "ERGM" (Hunter et al. 2008), the type of data it requires, and its associated data object referenced in the author's models.

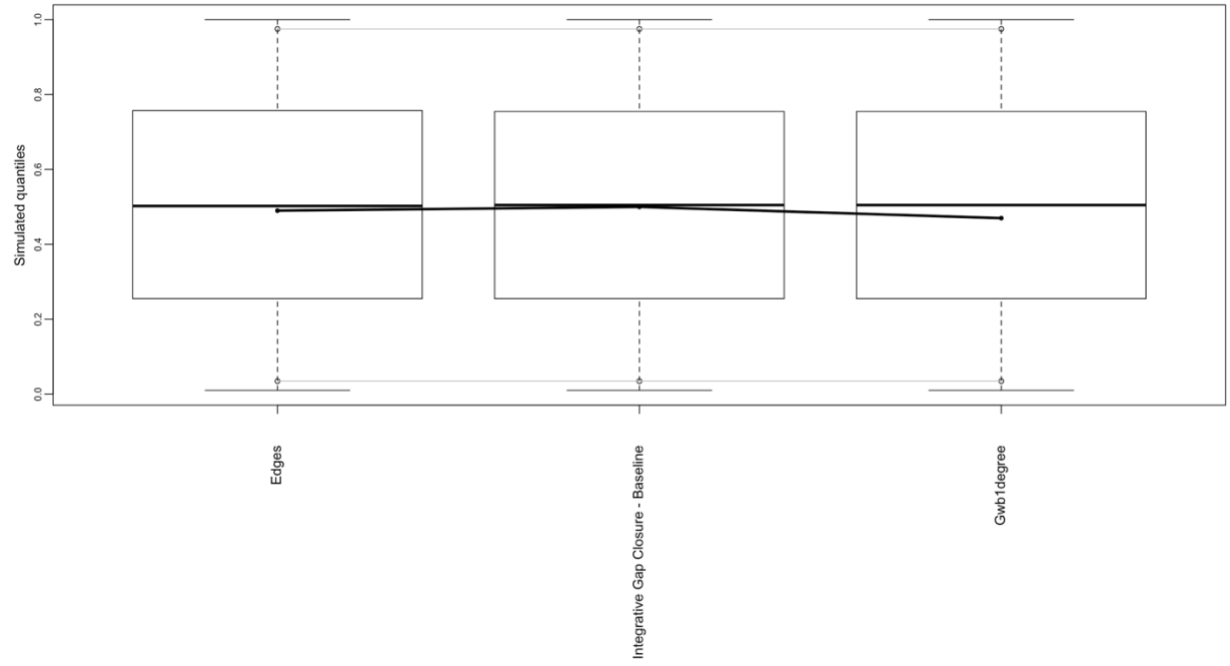
Term	ERGM-Term	Data Class	R Object
Integrative Gap Closure	"edgecov"	Covariate matrix	"ec_meanconnectivity_mat"
Issue Concern – Gap Closure	"edgecov"	Covariate matrix	"ec_concern_mat2"
Issue Progress – Gap Closure	"edgecov"	Covariate matrix	"ec_progress_mat2"
Actor Type – Gap Closure	"edgecov"	Covariate matrix	"ec_actortypeX_mat"
Actor Type – Issue Engagement	"b1factor"	Actor-level node attribute	"OrgType"
Actor Scope – Gap Closure	"edgecov"	Covariate matrix	"ec_orgscopeX_mat"
Actor Scope – Issue Engagement	"b1factor"	Actor-level node attribute	"Scope"
Edges	"edges"	Network-level	N/A
Actor-level Degree Distribution	"gwb1degree"	Network-level	N/A
Issue Concern – Issue Engagement	"b2cov"	Issue-level node covariate	"IssueConcern"
Issue Progress – Issue Engagement	"b2cov"	Issue-level node covariate	"IssueProgress"

Appendix C - Model diagnostics, from 'Chapter 2 - Closing integrative gaps in complex environmental governance systems.'

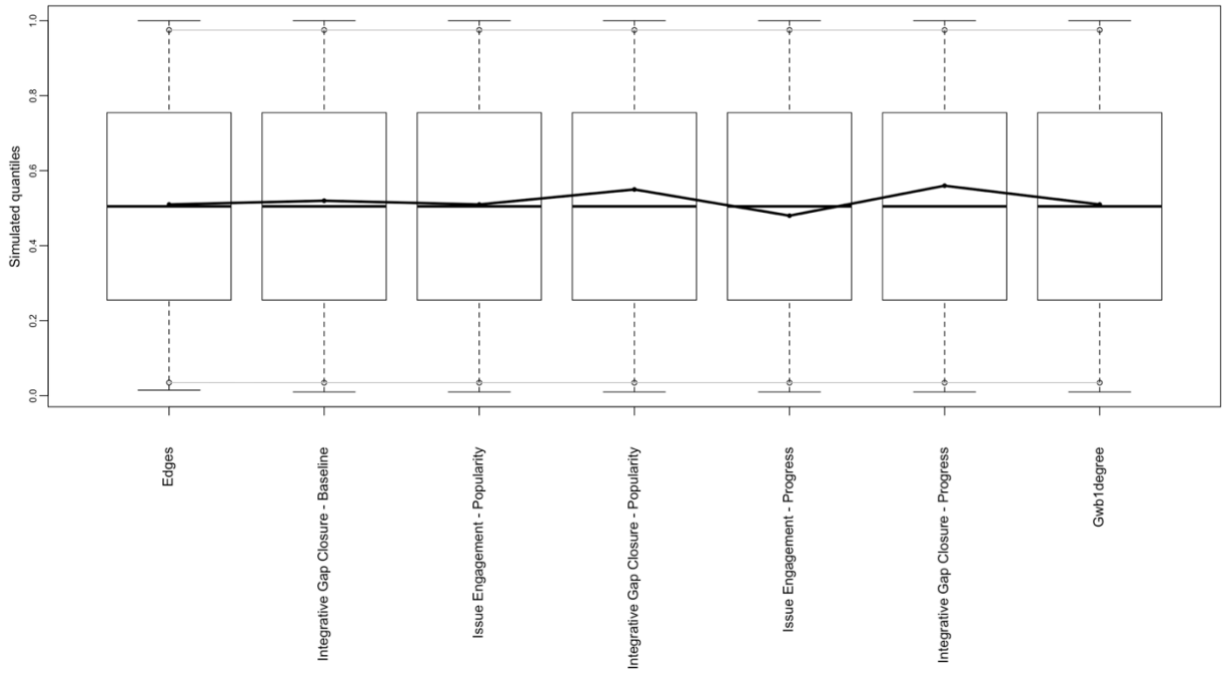
We measure goodness-of-fit for the parameters included in the models. The plots show good fit for the parameters that were included in the models (Figure C.1). Additionally, we considered several parameters that were not included in the models – *dyad-wise shared partners* and *minimum geodesic distance* – which we compared to estimates from 100 simulated networks based on model specification, for each of the four models (Figure C.2). The thick lines in each plot indicate empirical statistics and are displayed against corresponding boxplots that display the simulated distribution of the network statistic. The models slightly underestimated minimum geodesic distance in the simulated networks (Figure C.2).

Figure C.1. Goodness of fit for model parameters.

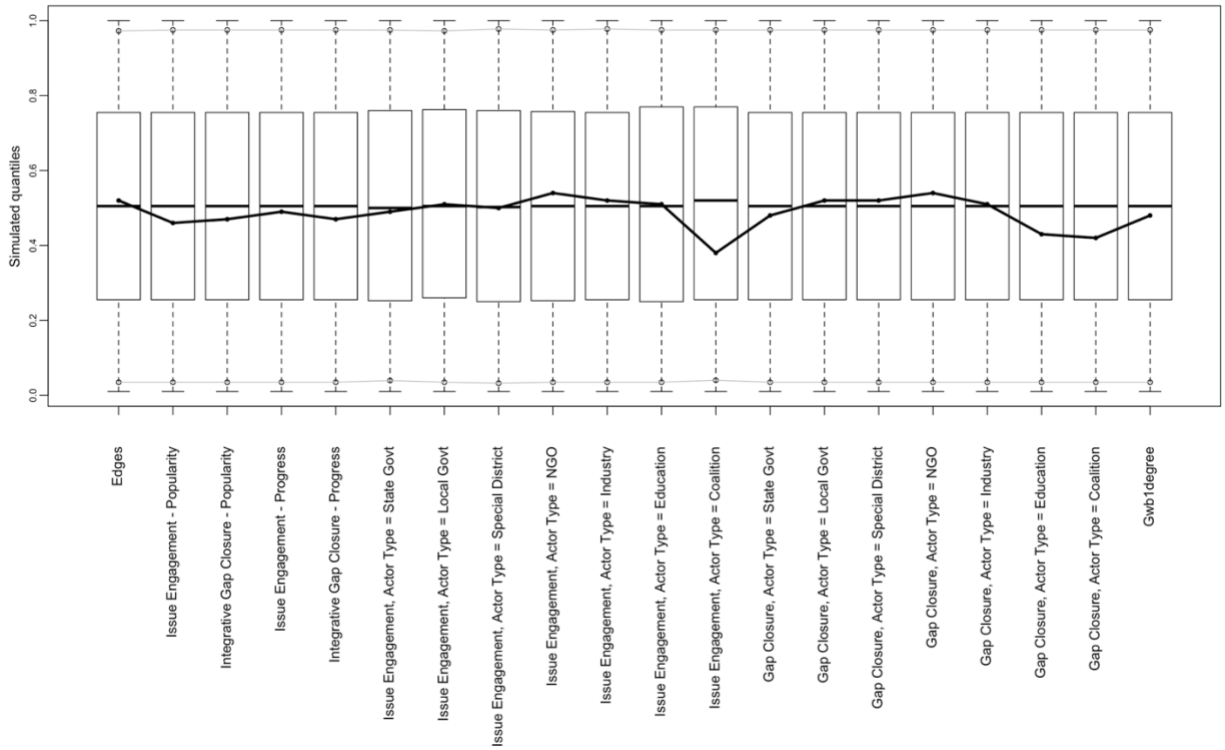
Model 1 (Baseline Model)



Model 2 (Integrative Gap Closure Hypotheses)



Model 3 (Actor Type Effects)



Model 4 (Actor Scope Effects)

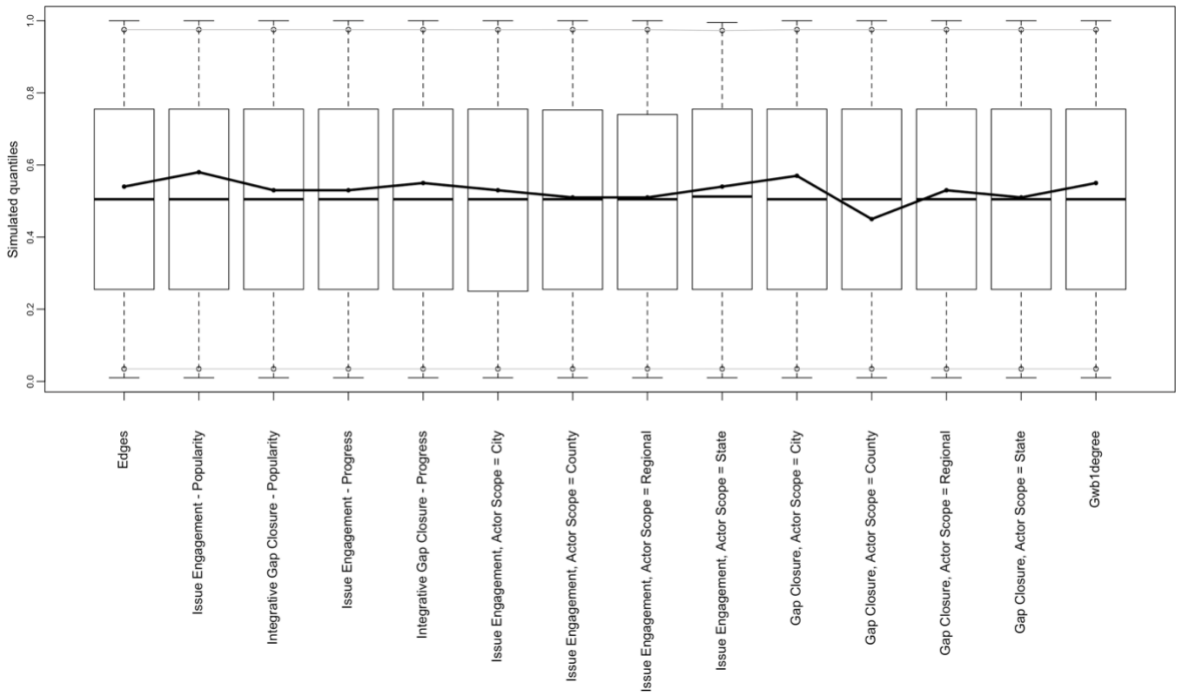
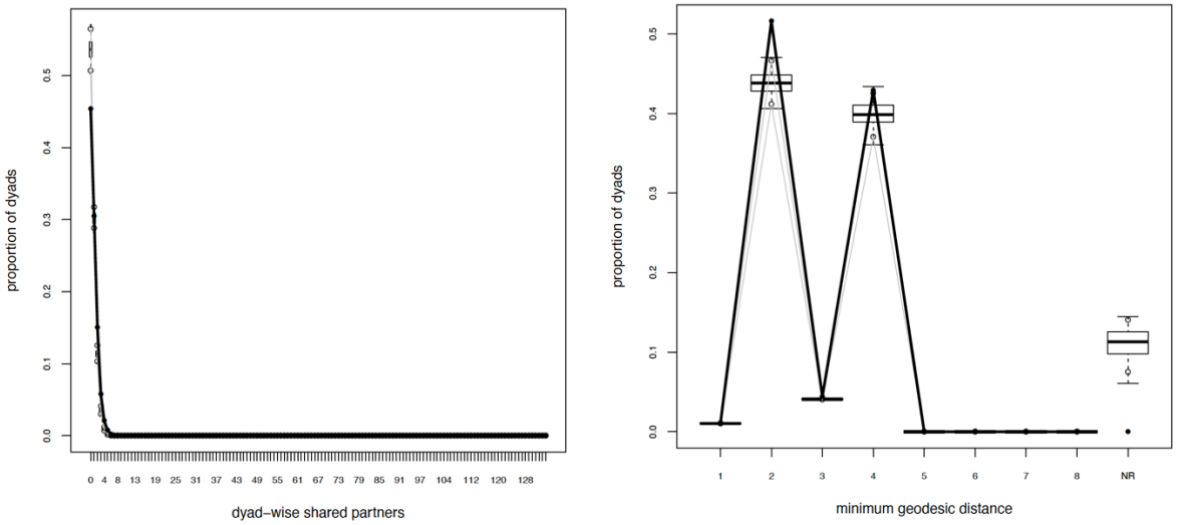
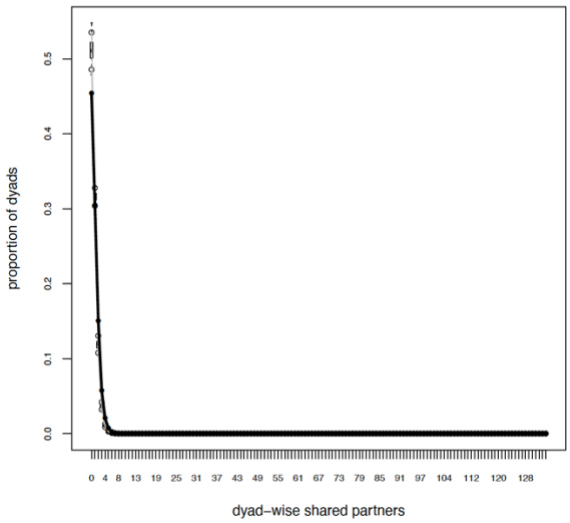


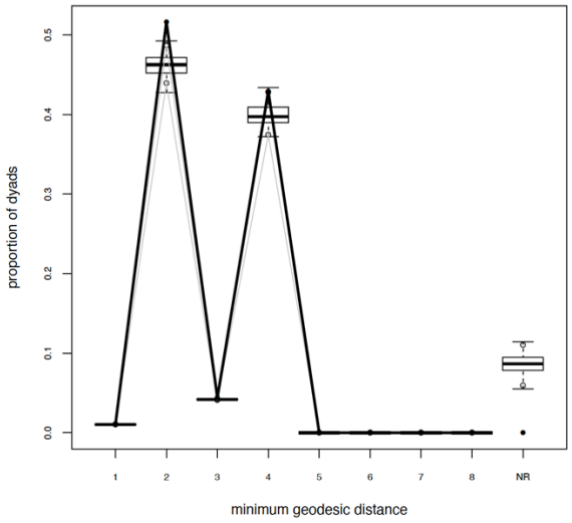
Figure C.2. Fit for parameters not included in the models, including dyad-wise shared partners and minimum geodesic distance.

Model 1 (Baseline Model)

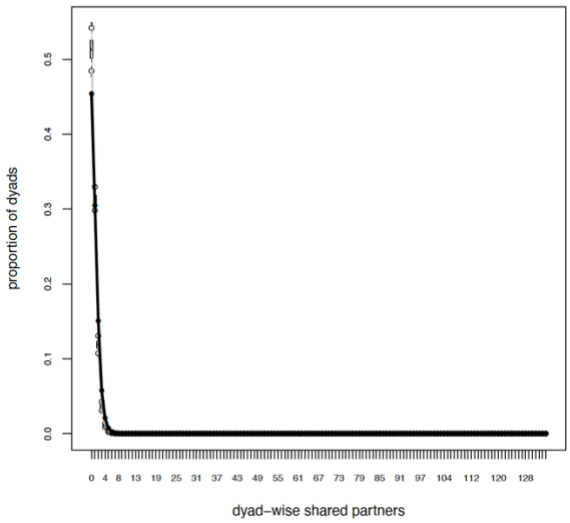


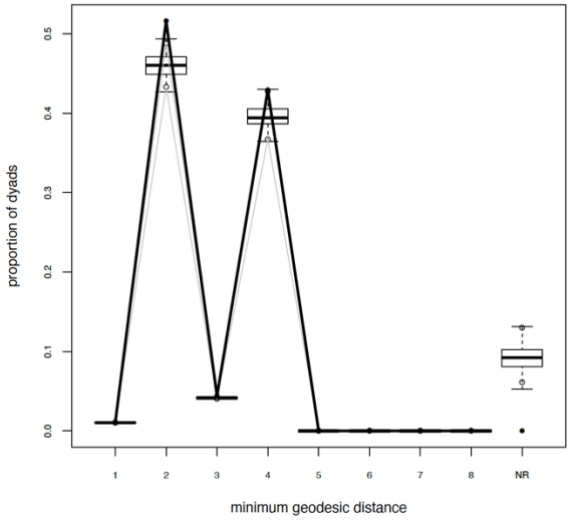
Model 2 (Integrative Gap Closure Hypotheses)



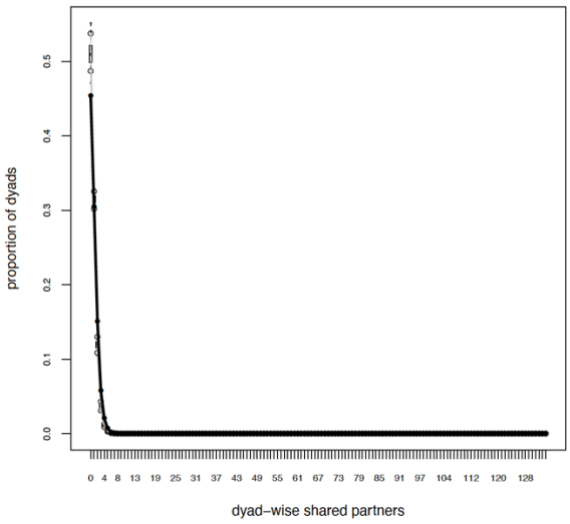


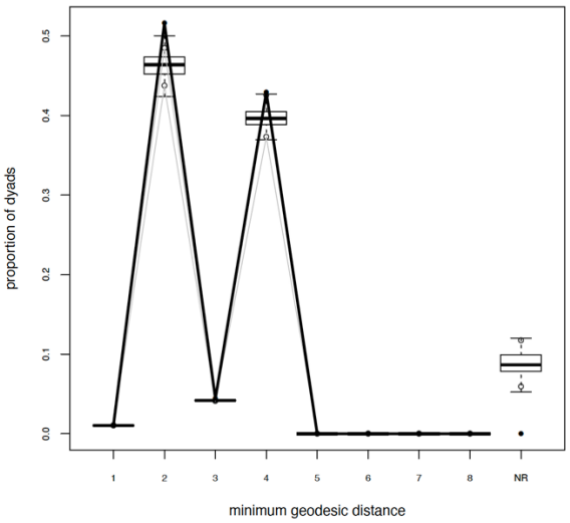
Model 3 (Actor Type Effects)





Model 4 (Actor Scope Effects)





Appendix D - Interpretation of control parameters from exponential random graph model, from 'Chapter 3 - Theorizing incentive structures for actor participation in forums.'

All analyses utilized the "statnet" suite of packages (Handcock et al. 2008), within which the package "ERGM" is included (Hunter et al. 2008). The burn-in for the model was 500,000 proposals discarded, the sample size was set to 50,000, and the thinning interval was set to 500. For replicability purposes, we used the seed '123'. The model results, which are referenced throughout this appendix, are shown in Table 3.1.

The parameters GOVERNMENT SPONSORED and UNIVERSITY SPONSORED are node covariate terms included in the model at the forum level ("b2cov"). Both forum attributes are coded in similar ways, where a forum receives a node covariate value of '1' for GOVERNMENT SPONSORED if it is indeed sponsored by a government actor and '0' otherwise. Neither of these parameters were significant, indicating that forums sponsored by government or university actors were not disproportionately popular for actors to attend.

We included three parameters to control for additional network dynamics that are not explicitly a part of the actor-forum bipartite network: FORUM # ISSUES ("b2cov"), ACTOR # PARTNERS ("b1cov"), and ACTOR # ISSUES ("b1cov"). "Degree" refers to the number of ties incident to a node, where a node attached to three other nodes is said to have a degree of '3'. These three parameters – each a separate node covariate term – control for the degree distribution of forums based on ties to issues, the degree distribution of actors based on ties to other actors, and the degree distribution of actors based on their ties to issues, respectively. None of these three separate degree distributions are inherent to the actor-forum bipartite network, which only

considers actor-forum edges in network formation. Despite their importance in ensuring a proper model specification, none of these parameters were significant.

The EDGES ("edges") parameter is added to the model to capture the baseline tendency for bipartite edge formation in the network (i.e., the likelihood for a given actor to participate in a forum), essentially capturing network density. The negative parameter estimate for EDGES indicates that the bipartite network is sparsely connected, which is not unusual for governance networks.

GW (ACTOR) DEGREE ("gwb1degree") and GW (FORUM) DEGREE ("gwb2degree") account for more complex network structures regarding the degree distribution for actors and forums, respectively. We operationalize the concept of degree to control for the degree distribution of actor and forum nodes. As such, GW (ACTOR) DEGREE controls for the number of forums each actor participates in, and the negative and significant parameter estimate for this parameter indicates that actors are more likely to participate in a forum if they participate in other forums, and thus become connected to many forums, therefore exhibiting preferential attachment. Oppositely, GW (FORUM) DEGREE controls for the number of actors that participate in a given forum. The negative and significant estimate for this parameter suggests that actors are more likely to participate in forums that have many other participants, which is another form of preferential attachment. The decay parameter (θ_s) was set to 0.4 and 0.5 for GW (ACTOR) DEGREE and GW (FORUM) DEGREE, respectively, to optimize model fit. Geometrically weighted statistics use down-weighting to avoid degeneracy in models with higher-order endogenous parameters, such as "gwb1degree" and "gwb2degree" (Snijders et al. 2006, Cranmer et al. 2021).

Appendix E - Model fit and markov chain monte carlo (MCMC) diagnostics for exponential random graph model, from 'Chapter 3 - Theorizing incentive structures for actor participation in forums.'

Before drawing conclusions based on exponential random graph model results, it is prudent to first ensure that the model is 'fit', meaning that the model specification is representative of the observed network, the network sample size is large enough, and that the model is not degenerate (Cranmer et al. 2021). Model fit is ensured when observed network statistics are not shown to be an outlier in a distribution of a large number of networks that are implied by the model specifciation. In goodness-of-fit plots, boxplots are used to represent the distribution of parameters (both included and not included in the model), where the box contains the inter-quartile range (IQR) and the dotted lines extend to 1.5 times the IQR. Good model fit is achieved when statistics from the observed network (shown with a thick black line) are within the boxplot (i.e., are not outliers). Our model achieves good fit, shown in Figure E.1 (parameters included in the model) and Figure E.2 (parameters not included in the model).

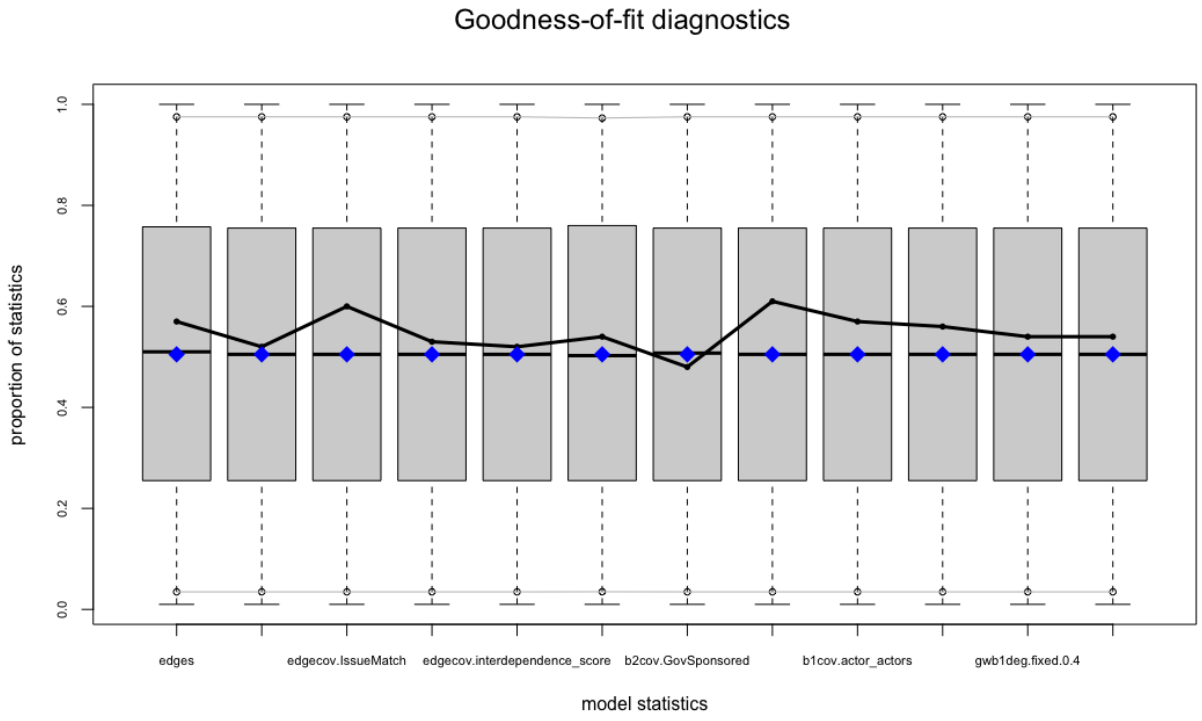


Figure E.1. Goodness of fit of parameters included in ERGM specification. The thick black line corresponds to statistics from the observed network, whereas the box plots represent the distribution of simulated networks implied by the ERGM specification.

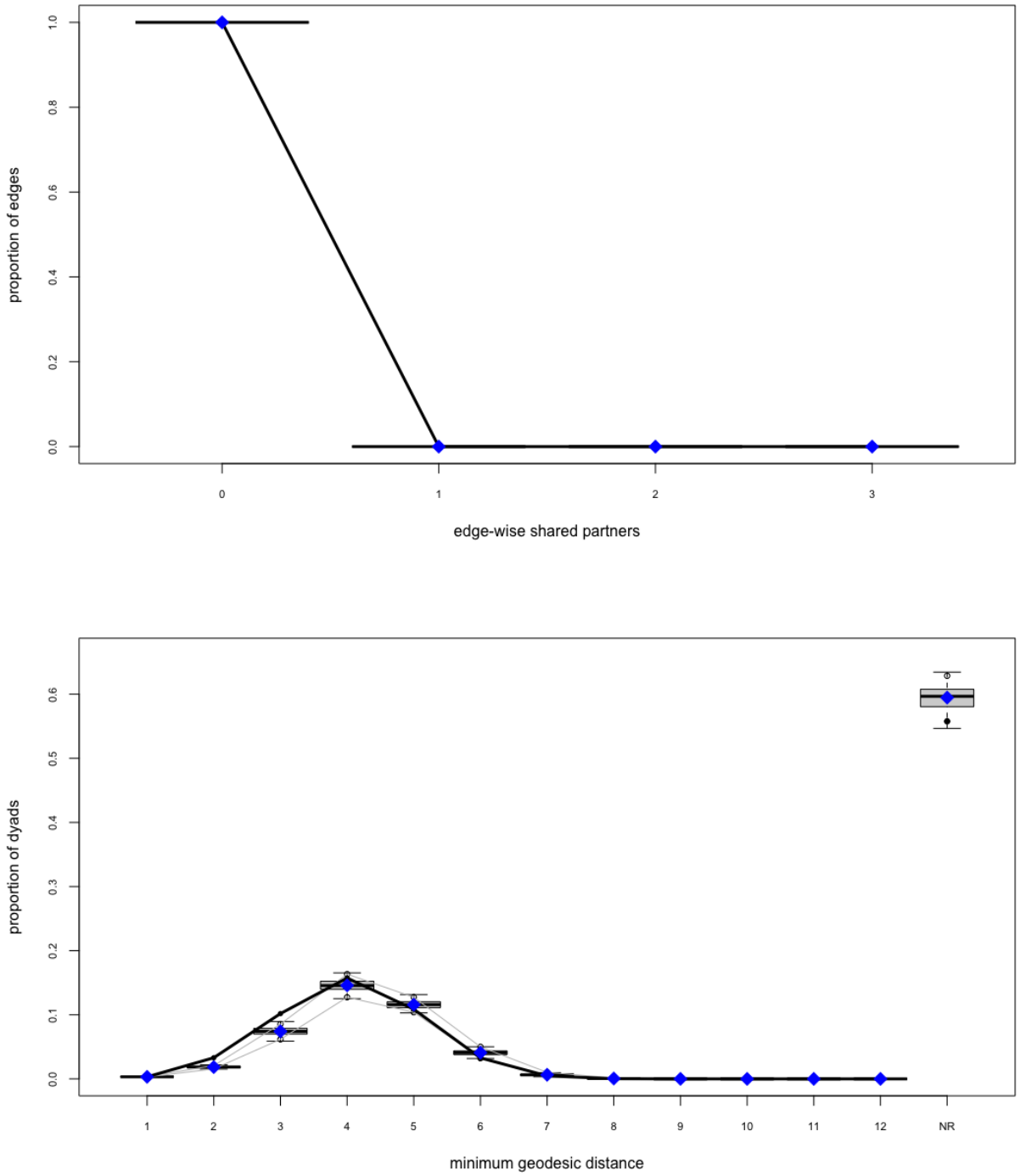
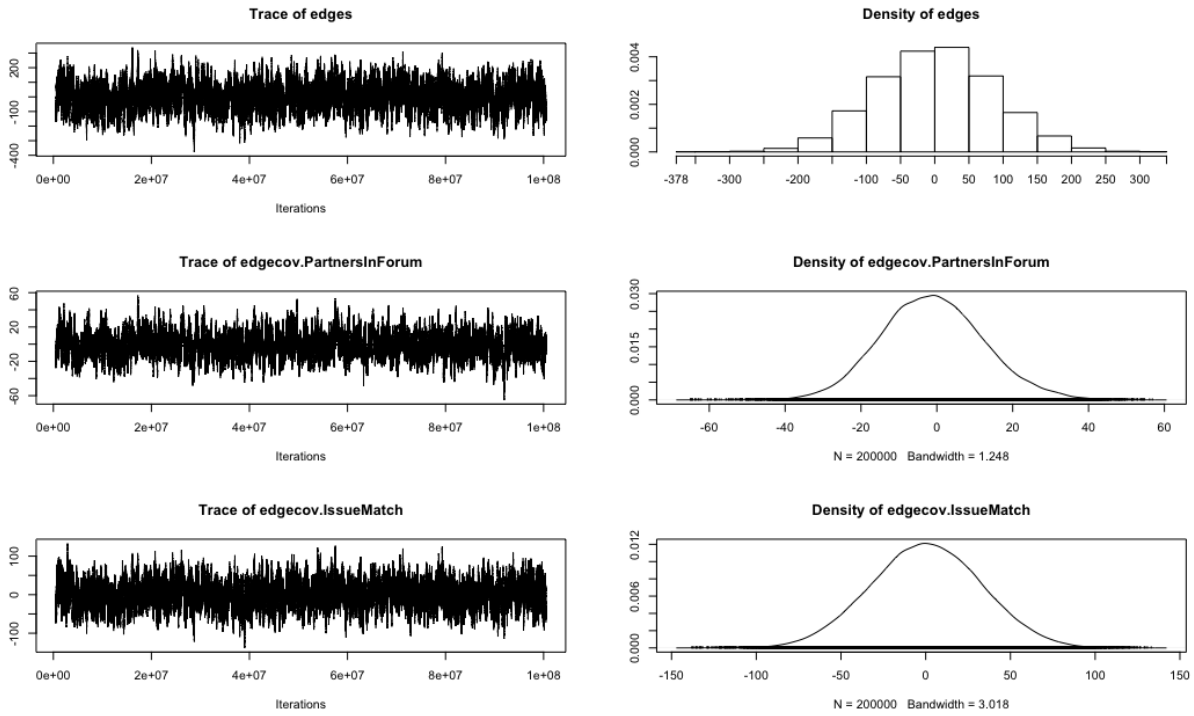
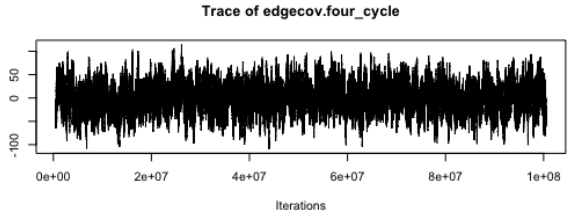


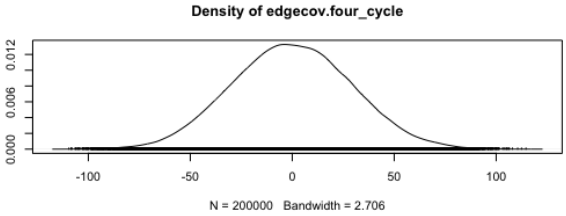
Figure E.2. Goodness of fit plots for edge-wise shared partners (top) and minimum geodesic distance (bottom) based on the simulation of 100 networks according to the exponential random graph model specification. The thick black line corresponds to statistics from the observed network.

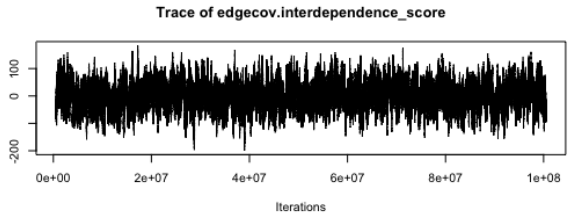
Markov chain Monte Carlo diagnostics are also useful to ensure that the model was not degenerate. Figure E.3 shows trace and density plots for each parameter in the model, representing the MCMC-maximum likelihood estimation process. The trace and density plots for the model show good mixing for the model, because for each parameter, the markov chain neither trended toward one extreme nor mixed slowly. Slow mixing could be indicative of a poorly specified model or too small of a MCMC burn-in, and would have a snaking pattern in trace plots. Our model shows good mixing and no discernible trending, indicative of sufficiently-large model specifications. The joint p-value Geweke diagnostic for the model specification is 0.362.

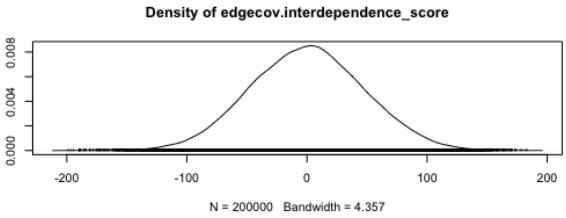
Figure E.3. MCMC diagnostic trace and density plots for each parameter included in the exponential random graph model.

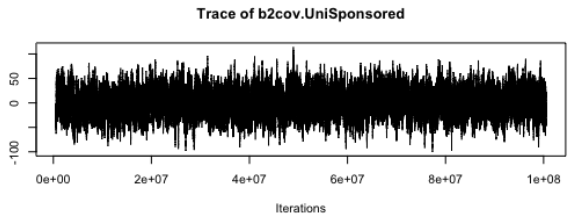


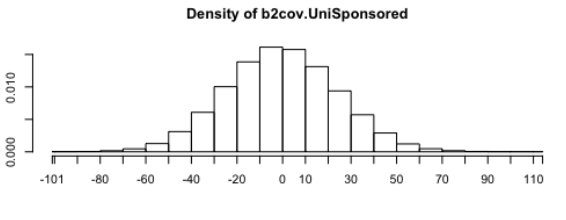

Trace of edgecov.four_cycle
Iterations

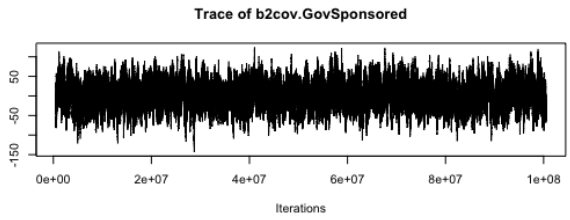

Density of edgecov.four_cycle
N = 200000 Bandwidth = 2.706

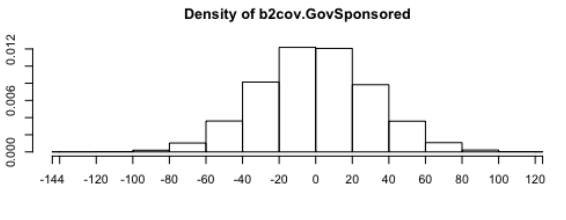

Trace of edgecov.interdependence_score
Iterations

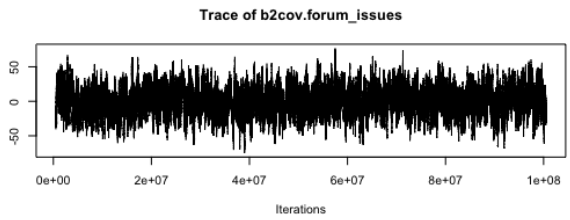

Density of edgecov.interdependence_score
N = 200000 Bandwidth = 4.357

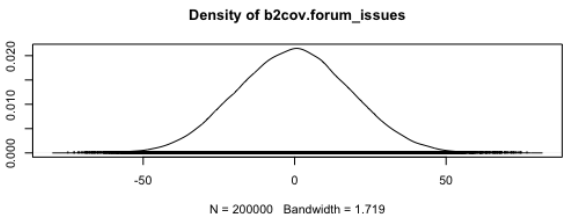

Trace of b2cov.UniSponsored
Iterations


Density of b2cov.UniSponsored

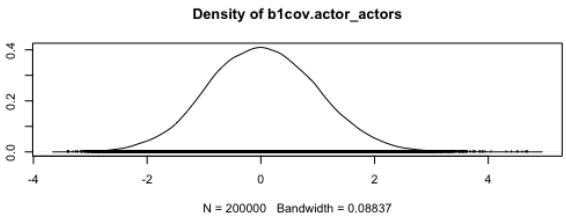

Trace of b2cov.GovSponsored
Iterations

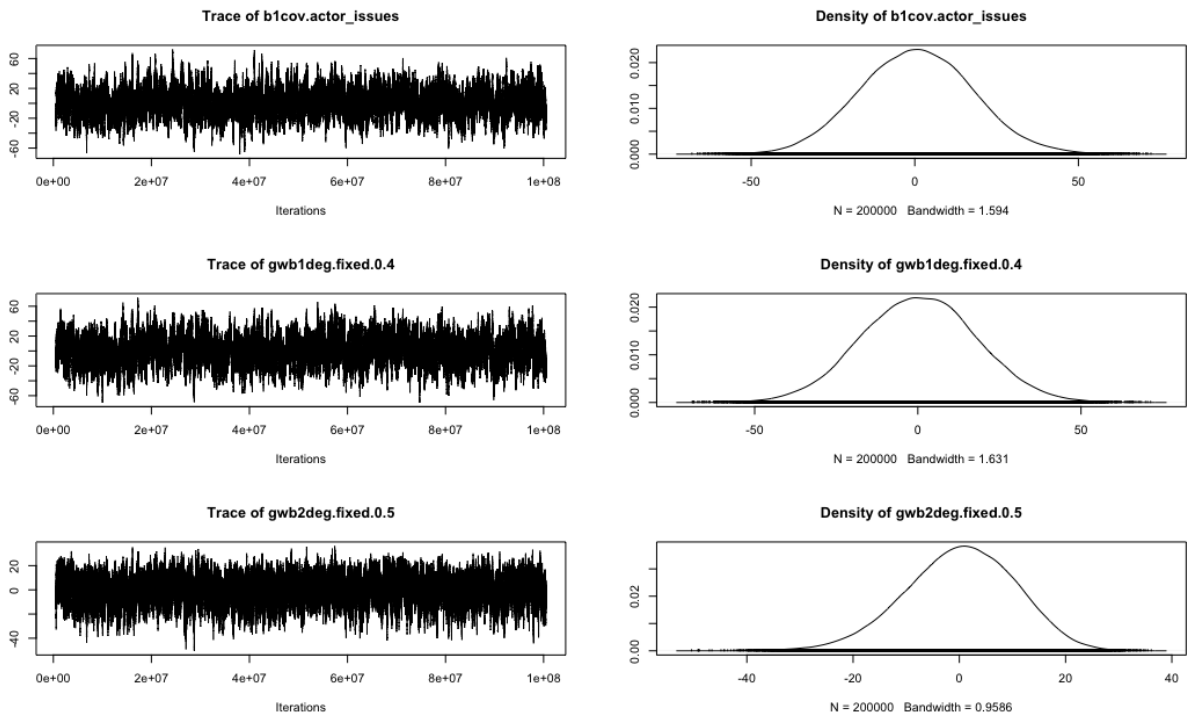

Density of b2cov.GovSponsored


Trace of b2cov.forum_issues
Iterations


Density of b2cov.forum_issues
N = 200000 Bandwidth = 1.719


Trace of b1cov.actor_actors
Iterations


Density of b1cov.actor_actors
N = 200000 Bandwidth = 0.08837



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