Research

Multilevel stakeholder networks for Australian marine biosecurity: well-structured for top-down information provision, requires better two-way communication

[Ryan R. J. McAllister](#)[1], [Heleen Kruger](#)[2], [Nyree Stenekes](#)[2] and [Robert Garrard](#)[1]

ABSTRACT. The structure of stakeholder networks impacts the ability for environmental governance to fulfil core functions: share information; agree on problem framing and actions; and resolve conflict. Managing pest and disease incursions presents particular challenges. Rapid coordination of action is needed in times of crisis, but any hope of success during crisis requires a foundation of ongoing communication and surveillance. Recent Australian strategic planning for marine biosecurity identified the critical role of an independent national marine pest network in providing ongoing communication. We surveyed stakeholders in the existing marine pest network to map how they share information. Constructing a multilevel, directed network, with 304 organizations and 12 policy forums, we applied statistical network theory to identify which subnetwork configuration patterns were present more or less than by chance. We mapped configurations against how they shape the network's propensity for information sharing. What we found was a marine pest network with a predisposition for bridging; evidence of hubs for both provision and receiving of information; and organizations reporting greater levels of information provision to others compared to receiving information. Our assessment is that the network is well structured for top-down information provision, but that a more sustainable network will require attention to building two-way communication particularly with community groups.

Key Words: *configurations; exponential random graph model; social network analysis*

INTRODUCTION

The environmental governance literature scrutinizes the role of stakeholder collaboration in solving complex problems (Lubell 2015). Collaboration is tricky and costly. But where problems span multiple interests, and diversity of stakeholders is either inevitable or desirable, then engaging in collaborative models is likely more successful than alternatives that may favor centralized control (governance over government). Case studies and theory have made enormous contributions to understanding collaborative governance (e.g., Ostrom 2010). What the structure of stakeholder interactions implies within such contexts is a somewhat newer scholarly endeavor. In this study we use a social network approach to examine how organizations both participate in environmental policy forums, and also interact outside of these formal structures. Our case data cover stakeholders with an interest in Australian marine biosecurity.

In Australia, biosecurity policy is changing, with industry groups, growers, and other community players now expected to have an increased role in pest governance (Kruger 2016, Mankad 2016, Maclean et al. 2018). This does not mean the government is not deeply involved (Curnock et al. 2017, Maclean et al. 2019). There is however recognition that government players are neither resourced sufficiently to fill all required roles and responsibilities, nor necessarily the most capable of filling all roles. In terms of governance, biosecurity now turns to multiple purpose networks that seek to mesh diverse tasks such as surveillance, policy development, response to incursion, awareness building, and research and development. Government has some role in shaping the network but there is a degree of emergence too. For the government to understand its role in shaping the network, a

deeper understanding of what preconditions its ability to function well is required.

Pests constantly threaten marine biodiversity and ecological integrity (Floerl 2014) and can result in enormous economic and ecological harm (Cook et al. 2016). For example, it is estimated an incursion of black-striped mussel (*Mytilopsis sallei*) could cause damages to Australian ports and key coastal infrastructure of between US$100 million to US$200 million in present value terms over a period of three decades (Summerson et al. 2013). Environmentally black-striped mussel's dense aggregations also out-compete native species, dominate habitats, and reduce water quality (Summerson et al. 2013).

Legislative and rule-making power for marine pest biosecurity resides within government organizations, with responsibility for various issues distributed across different levels. For example, on-ground Australian Government responsibilities include inspections and pathway management of international vessels, whereas state and territory governments are generally responsible for managing incursions within their jurisdictions.

The Marine Pest Sectoral Committee is the key national forum, comprising members from the Australian Government, states, and Northern Territory. The Committee includes observers with technical/scientific expertise and New Zealand as a standing observer. Government committee members engage with nongovernment stakeholders through partner workshops that are held in conjunction with Marine Pest Sectoral Committee's biannual face-to-face meetings. The Committee itself has considerable influence on jurisdictional dialogues and engagement, but has no enforcement powers. Other marine pest

[1]CSIRO, [2]Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), Department of Agriculture, Water and the Environment, Australian Government

policy forums are formed on a needs basis. At the time of writing, the Marine Pest Sectoral Committee had created task or working groups to develop strategies for marine pest biosecurity and surveillance, respectively, and to develop biosecurity guidelines for marina and slipways.

The marine pest network is the suite of organizational interactions that emerge around the Marine Pest Sectoral Committee. The network brings in many informal relationships and extends well beyond organizational participation in policy forums, spanning members of the public, scientists, industry, and government all with various interests in Australia's marine pest biosecurity. If pest outbreaks occur institutional responses create ephemeral networks that last during the emergency, but Australia's marine pest biosecurity network relates to the enduring relationships that foster ongoing communications and surveillance.

Two recent strategic documents recommended the Australian Government more actively manage the national marine pest network to strengthen collaboration and coordination between stakeholders for better marine pest biosecurity outcomes in Australia (Australian Government 2015, 2018). The 2015 review recommended the following:

- coordinating national communication, including strengthening education and awareness;
- facilitating passive surveillance from more sources, e.g., community groups and industry, including coordinated reporting and data sharing about detections;
- facilitating analysis of monitoring and active surveillance programs;
- facilitating national research and development initiatives.

The Australian Government representatives on the Marine Pest Sectoral committee commissioned this study to inform actions to improve communication and co-ordination among stakeholders. This study represents the first assessment of what formal and informal marine pest stakeholder networks are currently at play, and what functions they enable.

We adapt and contribute to a growing body of literature that seeks to understand networks by mapping substructures (configurations) of which the relative abundance allow statistical inference on social and political processes (e.g., Bodin and Tengö 2012, Berardo 2014*a*, Lubell et al. 2014, Guerrero et al. 2015, Nita et al. 2016, Barnes et al. 2017, Hamilton et al. 2018, Metz et al. 2020) including some specific to marine settings (Alexander et al. 2018, Barnes et al. 2019). We specifically tap into theoretical perspectives linking bonding capital to interactions where the potential for noncooperative behavior is greatest (Berardo 2014*a*). Bridging capital fosters learning and innovation, quickly disseminates information (or instructions), and connects actors to others in more distant parts of the network where information is more likely to be novel (Granovetter 1973). Bonding capital presents in networks as close-knit configurations, with dense and overlapping ties. Bonding capital helps build collaborative potential through trust, problem definition, and developing and/ or contesting shared expectations (Berardo 2014*b*, Berardo and Lubell 2019).

Even though as a whole biosecurity includes political processes involving a diversity of interests at multiple scales (Reed and Curzon 2015), the marine pest network that we study is focused on communication, surveillance, and engagement. The marine pest network does not directly deal with managing incursions and negotiating cost sharing agreements. Accordingly, the network should display a predominance of bridging capital, facilitating an open sharing of information across diverse stakeholders in an environment of low social risk.

We quantify both the formal and informal stakeholder networks in the Australian marine pest network, and then statistically analyze the patterns of configurations that test for configurations preconditioning bonding and bridging. The network itself is based on organizations identifying which other organizations they received/provided information from/to on key issues for marine biosecurity, e.g., surveillance, and combining this with data on which organizations participated in known policy forums for marine biosecurity.

The practical questions that motivated this study are the following:

1. How well predisposed is the network to enable effective information dissemination?

2. How do informal organizational stakeholder interactions structure around the suite of government working groups and committees tasked with improving marine pest biosecurity?

3. How well predisposed is the network to engage communities in two-way information flows?

METHODS

Multilevel networks

We modeled interactions between stakeholders using a social network. Social networks consist of a set of nodes, usually representing actors in the network, and a set of ties (or links), representing some relationship of interest between actors. A multilevel network (Wang et al. 2013) is a network with two distinct types of node. In our setting, we defined the 12 policy forums to be nodes of one type, and the 304 organizations to be nodes of the other. Multilevel networks have three levels, each denoting a different type of tie: micro, meso, and macro. Nodes of one type occupy the microlevel, while nodes of the other occupy the macrolevel. Ties that exist in the micro and macrolevels respectively denote linkages between nodes of the same level. Ties that exist in the mesolevel denote across-level linkages (Fig. 1). We let organization nodes form the microlevel, while the policy forums form the macrolevel.

The mesolevel of our network contained a tie between an organization and a policy forum if that organization was identified as a participant in that forum (Fischer and Leifeld 2015). We treated these ties as undirected because by definition policy forums must allow two-way information flows. The microlevel was defined by direct interactions between organizations that do not occur as part of the marine pest policy forums. Because a one-way flow of information was permitted in this setting, we considered ties to be directed, with a directed link from node A to node B if information was reported to flow from

A to B by either party. Because there was no immediate sensible notion of interaction between policy forums, except through mutual attendance by an organization, we did not allow macrolevel ties. The resulting network is illustrated in Figure 2 (a). Figures 2(b-e) display subnetworks according to ties of each nature.

Fig. 1. Examples of (a) multilevel policy network, and (b) configuration.
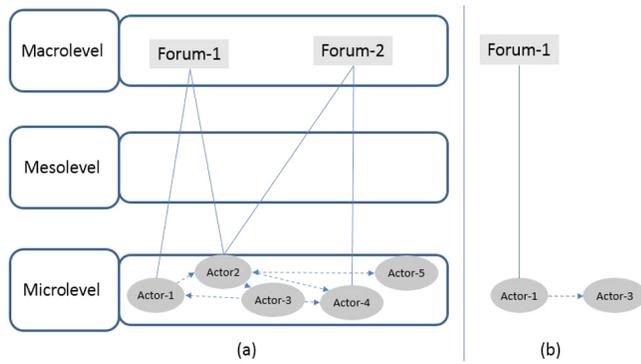
Fig. 2. Networks explored (a) to (f) using exponential random graph models. Squares represent policy forums, circles represent organizations in marine pest network. Ties represent information sharing (one-mode) or affiliations through forums (two-mode)

(a) Entire network (b) Passive surveillance (c) Passive and active surveillance

(d) Research and development (e) Education and awareness-raising (f) Forums only
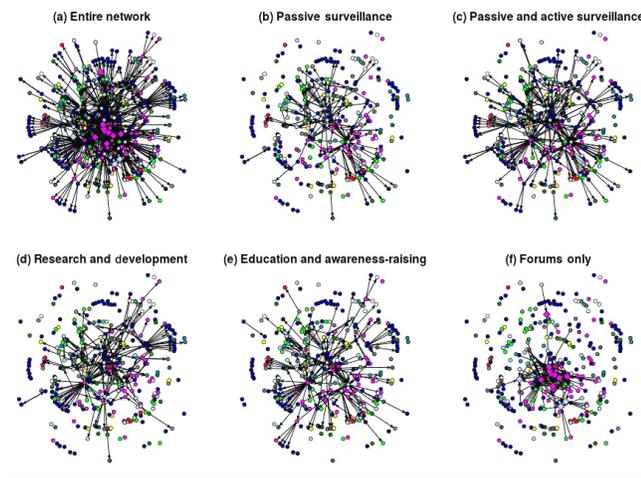
Framework

The distribution of network configurations emerge in networks as individuals make choices about if, how, and when they participate in a network (Hamilton et al. 2019). Social network analysis does not take into consideration the formal level of authority bestowed on certain actors, by which they may impose influence on decision making, regardless of their position in the network (Carlsson and Sandström 2007). Even if favorable structures are present, it provides no guarantee for success. Yet, poor or a lack of favorable configurations predispose a network to ineffectively respond to change and new information (Barnes

et al. 2017). We used a framework that maps network configurations showing homophily, reciprocity, and closed structures as indicative of bonding capital as a means to assess the balance between bonding and bridging capital (Fig. 3).

Statistical network modeling

Exponential random graph models, as implemented in the package MPNET (Wang et al. 2014), were used to analyze the data. This builds on advances in statistical modeling treating an observed network as a single observation that can be compared to a distribution of all possible networks with a shared core set of characteristics, e.g., number of nodes and ties (Frank and Strauss 1986, Wasserman and Pattison 1996, Robins and Morris 2007, Wang et al. 2013). Such approaches are well suited to statistically testing if selected characteristics in the form of configurations, are observed more-or-less often than by chance alone. By mapping selected configurations to important network processes (see Fig. 3), exponential random graph model can hence be used to test for the presence of structures that can sustain important social and political processes (Berardo 2014*a*, Lubell et al. 2015). Exponential random graph models also allow for statistical inferences to be made without the need for multiple networks for comparison.

Part of the explanatory power of exponential random graph model comes from its handling of nested configurations. Most configurations in networks are nested within other configurations. A configuration with four connected nodes also contains within it configurations with three connected nodes. Exponential random graph models assess the relative frequently of configurations in a network given the observed frequency of other configurations, including those that are nested. Note that in making accurate assessments of the representation of these configurations in our data, we controlled for the general level of activity displayed by each scale of stakeholder. This baseline activity can also be interpreted as a measure of how active stakeholders have been in the marine pest network.

One of the limitations of exponential random graph models is that the Markov chain maximum likelihood estimation approach used to find solutions often fails to converge to a sensible model; a phenomenon called degeneracy. This is particularly common when many configurations are included in the model. To overcome this, we used "goodness-of-fit" (analogous to the bootstrap, Efron 1979) to test for the over and under representation of configurations not in the model (e.g., see Lubell et al. 2014). A smaller model is fitted and used to produce simulated graphs, whereby standard errors may be computed for configurations not in the model under the null hypothesis that their coefficient is zero. These may then be used to test whether these configurations are over or underrepresented in the observed network.

DATA

We collected our multilevel social network by first looking at organizational participation in policy forums. We defined these formal interactions as those that take place in policy forums; repeated meetings that contain agenda items related to marine pests, either as a standing item or as part of the agenda for an extended period. We required that a policy forum exhibited dedicated two-way discussion or debate regarding marine pest

Fig. 3. Selection of network configurations of theoretical interest. References suggest recent reading.
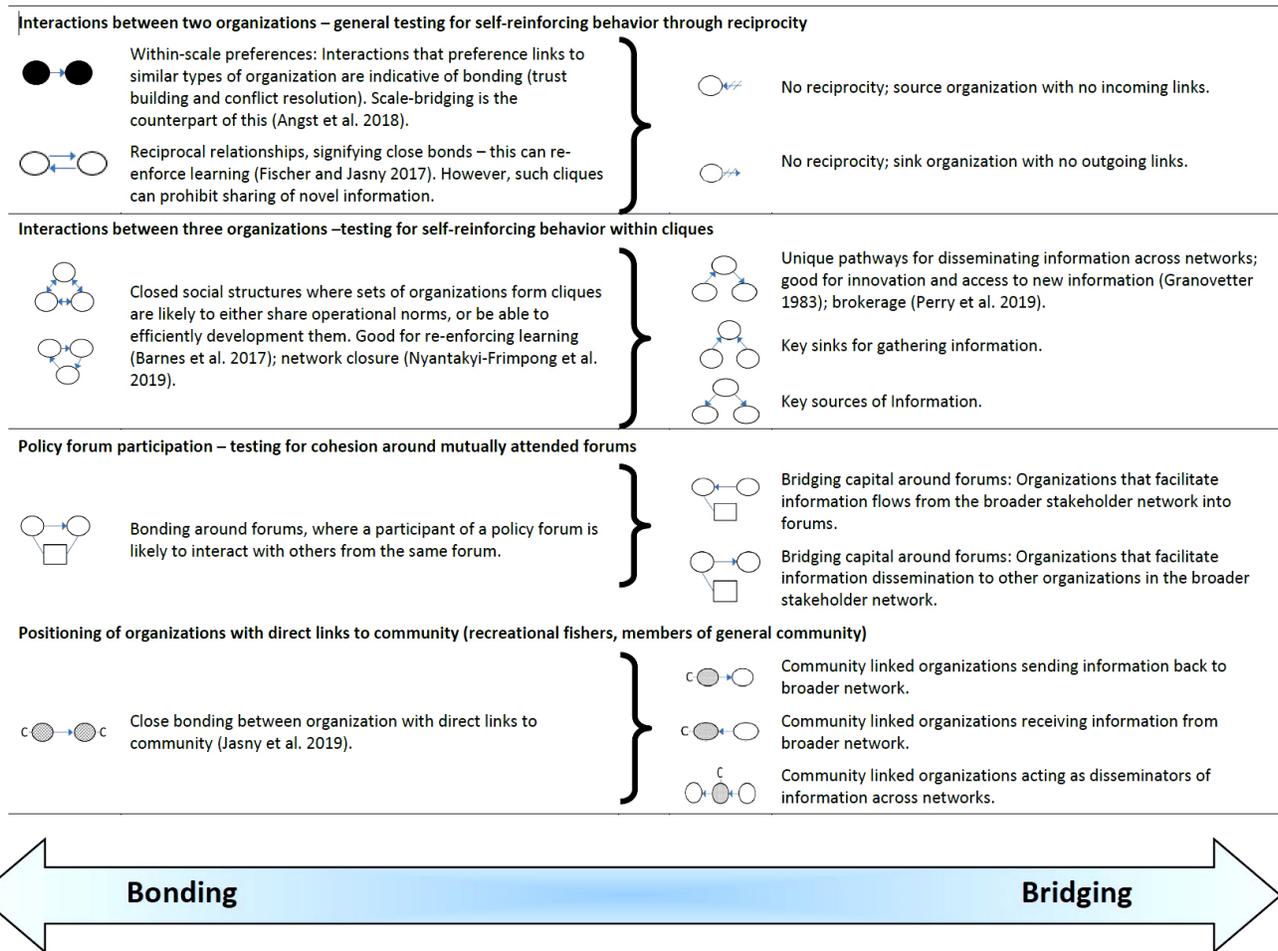
topics, and excluded settings with predominately one-way communication, such as conferences. Hence policy forums included: technical reference groups, working and steering committees, and advisory groups. Informal interactions were defined to be any interactions related to marine pests not in the formal setting.

We identified a set of policy forums through a series of phone interviews with 10 stakeholders. Eight of these stakeholders were members of the Marine Pest Sectoral Committee. These members represented each state and territory, except for the Australian Capital Territory. The two remaining interviewees were representatives of a research and development organization and a not-for-profit environmental NGO. In total, we identified 12 policy forums, which are displayed in Table 1.

In order to obtain a sample of individuals participating in the marine pest network, we consulted with Marine Pest Sectoral Committee members. Workshop participants provided us with contact details for known relevant stakeholders, as well as minutes of policy forum meetings. Contacts were supplemented with organizational stakeholders identified with an internet search.

The resulting database contained 681 observations of people who were likely to have a relation to marine pests.

We designed a survey instrument to measure interactions between stakeholders and capture the nature of those interactions. Respondents were asked to nominate stakeholders with whom they had contact regarding marine pest biosecurity. In the survey instrument we defined a contact as "an ongoing working relationship, including your work colleagues; and any other people with whom you have had personal interactions that you consider meaningful in relation to marine pest biosecurity." Respondents were also asked to describe the nature of their affiliated organization and aspects of marine pest biosecurity with which they are involved. The survey was hosted on SurveyGizmo between 6 December 2017 and 21 January 2018, with invitations to complete the survey emailed to the 681 individuals in the stakeholder database. A response rate of 35% was achieved, totaling 237 observations.

Ideally, the unit of analysis would be at the level of the individual stakeholder. However, many survey respondents were able to identify a particular organization with whom they interacted

Table 1. Policy forums.

Forum details	Participating organizations or their branches (node counts)	Individual attendances at the forum (tie counts)
Consultative Committee for Introduced Marine Pest Emergencies	16	87
Marine Pest Sectoral Committee	13	64
Marine Pest Sectoral Committee - Marina and Slipways Task Group	9	11
Marine Pest Sectoral Committee - Surveillance and Diagnostics Strategy Scoping Group	10	16
Marine Pest Sectoral Committee - Partner Workshop	39	96
Marine Pest Sectoral Committee - Strategy Development Task Group	7	8
Marine Pest Sectoral Committee - Surveillance Strategy Task Group	23	33
National Biosecurity Committee	15	61
New South Wales (state) Marine Pest Working Group	7	32
Queensland (state) - Inter-Agency Marine Pest Reference Group	8	17
West Australian (state) Biosecurity Senior Officer Group	3	9
South Australian (state) Marine Biosecurity Forum	10	16

Table 2. Organizations.

Organizational category	Count	(1) Provided information to community	(2) Asked community for information	Both (1) and (2)
Australian Government agency	28	2	0	0
State/territory government agency	31	12	3	2
State-owned corporation	2	0	0	0
Local government	2	1	0	0
Industry association/body	25	1	0	0
Nongovernment organization	9	0	0	0
Private company/business	114	5	0	0
Education/extension organization	9	2	1	1
Research/training organization	27	0	0	0
International government	10	2	0	0
NRM/Regional government	13	1	0	0
Vessel services (e.g., marina, slipway)	9	1	0	0
Port managers	25	1	0	0
Total	304	28	4	3

regarding marine pests, but did not recall or chose not to identify individuals. As such, it was necessary to aggregate responses so that the unit of analysis became the respondent's affiliated organization, rather than the respondent as an individual. For many larger organizations, this meant that multiple individuals could respond on behalf of their organization. Our analysis was nonweighted so that ties between organizations were defined simply as either existing or not, even if a tie happened to be based on interactions between multiple individuals across organizations. Note too that data regarding the Department of Agriculture and Water Resources, which serves a substantial and importantly diverse role in the network, was sufficiently rich that it could be disaggregated to the branch level rather than the department as a whole.

Survey respondents represented 118 distinct organizations and nominated interactions with an additional 186 organizations that were not surveyed, yielding a total of 304 organizations. Each organization was assigned to one of 13 categories based on the scope of their operation (Table 2.)

Not only were respondents asked to identify those with whom they interacted, but also the nature(s) of those interactions. In this paper we are specifically interested in interactions relating to research and development, active surveillance, passive surveillance, and education and awareness raising. Table 3 displays an extract from the survey related to these activities.

Table 3. Extracts from survey.

Have you provided any marine pest related information or advice to any other people over the last 12 months? Who did you provide marine pest related information or advice (individual and organisation?) The full survey had additional options for the nature of interaction which are not analysed (Emergency response; On-going management; Policy / regulation; Consultancies/services; and Preparedness)

Type of information you provided to them (select one or more from):
- R&D
- Active surveillance
- Passive surveillance
- Education/awareness

Have you asked for marine pest related information or advice from any other people over the last 12 months? Who have you asked for marine pest related information or advice over the last 12 months (individual and organisation?)

Type of information you asked them for (select one or more from):
- R&D
- Active surveillance
- Passive surveillance
- Education/awareness

When individuals responded that they interacted with vessel owners, the general public, or fishers, responses typically indicated general interactions with such a group without naming a specific person or organization. Capturing community interactions was critical, but these responses were too general and did not lend to having specific vessel/general public/fisher organizations as individual actors in the network analysis. In order to overcome this issue, we identified whether each individual organization interacted with a generic community and treated this as a binary (yes/no) attribute attached to each organization, rather than as network ties between network actors. The number of organizations reporting community interactions tabulated by organizational category is shown in Table 2.

Fig. 4. Over and under-representation of configurations. With +/++/+++ representing 90/95/99% significance for overrepresentation (- indicating under). For full results see Appendix 1, noting these results come from both exponential random graph model (Table A1.1) or goodness-of-fit (Table A1.2). The model fixes the structure of forum participation. Configurations [9] and [10] are both weighted configurations. See AinSA/AoutSA from Wang et al. (2014).

	a. All-Ties		b. Passive surveillance		c. Active or passive surveillance		d. Education and awareness		e. Research and development	
Ties shared with all ties:	643 ties, 100%		156 ties, 24.3%		321 ties, 49.9%		220 ties, 34.3%		238 ties, 37.0%	
	Count	Signif.	Count	Signif.	Count	Signif.	Count	Signif.	Count	Signif.
Bonding										
1.	186	+++	49	+++	96	+++	56	+++	71	+++
2.	153	+++	24	+++	58	+++	21	+++	36	+++
3.	38		0		4	--			7	++
4.	189		7		38		19		38	+++
5.	422	-	173		266		232		188	
6.	57	---	31		44		26	--	27	---
Bridging										
7.	125	+++	55		101	+++	106	++	65	
8.	26		17	--	22	--	22	---	23	---
9.	6895	+++	512		1847		766		1071	
10.	624.9	++	100.8		243.8	+++	111.8	+++	194.4	+++
11.	836.5	++	173.4		395.7	+++	270.9		271.3	+++
12.	1616	+++	439	+++	809	+++	441	+++	588	+++
13.	1992	+++	627	+++	1135	+++	991	+++	791	+++
14.	241	+++	76	+	151	+++	113	+++	105	+++
15.	172		44		81		42		55	
16.	4784	++	308		1315		495		613	

Semistructured interviews

Guided by the network data collection process, semistructured interviews with eight key informants were conducted to provide a more nuanced understanding of the network function and structure (Alexander et al. 2017). Interviewees were selected based on their position in the network, with the aim of achieving a spread across the states/territories and network roles. Interviewees represented Australian Government (n = 1) and state/territories government (n = 2), a community group (n = 2), training organization (n = 1), seafood industry body (n = 1), consultancy business (n = 2), and a port corporation (n = 1). Note that some interviewees represented more than one role and some interviews involved two interviewees. Interviews were focused on finding out what networks were used for, by who and how.

Limitations

A key assumption was that an organization could be included in the network data even where there were no respondents from that organization; nonrespondents could be represented in the network where they were identified by an organization that did have survey respondents. The assumption was that this was sufficient for their network position to be adequately represented in the data, noting that the data are a sample of an unobserved population. Because the analysis generally focused on the global network between organizations, the ties under consideration only involved the connection between different organizations. For example, if someone nominated a colleague within their branch, this tie was excluded. Networks are often discussed as if they are static entities. However, networks are evolving entities in terms of actors, resources, and power distribution (Carlsson and Sandström 2007). We are therefore only able to provide a snapshot in broad brush strokes of a network that is, in reality, dynamic. We provide limited insight into whether interactions form part of long-term collaborations or short-term engagements, whether they are the result of informal connections or formal agreements. We also acknowledge our dataset represents a sample rather than

a population, though the statistical methods used are robust to sample data.

RESULTS

We ran five exponential random graph models where actor-actor ties (microlevel network, Fig. 1) varied according to what knowledge was shared: (1) any, (2) passive surveillance, (3) either passive or active surveillance, (4) research and development, (5) education and awareness. The same fixed actor-forum network (meso, Fig. 1) was used in all model runs. Where selected configurations (Fig. 3) did not converge, we proxied a test for significance using goodness-of-fit (Appendix 1, Table A1.2). Figure 4 hence combines both network statistical modeling and simulation.

The propensity for network bonding is indicated by homophily, reciprocity, and closed structures. Results show actors of a certain type (Table 2) were significantly more likely to provide information to, or receive information from, actors of the same type (Fig. 4, [1]). The model also showed reciprocal sharing of information was statistically more likely than by chance [2]. Both homophily and reciprocity had the propensity to reinforce existing behaviors and knowledge. In contrast other modeled configurations showed a propensity for bridging [9-13]. There was statistical evidence of an abundance of key hubs for both receiving and providing information [10-11] and a corresponding lack of close-structures [3-5]. There was also evidence that more actors had no outgoing ties than can be explained by chance alone [7-8]. For attendees of policy forums there was no evidence they were more likely to share information with each other outside of the forum (Fig. 4, [5]).

Actors coded as having links to the community showed a strong predisposition for providing rather than receiving information (Fig. 4, [14-15]), and with more bridging structures than could be expected by chance alone [16]. Most community linkages were via state/territory government (31 organizations, 14 with community links, Table 2), and nearly all references to such community interactions involved actors providing information to communities (totaling 28, Table 2) rather than receiving information from community (totaling 4).

All networks were a subset of (a) all-ties, with (b) passive surveillance containing 24.3% of the all-ties network, (c) passive + active surveillance 49.9%, (d) research and development 34.4%, and (e) education and awareness 37.0%. All five models gave comparable findings with perhaps the exception of research and development, which showed bonding through selected closed structures (Fig. 4, 3e-4e]).

Note that 187 organizations were mapped in the network not because they responded to the survey, but because they were identified by one or more survey respondents. Our methods had no scope of measuring any potential ties between pairs within the set of 187 organizations. We assumed that we captured critical actors within the scope of survey respondents. However, we also tested if treating potential ties as "missing" influenced the results using a Bayesian exponential random graph model (Caimo and Friel 2011). Bayesian models can account for missing ties if the set of ties not sampled is known and ties are assumed to be "missing at random" (Koskinen et al. 2013); that is, the "missingness" of a tie does not depend on node-level covariates.

This assumption allows for missing ties to be imputed each time the algorithm simulates a network. We ran a Bayesian model specifying that ties between nonrespondents were missing. The results were not meaningfully different, suggesting our assumption that the survey provides a good sample of the network holds.

DISCUSSION

In the event of a marine pest incursion, emergency institutional responses are activated (Australian Government 2018). Preparedness for such emergencies relies on a foundation of coordinated communications in order to raise awareness, share research developments, and support surveillance. Although biosecurity emergencies require institutional structures that balance both rapid response across multiscales as well as venues for political decision making (McAllister et al. 2015, 2017), the Australian marine pest network primarily needs the propensity to disseminate and capture information across diverse geographies and stakeholders. Whereas emergency response needs to manage risky and contested social interactions, and hence needs regions of bonding capital with its dense and overlapping interactions (Berardo 2014*a, b*), the Australian marine pest network needs structural bridges to predispose information flows (Angst et al. 2018).

We studied the foundational role of the Australian marine pest network.

How well predisposed is the network to enable effective information dissemination?

We quantitatively tested 16 network configurations, each indicative of either bonding or bridging capital. Overall, despite evidence of bonding through homophily and reciprocity, the network is well structured for coordination and rapid dissemination of information. In particular, the Australian marine pest network shows a structural propensity for bridging configurations with key hubs for both provision and receiving of information (Fig. 4). There were significantly more actors than expected that sent information but did not receive information. This suggests that the network hubs for sending information have more clearly defined roles than do hubs for receiving information. Information flows around research and development were the exception in showing stronger elements of bonding through well-connected clusters of organizations.

Semistructured interviews suggested government organizations held key positions in the network's core, but their reach was deeply dependent on the network's connectivity with on-ground organizational types, such as consultancies, port authorities, and resource and energy companies. Interviews also suggested some collective learning across the network, where stakeholders not only received information, but synthesized before on-sharing. For example, a consultancy representative interviewed with specialist experience spoke to the information received from the different sources and the continual reshaping of his own knowledge and insights that he subsequently shared with others. A broad set of organizations support efficient information dissemination throughout the network, with many private companies well positioned to play brokering roles. Such actors are also likely to have insights into the barriers and opportunities that their clients face, including innovative practices and ideas with relevance for

other network actors. The combined picture that emerged from both quantitative and qualitative data was that of a network where government plays a key role in shaping the network, but where some brokering and knowledge integration was decentralized across nongovernment actors.

How do informal organizational stakeholder interactions structure around policy forums?

Our network contained 157 cases of organizational participation across 13 policy forums (Table 1). However, we found no evidence that any two participants of a forum were more likely to share information outside of that forum setting. The trust-building, problem-defining, and risk-management that might otherwise be associated with bonding capital around such forums (Berardo 2014*b*) may well be provided for within the policy forums (Fischer and Leifeld 2015). Regardless, the open-configurations associated with forums participation suggest a predisposition for bridging relationships with nonparticipants, adding to the network's ability to share information widely across the network.

This is supported by interviews suggesting state/territory governments are key participants in forums and are well-connected with other organization types in the network; they are well placed to translate information between different groups, such as research findings to different on-ground users. The role of Marine Pest Sectoral Committee - Partner Workshop in scale-bridging particularly suggests engagement is happening with a wide group of nongovernment actors. It shows the important role of key venues, like the Marine Pest Sectoral Committee - Partner Workshop (Table 1), in providing a forum for receiving and providing information to nongovernment partners. From the interviews, it was also clear that Marine Pest Sectoral Committee and the Australian Department of Agriculture and Water Resources staff greatly valued this forum. However, there were mixed views with some nongovernment interviewees perceiving the Partner Workshop as mainly involving Department of Agriculture and Water Resources staff providing updates to attendees.

How well predisposed is the network to engage communities in two-way information?

Actors with links to the broader community play more prominent bridging roles than could be expected by chance alone (Fig. 4). However, one potential concern is the imbalance between ties for providing information to the community compared to a near absence of ties for receiving information from the community (Table 2).

Discussions with Marine Pest Sectoral Committee members revealed some state/territory governments had elaborate community engagement strategies in place for marine pests. This may explain why state/territories had the most community links (31 organizations, 12 with out-ties to community, 3 with in-ties from community; Table 3). However, other states were lagging and still looking at ways to strengthen engagement with on-ground players, while education and awareness-raising was ad-hoc and occurring only during incursions, for example.

Two-way information flows are fundamental in building trust-based relationships (Kruger et al. 2010). Although statistically results show significant reciprocity, there are subtleties in the data. The survey asked respondents who they received/provided information to/from. In the network any in-tie between two actors was defined by either a receiver stating they sought information, or equally the sender stating they provided it. Overall 454 organizations reported providing information, while only 301 reported receiving. Survey respondents were most likely to come from the most active/central organizations, partly because those with clear roles were targeted, and partly because central players most completely identified with the content matter (Australian Department of Agriculture and Water Resources compared to a yacht owner, etc.). Yet the higher reporting of sending information over receiving may suggest a self-perception of providing rather than listening, or dissemination rather than learning.

The over-representation of information provision from government organizations to on-ground actors is unlikely to sustain any collective outcomes. This is not to suggest that the state/territory's roles should necessarily be active at the periphery in community engagement. In the absence of on-ground extension roles in Australian biosecurity, existing active local actors could be incentivized to boost links to the community and with a focus on capturing community information. For example, local government could logically play a role in filling this gap. Only three local government actors were active in the network data (three organizations, one with a community out-link; Table 3). Local government was not core to the sampling strategy, which is a limitation to the study, but they are well positioned through their connection with state/territory governments to engage with local groups about protecting the local marine environment.

Broad implications

Managing marine pest biosecurity along Australia's extensive coastline requires collaboration that is supported by a widely distributed on-ground network with diverse actors (Australian Government 2015). There are legislated responsibilities for marine pest management in times of emergency response, but as a foundation for any response, the marine pest network that structures on-going coordinated communications and both passive and active surveillance is essential. Our study shows the existing Australian marine pest network is well-structured for information dissemination and there is evidence that nongovernment actors already play some role in integrating and brokering information. Any improvements could focus on incentivizing local actors to facilitate stronger two-way relationships with communities, which are currently lacking.

This study not only unpacks an important case study. It also adds methodological progress to the empirical study of the interactions between policy structures and the related interactions that occur around them. Although the study has a practical focus, its theoretical roots are in how networks structure around issues of social and political risk. In interactions in the marine pest network there are low risks because most relate to sharing information, as opposed to making decisions which may directly effect the distribution of resources. Studies of biosecurity emergency response, where decisions are made around resource allocation, have shown related networks have regions of bonding capital (McAllister et al. 2015, 2017). Our finding that the marine pest network has a structure indicative of bridging capital adds evidence to theory suggesting stakeholder networks emerge in response to the particular social risks they face (Berardo and Scholz 2010).

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.
php/11583

Data Availability Statement:

The data are not publicly available because of restrictions as agreed as part of human ethics. Please contact lead author RRJMcA to discuss any data that may be potentially available.

LITERATURE CITED

Alexander, S. M., D. Armitage, P. J. Carrington, and Ö. Bodin. 2017. Examining horizontal and vertical social ties to achieve social-ecological fit in an emerging marine reserve network. *Aquatic Conservation: Marine and Freshwater Ecosystems* 27 (6):1209-1223. https://doi.org/10.1002/aqc.2775

Alexander, S. M., Ö. Bodin, and M. L. Barnes. 2018. Untangling the drivers of community cohesion in small-scale fisheries. *International Journal of the Commons* 12(1):519-547. https://doi.org/10.18352/ijc.843

Angst, M., A. Widmer, M. Fischer, and K. Ingold. 2018. Connectors and coordinators in natural resource governance: insights from Swiss water supply. *Ecology and Society* 23(2):1. https://doi.org/10.5751/ES-10030-230201

Australian Government. 2015. *Review of national marine pest biosecurity.* Department of Agriculture and Water Resources, Canberra, Australia.

Australian Government. 2018. *MarinePestPlan 2018-2023: the National Strategic Plan for Marine Pest Biosecurity.* Department of Agriculture and Water Resources, Canberra, Australia.

Barnes, M., Ö. Bodin, A. Guerrero, R. McAllister, S. Alexander, and G. Robins. 2017. Theorizing the social structural foundations of adaptation and transformation in social-ecological systems. *Ecology and Society* 22(4):16. https://doi.org/10.2139/ssrn.2932575

Barnes, M. L., Ö. Bodin, T. R. McClanahan, J. N. Kittinger, A. S. Hoey, O. G. Gaoue, and N. A. J. Graham. 2019. Social-ecological alignment and ecological conditions in coral reefs. *Nature Communications* 10:2039. https://doi.org/10.1038/s41467-019-09994-1

Berardo, R. 2014a. Bridging and bonding capital in two-mode collaboration networks. *Policy Studies Journal* 42(2):197-225. https://doi.org/10.1111/psj.12056

Berardo, R. 2014b. The evolution of self-organizing communication networks in high-risk social-ecological systems. *International Journal of the Commons* 8(1):236-258. https://doi.org/10.18352/ijc.463

Berardo, R., and M. Lubell. 2019. The ecology of games as a theory of polycentricity: recent advances and future challenges. *Policy Studies Journal* 47(1):6-26. https://doi.org/10.1111/psj.12313

Berardo, R., and J. T. Scholz. 2010. Self-organizing policy networks: risk, partner selection, and cooperation in estuaries. *American Journal of Political Science* 54(3):632-649. https://doi.org/10.1111/j.1540-5907.2010.00451.x

Bodin, Ö., and M. Tengö. 2012. Disentangling intangible social-ecological systems. *Global Environmental Change* 22(2):430-439. https://doi.org/10.1016/j.gloenvcha.2012.01.005

Caimo, A., and N. Friel. 2011. Bayesian inference for exponential random graph models. *Social Networks* 33(1):41-55. https://doi.org/10.1016/j.socnet.2010.09.004

Carlsson, L. G., and A. C. Sandström. 2007. Network governance of the commons. *International Journal of the Commons* 2 (1):33-54. https://doi.org/10.18352/ijc.20

Cook, E., R. Payne, A. Macleod, and S. Brown. 2016. Marine biosecurity: protecting indigenous marine species. *Research and Reports in Biosecurity Studies* 5:1-14. https://doi.org/10.2147/rrbs.s63402

Curnock, M., C. Farbotko, K. Collins, C. J. Robinson, and K. Maclean. 2017. Engaging with risk (or not): shared responsibility for biosecurity surveillance and the role of community gardens. *Geographical Research* 55(4):379-394. https://doi.org/10.1111/1745-5871.12231

Efron, B. 1979. Bootstrap methods: another look at the jacknife. *Annals of Statistics* 7:1-26. https://doi.org/10.1214/aos/1176344552

Fischer, A. P., and L. Jasny. 2017. Capacity to adapt to environmental change: evidence from a network of organizations concerned with increasing wildfire risk. *Ecology and Society* 22 (1):23. https://doi.org/10.5751/ES-08867-220123

Fischer, M., and P. Leifeld. 2015. Policy forums: why do they exist and what are they used for? *Policy Sciences* 48:363-382. https://doi.org/10.1007/s11077-015-9224-y

Floerl, O. 2014. Managment challenges and opportunities for marine biosecurity in the Arctic. Pages 57-68 *in* L. Fernandez, B. A. Kaiser, and N. Verstergaard, editors. *Marine invasive species in the Arctic.* Nordic Council of Ministers, Copenhagen, Denmark.

Frank, O., and D. Strauss. 1986. Markov graphs. *Journal of the American Statistical Association* 81(395):832-842. https://doi.org/10.1080/01621459.1986.10478342

Granovetter, M. 1983. The strength of weak ties: a network theory revisited. *Sociological Theory* 1:201-233. https://doi.org/10.2307/202051

Granovetter, M. S. 1973. The strength of weak ties. *American Journal of Sociology* 78:1360-1380. https://doi.org/10.1086/225469

Guerrero, A. M., R. R. J. McAllister, and K. A. Wilson. 2015. Achieving cross-scale collaboration for large scale conservation initiatives. *Conservation Letters* 8(2):107-117. https://doi.org/10.1111/conl.12112

Hamilton, M., A. P. Fischer, and A. Ager. 2019. A social-ecological network approach for understanding wildfire risk governance. *Global Environmental Change* 54:113-123. https://doi.org/10.1016/j.gloenvcha.2018.11.007

Hamilton, M., M. Lubell, and E. Namaganda. 2018. Cross-level linkages in an ecology of climate change adaptation policy games. *Ecology and Society* 23(2):36. https://doi.org/10.5751/ES-10179-230236

Jasny, L., M. Johnson, L. K. Campbell, E. Svendsen, and J. Redmond. 2019. Working together: the roles of geographic proximity, homophilic organizational characteristics, and neighborhood context in civic stewardship collaboration networks in Philadelphia and New York City. *Ecology and Society* 24(4):8. https://doi.org/10.5751/ES-11140-240408

Koskinen, J. H., G. L. Robins, P. Wang, and P. E. Pattison. 2013. Bayesian analysis for partially observed network data, missing ties, attributes and actors. *Social Networks* 35(4):514-527. https://doi.org/10.1016/j.socnet.2013.07.003

Kruger, H. 2016. Designing local institutions for cooperative pest management to underpin market access: the case of industry driven fruit fly area-wide management. *International Journal of the Commons* 10(1):176-199. https://doi.org/10.18352/ijc.603

Kruger, H., N. Stenekes, R. Clarke, and A. Carr. 2010. *Biosecurity engagement guidelines: practical advice for involving communities. Science for decision makers.* Australian Government Bureau of Rural Sciences, Barton, Australian Capital Territory, Australia.

Lubell, M. 2015. Collaborative partnerships in complex institutional systems. *Current Opinion in Environmental Sustainability* 12:41-47. https://doi.org/10.1016/j.cosust.2014.08.011

Lubell, M., G. Robins, and P. Wang. 2014. Network structure and institutional complexity in an ecology of water management games. *Ecology and Society* 19(4):23. https://doi.org/10.5751/ES-06880-190423

Maclean, K., C. Farbotko, A. Mankad, C. J. Robinson, M. Curnock, K. Collins, and R. R. J. McAllister. 2018. Building social resilience to biological invasions. A case study of Panama Tropical Race 4 in the Australian Banana Industry. *Geoforum* 97:95-105. https://doi.org/10.1016/j.geoforum.2018.10.018

Maclean, K., C. Farbotko, and C. J. Robinson. 2019. Who do growers trust? Engaging biosecurity knowledges to negotiate risk management in the north Queensland banana industry, Australia. *Journal of Rural Studies* 67:101-110. https://doi.org/10.1016/j.jrurstud.2019.02.026

Mankad, A. 2016. Psychological influences on biosecurity control and farmer decision-making. A review. *Agronomy for Sustainable Development* 36:40. https://doi.org/10.1007/s13593-016-0375-9

McAllister, R. R. J., C. J. Robinson, A. Brown, K. Maclean, S. Perry, and S. Liu. 2017. Balancing collaboration with coordination: contesting eradication in the Australian plant pest and disease biosecurity system. *International Journal of the Commons* 11(1):330-354. https://doi.org/10.18352/ijc.701

McAllister, R. R. J., C. J. Robinson, K. Maclean, A. M. Guerrero, K. Collins, B. M. Taylor, and P. J. De Barro. 2015. From local to central: a network analysis of who manages plant pest and disease

outbreaks across scales. *Ecology and Society* 20(1):67. https://doi.org/10.5751/ES-07469-200167

Metz, F., M. Angst, and K. Ingold. 2020. Policy integration: Do laws or actors integrate issues relevant to flood risk management in Switzerland? *Global Environmental Change* 61:101945. https://doi.org/10.1016/j.gloenvcha.2019.101945

Nita, A., L. Rozylowicz, S. Manolache, C. M. Ciocănea, I. V. Miu, and V. D. Popescu. 2016. Collaboration networks in applied conservation projects across Europe. *PLoS ONE* 11(10): e0164503. https://doi.org/10.1371/journal.pone.0164503

Nyantakyi-Frimpong, H., P. Matouš, and M. E. Isaac. 2019. Smallholder farmers' social networks and resource-conserving agriculture in Ghana: a multicase comparison using exponential random graph models. *Ecology and Society* 24(1):5. https://doi.org/10.5751/es-10623-240105

Ostrom, E. 2010. Beyond markets and states: polycentric governance of complex economic systems. *American Economic Review* 100(3):641-672. https://doi.org/10.1257/aer.100.3.641

Perry, E. E., D. H. Krymkowski, and R. E. Manning. 2019. Brokers of relevance in National Park Service urban collaborative networks. *Ecology and Society* 24(4):3. https://doi.org/10.5751/ES-11124-240403

Reed, M. S., and R. Curzon. 2015. Stakeholder mapping for the governance of biosecurity: a literature review. *Journal of Integrative Environmental Sciences* 12(1):15-38. https://doi.org/10.1080/1943815X.2014.975723

Robins, G., and M. Morris. 2007. Advances in exponential random graph (*p**) models. *Social Networks* 29(2):169-172. https://doi.org/10.1016/j.socnet.2006.08.004

Summerson, R., M. Skirtun, K. Mazur, T. Arthur, R. Curtotti, and R. Smart. 2013. *Economic evaluation of the costs of biosecurity response options to address an incursion of Mytilopsis sallei* (black-striped mussel) *into Australia.* Australian Governmnet (ABARES), Canberra, Australia.

Wang, P., G. Robins, P. Pattison, and J. H. Koskinen. 2014. *MNNet: program for the simulation and estimation of (p**) exponential random graph Models for Multilevel networks.* Melbourne University School of Psychological Sciences, Melbourne, Australia.

Wang, P., G. Robins, P. Pattison, and E. Lazega. 2013. Exponential random graph models for multilevel networks. *Social Networks* 35(1):96-115. https://doi.org/10.1016/j.socnet.2013.01.004

Wasserman, S., and P. Pattison. 1996. Logit models and logistic regressions for social networks. 1. An introduction to Markov graphs and *p*. *Psychometrika* 61:401-425. https://doi.org/10.1007/bf02294547

Table A1.1: Exponential Random Graph Models; fixed meso-level (actor-forums) network. Count, model parameter, t-score for parameter, with */**/*** signifying 90/95/99% significance.

Config.	See Wang et al. 2014	All-Ties	Passive Surveillance	Both Active and Passive Surveillance	Education and Awareness	Research and Development
	ArcA	[643] -7.82 (-48.56)***	[156] -8.73 (-35.49)***	[321] -8.72 (-46.36)***	[218] -8.56 (-39.25)***	[238] -7.41 (-57.91)***
	ReciprocityA	[125] 4.74 (25.10)***	[24] 3.66 (8.86)***	[58] 4.30 (15.53)***	[21] 3.04 (7.32)***	[36] 4.03 (13.25)***
	T1A	[38] -0.13 (-0.89)	*[0] no convergence*	[4] -1.05 (-2.14)**	*[0] no convergence*	[38] *no convergence*
	SinkA	[125] 1.44 (4.30)***	[55] 0.70 (1.10)	[101] 1.59 (3.36)***	[106] 2.56 (4.75)***	[65] *no convergence*
	SourceA	[26] -0.02 (-0.04)	[17] -1.31 (-2.07)**	[22] -1.32 (-2.47)***	[22] -2.62 (-4.22)***	[23] *no convergence*
	AinSA	[623.9] 0.39 (2.03)**	[100.8] 1.13 (2.54)***	[240.8] 1.19 (3.89)***	[111.8] 1.93 (5.27)***	[194.4] *no convergence*
	AoutSA	[832.1] 0.89 (5.34)***	[171.4] 1.13 (3.16)***	[390.3] 0.91 (3.43)***	[270. 9] 0.12 (0.35)	[271.3] *no convergence*
	SenderA	[247] 0.73 (6.48)***	[76] 0.43 (1.91)*	[151] 0.66 (4.28)***	[113] 1.02 (4.95)***	[105] 1.83 (8.74)***
	_ReceiverA	[172] 0.09 (0.50)	[44] -0.62 (-1.50)	[81] -0.37 (-1.37)	[42] 0.17 (0.47)	[55] 0.35 (1.12)
	_InteractionA	[57] -0.47 (-2.50)***	[31] 0.55 (1.38)	[44] 0.02 (0.08)	[26] -0.86 (-2.21)**	[27] -0.93 (-2.83)***
	_MatchA	[186] 0.62 (7.86)***	[49] 0.65 (3.90)***	[96] 0.64 (5.82)***	[56] 0.45 (2.70)***	[71] 0.69 (4.99)***
	In2StarAX	[1616] 0.23 (7.49)***	[439] 0.23 (3.76)***	[809] 0.21 (4.61)***	[441] 0.05 (0.85)	[588] 0.25 (6.32)***
	Out2StarAX	[1992] 0.15 (7.82)***	[627] 0.12 (3.29)***	[1135] 0.13 (5.27)***	[991] 0.19 (5.72)***	[791] 0.21 (6.89)***
	TXAXarc	[422] -0.07 (-1.69)*	[173] -0.10 (-1.35)	[265] -0.08 (-1.50)	[232] 0.11 (1.59)	[188] -0.01 (-0.25)

Table A1.2: Goodness-of-fit. Selected parameters in addition to fitted configurations from Table A1: Count, average from simulated graphs, t-score for difference, */**/*** signifying 90/95/99% significance. Note all fitted parameters reports <0.2 t-scores (Table A1). Only configurations where model convergence was not achieved are shown here.
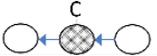
Config.	See Wang et al. 2014	All-Ties	Passive Surveillance	Both Active and Passive Surveillance	Education and Awareness	Research and Development
	SinkA					[65] 71.8 (-1.153)
	SourceA					[23] 48.7 (-4.62)***
	AinSA					[194.4] 139.5 (2.882)***
	AoutSA					[271.3] 192.3 (3.5)***
	TwoPathA	[6895] 5544.2 (1.99)**	[512] 420.0 (0.57)	[1847] 1672.6 (0.58)	[766] 874.1 (-0.44)	[1071] 894.0 (1.068)
	Cyclic-Triad	[189] 140.6 (1.45)	[7] 18.9 (-0.976)	[38] 34.0 (0.35)	[19] 26.4 (-0.53)	[38] 13.7 (3.559)***
	T1A		[0] 4.5 (-1.259)		[0] 6.0 (-1.40)	[7] 2.5 (2.2)**
	_Mix2Star010A	[4784] 4279.1 (2.014)**	[308] 365.4 (0.292)	[1315] 1343.0 (0.80)	[495] 749.3 (-0.90)	[613] 810.3 (-0.371)