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The emergent network structure of the multilateral environmental agreement system

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ABSTRACT

The conventional piecemeal approach to environmental treaty-making has resulted in a 'maze' of international agreements. However, little is known empirically about its overall structure and evolutionary dynamics. This study reveals and characterizes the evolving structure of the web of international environmental treaty law. The structure was approximated using 1001 cross-references among 747 multilateral environmental agreements concluded from 1857 to 2012. Known network analysis measures were used to answer the following questions: has a complex system of international environmental treaty law emerged? If so when, and what does it look like? What are its topological properties? To what extent is the institutional complex fragmented? The network analysis suggested that multilateral environmental agreements have self-organized into an interlocking system with a complex network structure. Furthermore, the system has defragmented as it coevolved with the increasing complexity and interconnectivity of global environmental challenges. This study demonstrates the need to approach multilateral environmental agreements in the context of a complex networked system, and recommends against assuming the overall institutional structure is fragmented. Proposals for global environmental governance reform should pay attention to this network's emergent polycentric order and complexity and to the implications of these features for the functioning of the multilateral environmental agreement system.

1. Introduction

It is generally accepted that a *de facto* 'system' of international environmental law and governance has emerged (Freestone, 1994; Boyle and Freestone, 1999; Najam et al., 2004; Bodansky, 2006). This acknowledgement stems from the observation that international norms and institutions do not exist in isolation but as embedded in a maze-like structure (Young, 1996, 2002). However, we know little about the macroscopic structure and evolutionary dynamics of this system (Biermann and Pattberg, 2008; Young, 2010a). Our understanding has not advanced much beyond 'congestion' and 'fragmentation' rhetoric based on anecdotal evidence (Ivanova and Roy, 2007). There is a clear need to study the system empirically and *in toto*, and unravel this alleged institutional maze. Such an understanding of the emerging complexity would prove useful in improving the alignment between the governance system and the multifaceted challenges of governing the interactions of different Earth system processes (Rockström et al., 2009; Walker et al., 2009; Galaz et al., 2012; Nilsson and Persson, 2012).

This study fills the knowledge gap by revealing and analysing dynamic patterns in the structural organization of international environmental law and governance. I take a network-based approach, which uncovers the underlying system architecture by reducing the system to an abstract structure capturing only the basics of connection patterns between its components (Newman, 2010). The core analytic unit is neither the whole system nor individual components, but rather the *relation* between components that gives rise to large-scale connection patterns. The emergent patterns are then treated as mathematical objects or graphs, and analyzed with network metrics such as modularity, clustering coefficient, and average path length. These topological properties reflect differences in the governing system structure that may lead to significant differences in governance processes and outcomes (Bodin and Crona, 2009; Orsini et al., 2013).

For constructing a network representation of the institutional structure of international environmental governance, I chose multilateral environmental agreements as nodes and their cross-references as links that define the relation between the agreements. Multilateral environmental agreements are treaties,

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conventions, charters, statutes, or protocols between three or more governments relating to the environment (Mitchell, 2003; Carruthers et al., 2007). They typically include cross-references to a number of other such agreements that their parties consider relevant. According to Kiss and Shelton (2007), these cross-references can be viewed as extending the legal effect of cited texts to the texts that cite them.

I selected a list of 747 multilateral environmental agreements concluded between 1857 and 2012, and identified 1001 cross-references to other agreements in the list. Using this dataset, I produced a series of agreement-level connectivity maps of international environmental treaty law. I investigated the structural dynamics of the network by focusing on the following questions: has a complex polycentric system emerged among multilateral environmental agreements through self-organization? If so, when, and what does it look like? What are its topological properties? To what extent is the institutional complex fragmented?

The questions relating to the dynamics *on* the network, that is, how the functioning of the system depends on its topological properties, are beyond the scope of this paper. Such an enquiry would require representing each multilateral environmental agreement as a dynamic system in itself (Churchill and Ulfstein, 2000; Brunnée, 2002, 2012; Gehring, 2007; Wiersema, 2009; Young, 2010a, 2010b) and further specifying the causal mechanisms of institutional interaction (Young, 2002; Gehring and Oberthür, 2009). As the institutional citation network is an abstract representation of symbolic relationships, it is yet unclear how its network measures such as modularity should be interpreted with respect to their consequences for some process on the network. Nonetheless, where possible, explanations were offered by juxtaposing the observed structural changes with what had actually happened in the real world.

The paper starts with a brief review of relevant literature to which the present network analysis contributes. The methods section then follows, explaining what cross-references mean in the context of multilateral environmental agreements and how the data were collected. Key empirical findings are presented in two sections focusing respectively on the evolution of network topology from 1857 to 2012, and static topological properties of the network in 2012. I conclude by identifying implications of the analysis of this structure for governance outcomes.

2. Fragmentation, polycentricity, and networks

Institutional fragmentation has received significant scholarly attention as a macroscopic feature of international environmental law and governance (e.g., Doelle, 2004; Stephens, 2007; Carlarne, 2008; van Asselt et al., 2008; Biermann et al., 2009; Boyd, 2010; Scott, 2011; van Asselt, 2012; Zelli and van Asselt, 2013). Although there is no consensus on its meaning and implications (Biermann et al., 2009; Zelli and van Asselt, 2013), the underlying idea can be traced to the notion of treaty congestion (Brown Weiss, 1993; see also Hicks, 1999; Anton, 2012), that institutional proliferation has led to chaos and anarchy.

From a polycentric perspective, however, "fragmentation at the international level does not imply anarchy" (Galaz et al., 2012, p. 22). Numerous independent centres of decision-making may self-organize and make mutual adjustments that order their relationships with one another (Ostrom, 1999b, 2010). This process may give rise to different forms and degrees of polycentric order, where stronger forms can be denoted as polycentric systems (Galaz et al., 2012). These systems are comparable in their structure and function to complex adaptive systems (Ostrom, 1999a), which have the capacity to adapt to external conditions by changing their rules as experience accumulates (Holland, 1995; Levin, 1998; Arthur, 1999; Miller and Page, 2007; Mitchell, 2009). Because of the complexity-handling capacity of these systems, polycentrism has been considered as one appropriate model for international environmental law and governance (e.g., Folke et al., 2005; Ostrom, 2010).

However, empirical research on fragmentation and polycentricity at the international level has been hampered by inadequate methods and a lack of large datasets. For example, whereas these concepts are about macro-level architecture in a time-dependent sense, most previous studies have examined isolated cases of dyadic institutional interaction over a limited period of time (Zelli and van Asselt, 2013). We need to go beyond such reductionist methodologies and study the architecture, that is, the *system* of institutions at the macro-level (Biermann, 2007). Many important questions remain unexplored from a dynamic systems perspective.

Network theory has recently emerged as a widely applied tool kit for studying complex systems (Amaral and Ottino, 2004; Newman, 2011). The most important breakthrough in network science has been the discovery of striking regularities in the macro-structures of many complex systems that exist in the real world (Barabási and Albert, 1999; Watts and Strogatz, 1998; Ravasz et al., 2002). These common design principles provide a powerful justification for a network approach. By providing a common language and empirical methods, network theory has the potential to bring together fragmentation, polycentricity, and complexity studies, and provide some novel insights into the structure and dynamics of international environmental law and governance (e.g., Orsini et al., 2013).

3. A citation network perspective on international environmental treaty law

This study used cross-references as proxies for the evolving structure of international environmental treaty law, a strategy justified and explained below.

3.1. Cross-references as proxies for relationships among multilateral environmental agreements

To construct the complete network of multilateral environmental agreements, I needed to define objective criteria to connect them. In this study, I used "interrelated or cross-referenced provisions from one instrument to another" (Kiss and Shelton, 2007, p. 74) or simply citations or cross-references (these terms are used interchangeably in this paper) as proxies for an approximation of the relationships among multilateral environmental agreements. Most agreements contain references to a small number of pre-existing agreements by including their titles in the treaty texts, often in preambles, that the negotiating states consider as being highly relevant. This cross-referencing has been noted as a unique common characteristic of modern environmental treaties (Kiss and Shelton, 2007). Kiss and Shelton (2007, p. 87) observed that:

> recent environmental agreements increasingly cross-reference other international instruments. Marine environmental treaties, for example, often cite to [the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978] or [the United Nations Convention on the Law of the Sea], including their rules by reference. The result could be to extend the legal effect of these instruments to states that have not ratified them but which ratify the texts that cite them, especially when the citation affirms the norms as customary international law.

States drafting and negotiating a multilateral environmental agreement would cross-reference other agreements for various reasons. The most frequently observed instances are when states acknowledge the positive relevance of the cited agreement on the issue and build upon it. This type of cross-reference usually appears in the preamble where the parties to the agreed agreement are, for example, 'noting', 'recalling', 'reaffirming', 'recognizing', 'bearing in mind', or 'taking into account' relevant agreements. A typical example can be found in the preamble to the 1992 United Nations Framework Convention on Climate Change, where its parties recalled the 1985 Vienna Convention for the Protection of the Ozone Layer and the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer. In some cases, such as in the United Nations Convention to Combat Desertification, a multilateral environmental agreement includes a cross-reference to recognize the contribution that it can make to the cited agreement.

Furthermore, regional agreements often cite relevant global agreements, such as the United Nations Convention on the Law of the Sea (UNCLOS), to include the basic norms previously articulated in those instruments (UNEP, 2001a; Kiss and Shelton, 2007). Such cross-references are also used when sharing definitions of key terms, such as "pollution of the marine environment" (UNCLOS Article 1.1(4)) and "dumping" (UNCLOS Article 1.1(5)), creating consistency across international regimes.

Another key reason for citing a multilateral environmental agreement is to define the relationship between the citing and the cited agreements, typically in conflict clauses (Wolfrum and Matz, 2003) or choice-of-law provisions (Kiss and Shelton, 2007). For example, the 1992 North American Free Trade Agreement gives priority to the obligations set out in named environmental agreements in the event of any inconsistency (Article 104). Moreover, a protocol to a framework convention often includes a specific provision that defines its relationship to the convention. Less frequently, a multilateral environmental agreement cross-references when replacing an existing agreement to define the relationship between the old and new agreements until the former terminates.

It should be carefully noted at the outset how citation networks differ from other networks (Leicht et al., 2007; Radicchi et al., 2012). First, citation networks are *directed*. Citations go from one document to another, involving an inherently asymmetric relationship between the agreements involved. Second, citation networks are *acyclic*, meaning there are no closed loops of citations of the form 'A cites B cites C cites A', or longer. In other words, when a new agreement is added to the network, it can cite any of the previously existing agreements, but it cannot cite agreements that have not yet been created. This gives the network an 'arrow of time', with all links pointing backwards in time. Third, the time evolution of citation networks takes a special form, in that nodes and links are added to the network at a specific time and cannot be removed later (see Appendix A.1). This permanence of nodes and links means that the structure of the network is mostly *static*: it changes only at the leading edge of the network, as new agreements are added.

In principle, citations suggest links that do not require any preceding or anticipated institutional interplay. They simply capture the interests of the parties at the time of treaty negotiations. Therefore, the multilateral environmental agreement citation network should be considered as a 'symbolic' network, a network representation of abstract relations between discrete entities, as opposed to an 'interactive' network, whose links describe tangible interactions that are capable of transmitting information, influence, or material (Watts, 2004). In other words, one should be cautious in assuming that the legal and governance processes as practiced are reflected in the citation network structure.

For the purpose of estimating the basic system architecture of international environmental treaty law, however, the citation data should suffice. The validity of such a citation network approach to unravelling legal and institutional complexity has been proven in previous studies. For example, several scholars have used legal cross-references when studying the aggregate structures of the United States case law (Post and Eisen, 2000; Fowler et al., 2007; Smith, 2007; Fowler and Jeon, 2008), the United States Code (Katz and Stafford, 2010; Bommarito and Katz, 2009, 2010), and the French legal system (Boulet et al., 2010, 2011). In particular, Smith (2007, pp. 310–311) considered cross-references as linking "cases, statutes and other legal authorities" together, hence allowing a study of law's overall shape, that is, "how law is organized and evolves". Furthermore, given the technical difficulties associated with collecting other types of connection data (see Appendix A.2), cross-references provide practical and reliable proxies for the purpose of this research.

3.2. Dataset compilation

Agreeing on what is and what is not a multilateral environmental agreement is not a straightforward task (Mitchell, 2003; Scott, 2003; Kiss and Shelton, 2007). To be as objective and comprehensive as possible in building my dataset, I combined the lists of multilateral environmental agreements contained in the two most comprehensive international environmental agreement databases: the IEA Database (Mitchell, 2013) and the ECOLEX (IUCN et al., 2013). I also added a small number of agreements that were missing from both of these databases, and ended up with 747 in my dataset (see Table A.1 in the appendix). Amendments were excluded, as they are not separate agreements but form an integral part of a convention or a protocol (Carruthers et al., 2007).

Examination of the texts (title, preambular paragraph, operational provisions, and annexes) of 747 multilateral environmental agreements identified 1001 cross-references (see Appendix A.3 for citation data collection rules). A computer programmed and automated search-and-find operation was not considered feasible, as formal titles of these agreements were not used consistently across the agreements.

After compiling the dataset, I constructed and visualized the institutional network. I conducted various analyses on it with tools developed by network scientists (e.g., Albert and Barabási, 2002; Newman, 2003). Network analysis computer programmes, Pajek and Netminer, were used to provide graphical and statistical representations of the system.

4. Evolution of the institutional network structure from 1857 to 2012

Analysis of topological changes of the multilateral environmental agreement citation network between 1857 and 2012 provide insight into the evolution of the institutional system.

4.1. Network connectivity

The network representation of the multilateral environmental agreement system I constructed evolved in 156 steps, from a single node in 1857 to 747 nodes with 1001 directed links (or 986 undirected links with multiple lines removed) in 2012. Fig. 1 shows eight graphical snapshots of the network taken at ten-year interval from 1941 to 2011 (and 2012). Increases in the cumulative number of agreements adopted and cross-references made since 1857 are shown in Fig. 2(a). Multilateral environmental agreements concluded before the mid-1940s often contained no cross-references. The average number of cross-references made (i.e., outward citations) per agreement grew rapidly after 1992, when the number of outward citations made each year clearly surpassed the number of agreements adopted each year (Fig. 2(a)). The total number of outward citations surpassed the total number of

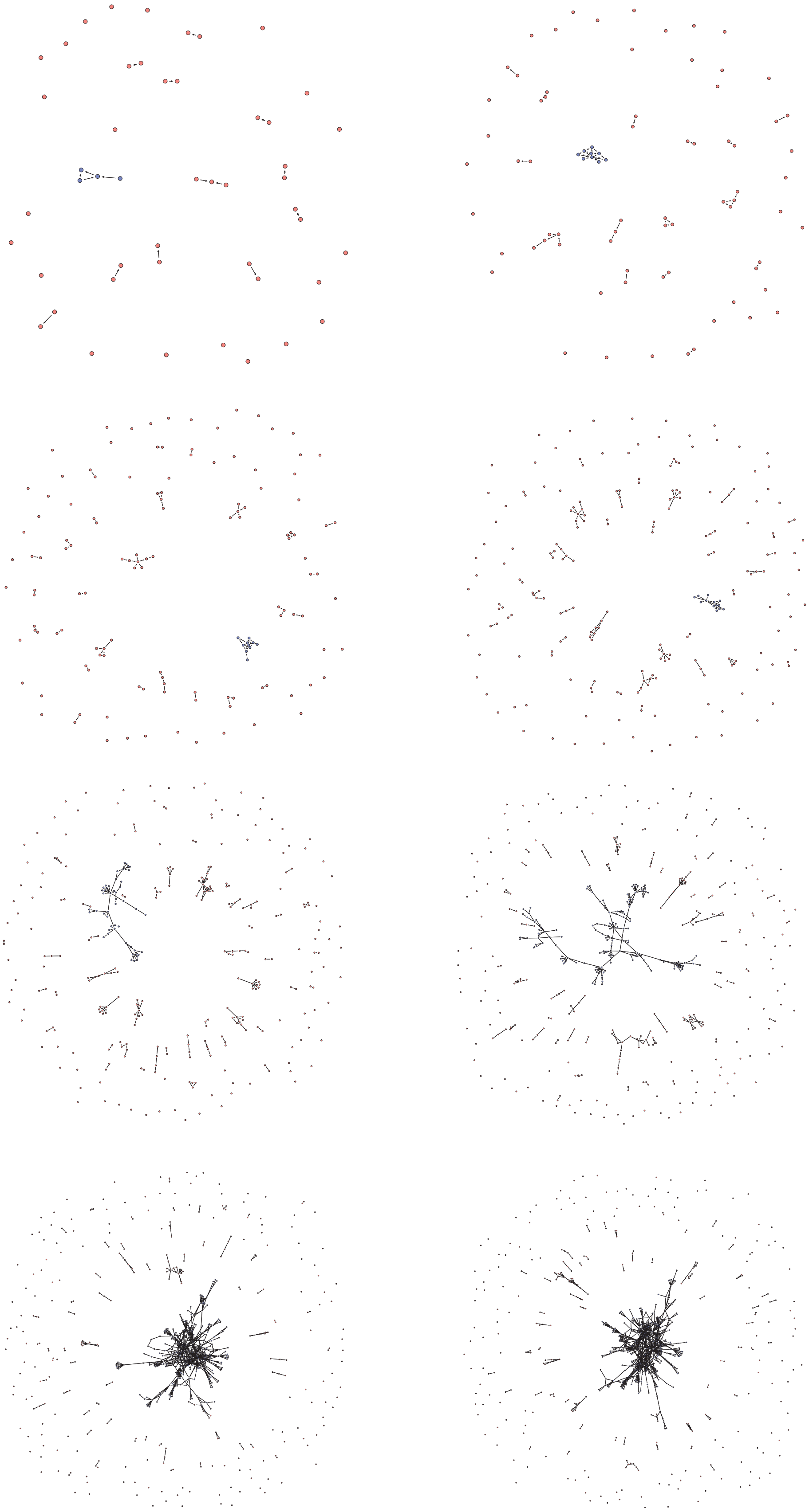

Fig. 1. Graphical representations of the multilateral environmental agreement citation network as at 1941, 1951, 1961, 1971, 1981, 1991, 2001, and 2011 (and 2012) drawn using the layout algorithm of Fruchterman and Reingold (1991). The nodes of the largest components appear in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

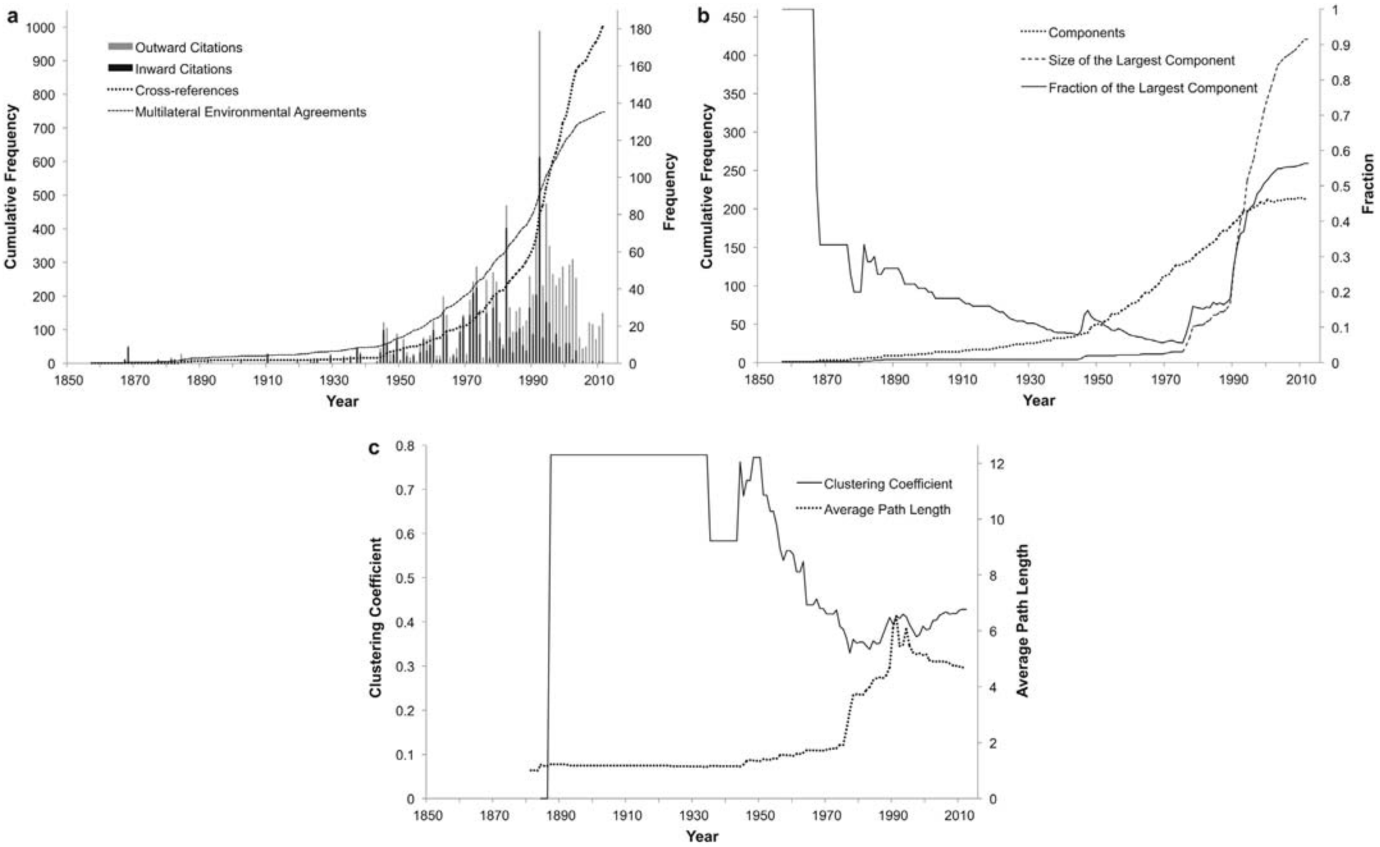

Fig. 2. (a) Cumulative number of multilateral environmental agreements and cross-references; and number of new agreements each year, and different distributions of inward and outward citations as a function of the year in which cited and citing agreements were adopted, respectively. This network is symmetric, where the total number of inward citations equals the total number of outward citations. (b) Number of components, the size of the largest component, and the fraction of the largest component. (c) The average path length and the clustering coefficient of the multilateral environmental agreement network.

agreements in 1996 when each agreement adopted thus far had, on average, one outward citation.

By 2012, the average multilateral environmental agreement made and received 1.3 citations to and from other agreements, which means that an average agreement has 2.6 direct neighbours. The number of outward citations varies from 0 to 18 with a standard deviation of 1.9 and a median of 1. The number of inward citations varies from 0 to 66 with a standard deviation of 3.7 and a median of 0. Among the 747 agreements, 595 (80 percent) have at least one connection (i.e., either inward or outward citation), and 152 (20 percent) stand alone as isolated components.

4.2. (De)fragmentation

Before the United Nations was established, there were only a few multilateral environmental agreements, most of which were not related to each other. Roughly coinciding with the conclusion of the Charter of the United Nations in 1945, the number of agreements increased incrementally over the next three decades, but without fundamentally changing their macro-structure. Small discrete components grew bigger in size, but at the same time more isolated nodes or dyads randomly appeared on the institutional landscape. This network representation corresponds to Birnie (1977) who observed that the development of international environmental law at the time was not systematic. The network was becoming an increasingly disaggregated set of discrete international institutions. This process conforms to the classic definition of fragmentation as "the process or state of breaking or being broken into small or separate parts" (Oxford English Dictionary, 1989).

Such structural changes could be quantified by a simple measure of the fraction of the largest component, which I plotted in Fig. 2(b). The fraction of the largest component was 1 with a single node in 1857. It continued to decrease, as more and more nodes with no links were inserted into the network, until the fraction reached the minimum at 0.056 (or 5.6 percent) in 1975. The network then consisted of 252 multilateral environmental agreements grouped into small and separate 128 components, with the largest component consisting of only 14 agreements. Since 1976, however, the fraction of the largest component has increased until today, and it stabilized around 0.564 (56 percent).

If we accept a definition of fragmentation based solely on the fraction of the largest component, the international environmental governance architecture was most structurally fragmented in 1975. Furthermore, the institutional network has since increasingly *defragmented*.

I acknowledge that such a structuralist definition might be overly simplistic by neglecting the complex nature of institutional interaction, which may be functionally cooperative or disruptive (Gehring and Oberthür, 2006; Biermann et al., 2009). The definition adopted here, however, focuses on a different aspect of the institutional architecture. Whereas the existing scholarship focuses primarily on the fragmented implementation of multilateral environmental agreements, this study is directed towards their texts, each of which is a product of negotiation. Therefore, the findings on defragmentation should not be seen as completely contradicting the existing literature on institutional fragmentation, but as providing a complementary perspective.

There are also other ways in which the concept of defragmentation relates to and differs from the mainstream understanding of the fragmentation of global environmental governance (e.g., Biermann et al., 2009; Zelli and van Asselt, 2013). Like fragmentation, defragmentation is a value-free concept for describing the overall institutional structure. The concept of defragmentation, however, is intended to place a greater emphasis on the need to harness, rather than manage, institutional complexity (c.f., Axelrod and Cohen, 1999). It differs from integration, a term commonly used as an antonym of fragmentation (e.g., Keohane and Victor, 2011; Young, 2011), in that integration generally involves interplay management towards policy coherence (Nilsson et al., 2012). Defragmentation, on the other hand, is not a management response to fragmentation, but a self-organizing, counteracting process which may occur simultaneously with fragmentation.

The beginning of structural defragmentation of the multilateral environmental agreement network roughly coincided with the emergence of modern international environmental law, which was marked by the 1972 United Nations Conference on the Human Environment (also known as the Stockholm Conference) (Bodansky et al., 2007). The 1970s also witnessed the births of the earliest forms of modern multilateral environmental agreements, such as the 1971 Convention on Wetlands of International Importance, especially as Waterfowl Habitat, the 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, and the 1973 Convention on International Trade in Endangered Species of Wild Fauna and Flora. Furthermore, the Regional Seas Programme was launched with the creation of the United Nations Environment Programme, which has led to the conclusion of a number of regional seas agreements. The emergence of these modern agreements contributed significantly to the increasing network connectivity.

Does structural defragmentation alone indicate a 'systematization of anarchy' (c.f., Backer, 2012)? Just as fragmentation does not imply anarchy (Galaz et al., 2012), defragmentation does not necessarily imply order. Although the Stockholm Conference brought about a change in the old *laissez-faire* thinking, it is still questionable whether it introduced a new *system* of law (Birnie, 1977).

4.3. Systematization of anarchy

The density of local neighbourhoods, as measured by the clustering coefficient, began to increase in the 1980s (Fig. 2(c)). The clustering coefficient measures the fractions of potential connections among network neighbours that are realized (Watts and Strogatz, 1998). In other words, it quantifies how close the local neighbourhood of a multilateral environmental agreement is to being part of a 'clique', in which every agreement is connected to every other agreement. Therefore, the increasing average clustering coefficient of the network indicates a corresponding increase in the level of redundancy and cohesiveness.

The 1990s was a particularly critical period in the evolution of the multilateral environmental agreement network. The network reached a critical level of connectivity at which its structure changed from a loose collection of small clusters to a system dominated by a single 'giant component' (Janson et al., 1993; Dorogovtsev et al., 2008; Newman, 2010). This system state transition happened around 1992 when new agreements brought a few shortcuts into the network. These shortcuts shrunk the size of the network while maintaining the level of local clustering. The average path length, which had consistently increased since 1857, started decreasing after reaching the peak of 6.53 in 1991 (Fig. 2(c)). The average path length is the average number of links that must be traversed in the shortest path between any two reachable pair of nodes, and it can be understood as a global measure of separation (Watts, 1999, 2004). By 1992, the average path length dropped from 6.53 to 5.47 (Fig. 2(c)). The network diameter, which is the maximum internode distance, also declined from 16 to 13 between 1991 and 1992. In 1992, the multilateral environmental agreement network started to become a small-world, and it has become smaller ever since.

It can be argued that, during the 1990s, the "partial and uneven" body of international environmental law (Schachter, 1991, p. 457) underwent systematization. The analysis of institutional cross-references questions the conventional wisdom that "since 1992, there had been a fragmentation of environmental governance and issues" (UNEP, 2001b, p. 2). Empiricism rather confirms the claim that a *system* of international environmental law emerged on the landscape in 1992 from a mere collection of environmental norms (Freestone, 1994; Boyle and Freestone, 1999; see also Najam et al., 2004). This emergence coincided with the Earth Summit in 1992, when states adopted the landmark Rio Declaration on Environment and Development, Agenda 21, the Convention on Biological Diversity, and the United Nations Framework Convention on Climate Change.

4.4. Self-organized growth

The multilateral environmental agreement system matured in the 2000s, when only a few agreements were concluded (Fig. 2(a)). This recent trend can be attributed to what some called "negotiation fatigue" (Najam, 2000, p. 4048; see also Muñoz et al., 2009). Anton (2012), for example, observed that, since 2002 and more noticeably 2005, the negotiation and adoption of multilateral environmental agreements have slowed. Struggling to meet current treaty obligations, states may have become less interested in creating new agreements and more concerned about making the law work. This is also reflected in the 2002 Johannesburg Plan of Implementation. The noticeable shift of resources towards implementation after three decades of international cooperation can be considered as a sign of system maturity and self-regulation of its own growth.

Although the horizontal expansion of the multilateral environmental agreement network has almost halted, its internal complexity has increased. This has occurred primarily through decisions and amendments adopted by treaty bodies, which this study did not consider. The internal changes have often been made in response to new scientific information about the state of the target environmental phenomenon (Gehring, 2007; Huitema et al., 2008; Wiersema, 2009; Brunnée, 2012). Such "coherence under change" (Holland, 1995, p. 4) exhibited in recent years implies that the multilateral environmental agreement system may have self-organized at a critical state of 'stable disequilibrium' (Bak, 1996). That is to say, international environmental law has reached maturity as a complex system which displays a degree of institutional resilience and adaptability. This may also suggest that the system as a whole is now at a stage where further institutional stresses may trigger abrupt, non-linear changes, through which a radically new system is installed (Young, 2010b; see also Walker et al., 2009; Biermann et al., 2012).

4.5. A periodization of the network evolution

From a structural evolutionary perspective, the development of the multilateral environmental agreement system can be divided into six stages: (1) from the 1850s to the mid-1940s (the 'beginning'); (2) from the mid-1940s to the mid-1970s (the period of 'incoherency'); (3) from the mid-1970s to the 1980s (the period of 'clustering'); (4) the 1990s (the period of 'emergence'); (5) the 2000s (the period of 'consolidation'); and (6) the 2010s (the period of 'criticality'). It is interesting to compare this periodization with the conventional description of the historical evolution of international environmental law, which identifies the years 1945, 1972, and 1992 as critical transition points (Brown Weiss, 1993; Steiner et al., 2003; Redgwell, 2006; Sand, 2007; Birnie et al., 2009; Sands and Peel, 2012). The network analysis also supports the contention that these years indeed were critical turning points in the course of development, given that we accept a lag of a few years since the year 1972 until an increasing number of modern multilateral environmental agreements started to appear in the mid-1970s.

5. Analysis of static topological properties

Topological properties of the multilateral environmental agreement network in 2012 are characterized below with key network measures and metrics.

5.1. Small-world

The network has a single giant component of 421 multilateral environmental agreements and 870 citations, constituting 56 and 87 percent of the entire network, respectively (Fig. 1). The average path length is 4.70 (4.71 for the giant component) (Fig. 2(c)), and the two reachable agreements that are furthest apart are 12 steps away (Fig. 3). The clustering coefficient for the network is 0.43 (0.41 for the giant component) (Fig. 2(c)), which is orders of magnitude higher than 0.005 ($\pm$0.002), the clustering coefficient of a corresponding Erdős–Rényi random network which has the same number of nodes and links (Erdős and Rényi, 1960).

The high clustering coefficient and short characteristic path length suggest that the giant component is a small-world network. In other words, most agreements in the component can be reached from every other by a small number of steps. This is so despite the fact that the network contains a large number of agreements, that each agreement is connected to relatively few other agreements, and that the network has no dominant central agreement to which most others are directly connected.

5.2. Scale-free

The multilateral environmental agreement network has an approximately scale-free topology. This means that the degree distribution, the probability that a node selected uniformly at random has a certain number of links, is far from random, but heterogeneous with a highly skewed tail that follows a particular mathematical function called a power law (Barabási and Albert, 1999).

I tested whether the network is scale-free using the method developed by Clauset et al. (2009). This method combines maximum-likelihood fitting methods with goodness-of-fit tests based on the Kolmogorov–Smirnov statistic and likelihood ratios. After goodness-of-fit tests with 1000 iterations, with the null hypothesis that the degree distribution follows a power law, the result was P-values of 0.39 and 0.75 for the indegree and outdegree distributions, respectively. P-values significantly larger than 0.1 support the conclusion that they are drawn from a power-law distribution (Clauset et al., 2009). Furthermore, the degree distributions in log-log scale (Fig. 4) show that straight lines would fit reasonably well through the dots, which is roughly suggestive of power-law scaling.

The heavily right-skewed degree distributions point to the presence of relatively few agreements with extraordinary numbers of links, hence power and authority, despite the few links that an average agreement has. In fact, the top 10 percent of the 747 multilateral environmental agreements garnered about 65 percent of the total cross-references. The presence of such ‘hubs’ has originated from a micro-process called ‘preferential attachment’, whereby new agreements are more likely to make connections to those that already have many links (Barabási and Albert, 1999). From a network theoretical perspective, such degree heterogeneity fosters system resilience to random failures but system vulnerability to the failure of hubs (Albert et al., 2000; Tu, 2000; see also Young, 2010b).

To identify the hubs, I used a variety of node-level algorithms and measures, such as the Hyperlink-Induced Topic Search

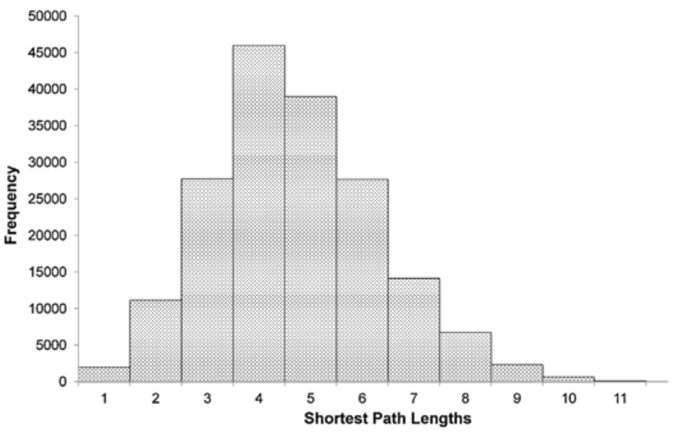

Fig. 3. Distribution of shortest path lengths between all reachable pairs.

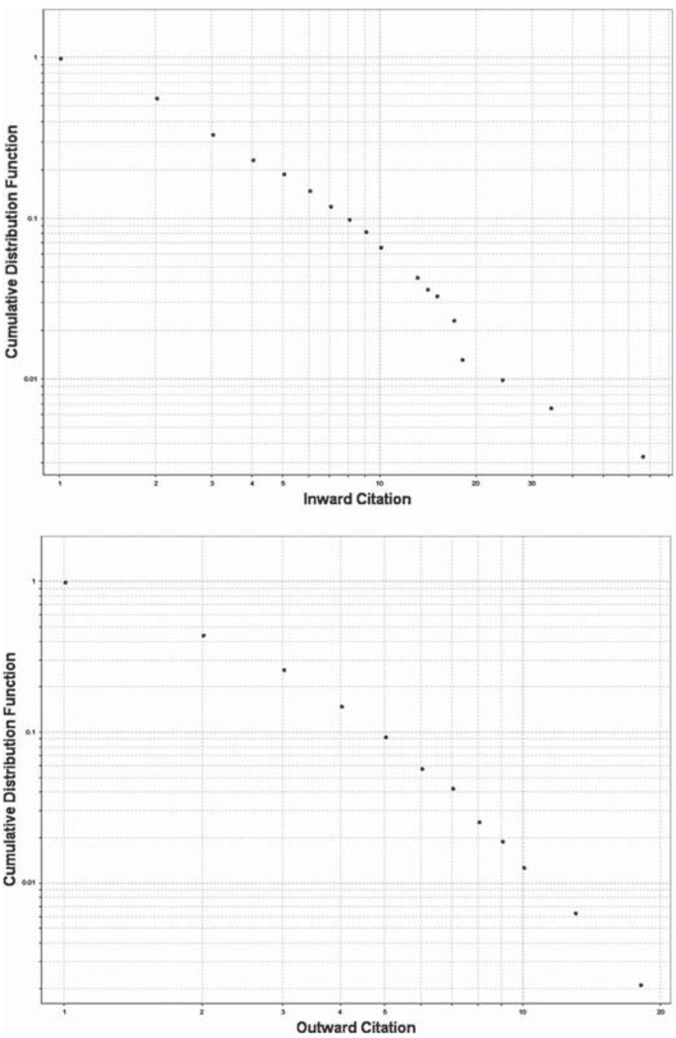

Fig. 4. Inward citation and outward citation distributions in log-log scale. The data have been binned logarithmically to reduce noise.

(Kleinberg, 1999) and betweenness that measures "the degree to which a point falls on the shortest path between others" (Freeman, 1977, p. 35; see also Wasserman and Faust, 1994). In 2012, the United Nations Convention on the Law of the Sea had 66 citations and is currently the most structurally central and authoritative multilateral environmental agreement. A possible explanation for its central position in the network is the sheer number of agreements relating to regional fisheries management, most of which cite the Law of the Sea Convention. The runner up is the Convention on Biological Diversity with 34 inward citations and 1 outward citation.

5.3. Modularity

Modules are locally dense subgroups of multilateral environmental agreements that are relatively densely connected to each other but sparsely connected to agreements in other dense groups (Porter et al., 2009; Fortunato, 2010). In governance terminology, modules are 'agreement clusters' (von Moltke, 2005) or 'regime complexes' for different issue areas such as plant genetic resources (Raustiala and Victor, 2004), climate change (Keohane and Victor, 2011), or the Arctic (Young, 2011). The notion of clustering of agreements has been the subject of increasing interest to governance scholars, especially for those concerned about the challenges of institutional fragmentation and coordination (Oberthür, 2002; Roch and Perrez, 2005; von Moltke, 2005). However, their arguments have been largely normative and based on anecdotal evidence of, for example, deliberate efforts in 'clustering experiment'. Here I take a broader view of the multilateral environmental agreement system and present empirical evidence for the presence of naturally emergent, topical agreement modules.

Modularity does not always mean clear-cut subgroups, but there may be overlap between modules. To find the best partition of the network into modules, I applied a community detection algorithm developed by Newman (2006). This algorithm frames the problem of detecting modules as an optimization task in which one searches for the maximal value of 'modularity' over possible divisions of a network (Newman, 2006). Modularity is quantified by calculating "the number of edges falling within groups minus the expected number in an equivalent network with edges placed at random" (Newman, 2006, p. 8578).

The results showed that the multilateral environmental agreement network exhibits a modular structure consisting of a high modularity score of 0.75 (with a maximum of 1), which is comparable to the modularity of a co-authorship network of scientists working in condensed matter physics (0.72) (Newman, 2006). Newman's algorithm identified 20 modules within the giant component. A scan of agreements in each module revealed that they share similar subject matter or topic, confirming the presence of homophily (McPherson et al., 2001). Sizeable and clearly distinguishable modules include the marine environment, biodiversity, maritime safety and liability, watercourses, atmosphere, hazardous wastes, plant protection, and nuclear-related. The modular structure conformed to the conventional organization of law with its modules correlating highly with underlying legal semantics (UNEP, 2001a; von Moltke, 2005; Smith, 2007).

Furthermore, the high modularity score suggests the presence of sparse inter-module connections called 'weak' ties (Granovetter, 1973). These weak ties play an important role in global connectivity. For example, the network would still retain its macro-structure even if some of the 'strong' intra-module ties were removed, whereas removal of the same number of 'weak' inter-module ties may lead to a fragmentation of the entire network.

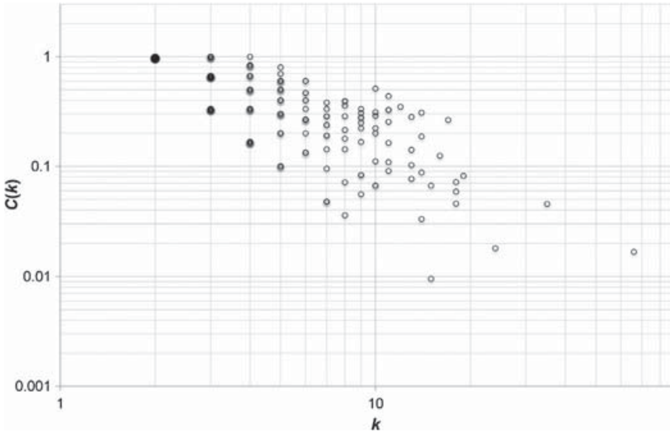

Fig. 5. $C(k) \sim k^{-1}$ in a double logarithmic plot showing the higher a node's degree (k), the smaller is its clustering coefficient, asymptotically following the $1/k$ law.

5.4. Nested hierarchy

Low-degree agreements tend to belong to highly cohesive neighbourhoods whereas higher-degree agreements tend to have neighbours that are less connected to each other (Fig. 5). Such an inverse correlation between degree and clustering coefficient, taken together with a heterogeneous degree distribution and modularity, suggest a hierarchically nested organization (Ravasz et al., 2002; see also Dorogovtsev and Mendes, 2002).

This hierarchical organization does not, however, refer to dominance and subservience but to the nested structure of separate but interrelated layers that expand exponentially in width. In other words, agreement modules are generally made up of smaller and more cohesive modules, which themselves are made up of smaller and more cohesive modules (Ravasz et al., 2002).

6. Interpreting the emergent complexity: from structure to function

What can we make of the measured structural features in terms of collective dynamics? Unfortunately, the relationship between governance system structure and function is not straightforward (Ruhl, 2008; see also Watts, 2004). This is particularly so as cross-references do not necessarily reflect the functionality of the connections between multilateral environmental agreements. Nonetheless, the observed structural patterns provide some insight into the nature of the emergent system and, hence, likely governance outcomes.

The multilateral environmental agreement network seems to have coevolved in relationship to its target, the Earth system, in ways similar to how road networks expand in response to traffic loads (Gross and Blasius, 2008). For example, when a new environmental issue escaped the scope of pre-existing institutions, a new agreement was negotiated and inserted into the network to fill the regulatory gap. Most of these new agreements used cross-references to connect to a small number of pre-existing agreements. Through that process, the network became structurally defragmented and a complex architecture emerged.

There were distinct moments when highly cited agreements were adopted, such as the year 1982 that witnessed the conclusion of the United Nations Convention on the Law of the Sea (Fig. 2(a)). Time-dependent analysis indicated that these years (e.g., 1982) were followed by other years (e.g., 1992) in which the initially favoured set of agreements fell out of favour to be replaced by a different one, such as the Rio Conventions. A similar pattern could probably be observed at the level of norms. New norms such as 'precaution' and 'common but differentiated responsibilities' have emerged as unifying principles through repeated use, while others have been less popular and withered on the vine.

This non-random process is similar in principle to natural selection. From the existing pool of norms, a subset comes to be selected for replication or enhancement through an autonomous process (Levin, 1998). This process, however, does not necessarily mean that the international environmental governance system has been able to adapt adequately to the constantly changing *biophysical* environment. Given the loose connection between science and policy, institutional responses might have been more strongly influenced and constrained by international politics (Axelrod, 2011). The structural analysis does not suffice to support the argument that the multilateral environmental agreement system as a whole has been coevolving with its external environment by inducing changes on itself and improving the 'fit' with the target biophysical systems or processes (Young, 2002; Folke et al., 2007; Galaz et al., 2008). Case studies at the level of regime complexes would be necessary (e.g., Raustiala and Victor, 2004; Keohane and Victor, 2011; Kim, 2012).

Nonetheless, the emergent network structure documented here exhibits several important topological properties of real-world systems, including those that are complex and adaptive. For example, the network has polycentric institutional arrangements, which may provide adaptive capacity and a balance between centralized and decentralized control (Ostrom, 1999a; Folke et al., 2005; Olsson et al., 2006). Multilateral environmental agreements vary to a significant degree in terms of subject matter, objectives, memberships, geographical scope, regulatory mechanisms, and underlying jurisprudence. Such institutional diversity may increase the capacity of international environmental law and governance as a control system to cope with uncertainty and complexity (Ashby, 1956; Low et al., 2003; Ostrom, 2005). The modular architecture is known to help accumulate 'local' knowledge and sustain 'local' mutualism, while simultaneously facilitating efficient 'global' cooperation through bridges between modules (e.g., Levin, 1999). The hierarchically nested structure tends to provide stability and flexibility at the same time, enabling both exploitation and exploration for enhanced adaptive capacity (Duit and Galaz, 2008; Duit et al., 2010; Ebbesson, 2010). These points identify plausible hypotheses about the impact of the network structure that could be tested in future research.

In particular, the small-world architecture may have dramatic implications for the collective dynamics of the multilateral environmental agreement system (e.g., Watts and Strogatz, 1998; Watts, 1999, 2004). Any response to environmental problems such as climate change requires that information about the external perturbation spread within the regulatory network. Thus, the short path lengths, which support rapid dissemination of information, are an imperative feature that may ensure fast and efficient reaction to global environmental change. Shortcuts provide alternative pathways and contribute to path redundancy that may enable the robust functioning of the system by relying less on individual pathways or mediators (Albert, 2005). Furthermore, archetypal small-worlds are known to have an enhanced ability to synchronize (Watts and Strogatz, 1998; Watts, 1999). This structure may be critical to explaining the current level of harmonization of international environmental law achieved through the horizontal expansion of norms and their inclusion in different multilateral environmental agreements (Kiss and Shelton, 2004; Long, 2010).

A real test for the adaptability of international environmental law has recently begun as the multilateral environmental agreement system has reached maturity with slow growth. However, the capacity of each agreement as an autonomous lawmaker and administrator is increasing (e.g., Churchill and Ulfstein, 2000; Brunnée, 2002; Wiersema, 2009). To the extent governance processes such as information sharing, learning, collaborating, and resolving conflicts are effective, multilateral environmental agreements may self-organize and function as a complex and adaptive, polycentric system (Galaz et al., 2012).

7. Conclusion

Conventionally, the architecture of international environmental law and governance has been characterized as fragmented (Biermann et al., 2009). Fragmentation has been a useful concept in many ways, such as highlighting that multilateral environmental agreements rarely cross issue-specific lines to address more cross-cutting questions (Carlarne, 2008). However, the presumptive notion of fragmentation may have led us to ignore systemic properties that emerge from institutional interconnections.

What this study revealed beyond a fragmented institutional landscape is a rather cohesive polycentric legal structure that forms the backbone of the international environmental governance system. If one focuses on texts as the outcome of treaty negotiations, the multilateral environmental agreement system has the architecture of a complex system that exhibits small-world and scale-free properties with a hierarchical and modular organization. International environmental law, in this sense, is neither a fragmented system nor a completely connected unity, but a complex network of norms and institutions.

The system of multilateral environmental agreements has evolved through different phases in time, and has become increasingly interconnected in complex ways. From an evolutionary perspective, multilateral environmental agreements were most disconnected in 1975. Since the mid-1970s, the institutional network has been structurally defragmenting. In 1992, a complex network structure dominated by the giant component emerged. During the rest of 1990s, the then-partial and uneven body of international environmental law underwent systematization. The emergent system matured throughout the 2000s with new agreements forming increasingly dense and redundant connections. Most recently, the growth of the system has almost halted.

Although the multilateral environmental agreement network has coevolved with the increasing complexity and interconnectivity of global environmental challenges, its institutional responses are not clearly coherent. Structural defragmentation does not necessarily mean that multiple treaty regimes are in a functionally "compatible and mutually reinforcing" relationship (Keohane and Victor, 2011, p. 16; see also Nilsson et al., 2012). What can be concluded, however, is that the observed network structure is suggestive of a complex and adaptive, polycentric system of law and governance.

This study has demonstrated the need to understand the emerging complexity by viewing multilateral environmental agreements as a dynamic network system. It suggests caution in naïvely dismissing international environmental law as 'fragmented'. Such a dismissal may reflect our inability to comprehend and embrace complexity in both the subject matter and the legal system itself. Rather than trying to reduce complexity through centralized control, the system structure is consistent with Kanie's claim (2007, p. 82) that the "strengths of the [multilateral environmental agreement] system [are] mostly the same as the very strengths of a decentralized system" and that "[multilateral environmental agreements] should be placed in . . . a decentralized and densely networked system" (see also Haas, 2004). Therefore, any reform options for global environmental governance should pay attention to the emergent polycentric order and complexity and what these features imply for the function of the multilateral environmental agreement system.

In terms of methodology, this study has demonstrated the value of a network approach to gaining system-level insights into the structure and dynamics of international environmental law and governance. There is considerable scope for additional research in this direction. The network analysis would greatly benefit from enriching the citation dataset with treaty membership data. Future research could also link the institutional network to a network map of global social-ecological systems (e.g., Janssen et al., 2006; Ekstrom and Young, 2009; Ernstson et al., 2010; Stein et al., 2011; Rathwell and Peterson, 2012). This would allow the design of a three-layer representation of the biophysical systems, international environmental law, and broader governance systems. The findings could be used as a basis for improving their alignment.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2013.07.006.

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