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# What does network analysis teach us about international environmental cooperation?

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ABSTRACT

This paper uses network analysis to study the structural properties of international environmental cooperation. We investigate four pertinent hypotheses. First, we quantify how the growing popularity of environmental treaties since the early 1970s has led to the emergence of an environmental collaboration network and document how collaboration is accelerating. Second, we show how over time the network has become denser and more cohesive, and distances between countries have become shorter, facilitating more effective policy coordination and knowledge diffusion. Third, we find that the network, while global, has a noticeable European imprint: initially, the United Kingdom and more recently France and Germany have been the most important players to broker environmental cooperation. Fourth, international environmental coordination started with fisheries and the sea but is now most intense on waste and hazardous substances. The network of air and atmosphere treaties has distinctive topological features, lacks the hierarchical organization of other networks, and is the network most significantly shaped by UN-sponsored treaties.

## 1. Introduction

Many urgent environmental dilemmas require international collaboration. Sometimes cooperation involves a relatively limited number of parties (e.g., to manage a shared water body), sometimes it requires broad coalitions of many nations (e.g., to address global threats like climate change).

Understanding how environmental coalitions have emerged and expanded is therefore an important question in international cooperation and global governance research. The literature has tackled the problem both theoretically and empirically, using among others the tools of game theory (e.g. Barrett, 2003, 2007; de Zeeuw, 2015; Harstad, 2016; Battaglini and Harstad, 2016; O'Neill, 2017), international relations (e.g., Falkner, 2013b; Mitchell, 2002) and experimental economics (e.g., Milinski et al., 2006, 2008; Tavoni et al., 2011; Barrett and Dannenberg, 2012).

The subject of interest in these studies is typically a particular international environmental agreement (IEA). Researchers are interested in the political, game theoretic or behavioral dynamics that explain the emergence, design or effectiveness of a treaty (e.g., Barrett, 1994; Young, 1999; Breitmeier et al., 2011).

What tends to be overlooked by studies concerned with individual treaties is that, as a collective, IEAs have given rise to a dense network of environmental cooperation. Recent decades have witnessed a significant increase in the number of IEAs, reaching a total of almost 2000 in 2015. The number of signatories has increased from 6 in 1869 (when there were fewer sovereign nations) to 238 in 2015, including not just nation-states, but also international organizations, dependent territories, and sub-national entities.

The breadth and depth of environmental cooperation through IEAs have been documented in information sources such as ECOLEX (IUCN, FAO, UNEP, 2017) and the International Environmental Agreements Data Base (Mitchell, 2003; Mitchell et al., 2020). The main interest of such databases is often the classification and categorisation of different

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treaty types.

Here, we are interested in the network of cooperation these treaties create. While every environmental agreement has its own particular objectives, the ability to manage global environmental threats successfully depends on the synergies between multiple treaties and the resulting interaction between signatories. The effectiveness of cooperative ties between countries is affected not only by the countries' individual attributes (Mitchell, 2002), but also by the structure of the network connecting them (Kinne, 2013).

The structure of a network provides insights into its functioning as a system of interacting components (Jackson, 2010). Many important mechanisms that determine the likelihood of cooperation, such as shared interests, reputation, and the pursuit of common goals through the mitigation of self-interest (Dai et al., 2010; Hafner-Burton et al., 2009), are typically associated with common third-party ties. Further, agents in a certain position of a cooperation network may play an important role in maintaining its stability (Lozano et al., 2008), while also possibly benefiting from their particular position (Li and Schurhoff, 2019). As such, the network not only reflects existing cooperative relationships, but also influences the costs and benefits of future cooperative attempts (Kinne, 2013).

We apply theories and methods of network analysis to ECOLEX, one of the largest collections of data on IEAs, to better understand the structure and dynamics of global environmental cooperation. In this context, IEAs are treated as a reflection of cooperative relationships and the intensity of cooperation across countries.

We use network metrics to elucidate, with new quantitative evidence, some long-standing debates in the economics and political science of international environmental cooperation, and offer topological corroboration for several conjectures supported so far mostly by qualitative or preliminary correlational evidence.

Specifically, we create an inter-temporal environmental cooperation network, where each node is a country that has signed IEAs and each link connecting any two nodes reflects the number of treaties the two corresponding countries have co-signed. Our data cover 546 environmental treaties agreed between 1948 and 2015. Each co-signed treaty is generally assigned the same weight, but we also introduce new ways to reflect the differing importance of treaties. Crucially, the global structure of the cooperation network is assessed against a properly constructed null model, which allows us to filter out connections that would be established simply by random expectation.

We derive four pertinent hypotheses from the IEA literature and test them using topological metrics that describe the structural landscape and evolution of international environmental cooperation.

The first hypothesis concerns the emergence and evolution of international environmental cooperation. We find that a statistically significant environmental cooperation network began to materialize in 1971 and reached stability in 1980. Before then, treaty links were too weak. Since then the network has grown steadily in size and strength, resulting in higher connectivity between signatory countries. Indeed, cooperation is accelerating: Treaty membership is associated with the faster ratification of subsequent IEAs. These results hold even when we introduce "retiring" treaties with low levels of ongoing activity, and when we differentiate treaties by their importance. As such, our data support earlier findings on the pivotal role played by events like the 1972 UN Conference on the Human Environment in Stockholm, as posited in Falkner and Buzan (2019).

The second hypothesis concerns the ability of IEAs to foster policy cooperation. The literature sees IEAs as vehicles for engagement, which provide organisational structures, sustain a shared purpose, and engender trust (e.g., Meyer et al., 1997; Ostrom, 2009; Bernauer et al., 2010; Carattini et al., 2019). Our analysis quantifies how, through membership interconnections, environmental cooperation has become denser and more cohesive. The paths through which countries can reach each other have shortened, creating more effective platforms for policy coordination and knowledge diffusion. Again, these results hold when accounting for activity levels and the importance of treaties.

The third hypothesis concerns environmental leadership and its implication for network acceleration. We find that the environmental cooperation network, while global, has a noticeable European imprint. Initially, the United Kingdom and, more recently, France and Germany have been the most important network nodes, through which IEAs have been facilitated. They occupy these positions in their own right, rather than through membership of the European Union, which is itself a party to many IEAs. These findings support the view of international relations scholars such as Vogler and Stephan (2007) and Kelemen and Vogel (2010) who discuss the leadership role of European countries in (domestic and international) environmental issues. We further show that more central network positions are associated with an increased appetite for future cooperation, with central countries more ready to ratify new IEAs.

The fourth hypothesis concerns differences in international environmental cooperation by subject area. We find that international environmental coordination started with the management of fisheries and the sea, but is now most intense on waste and hazardous substances. The networks on species, waste and natural resources have a hierarchical structure, which is absent in the networks on sea and fisheries and air and atmosphere. Despite its policy salience, the network of air and atmosphere treaties is comparatively less cohesive and intense. It is also the subject area where treaties negotiated under the auspices of the United Nations (such as those on climate change and trans-boundary air pollution) have most impact on the topological properties of the network. The results speak to the "regime complexity" of global climate governance (Meyer et al., 1997; Keohane and Victor, 2011), and might explain the ambivalence toward the UN in much of the environmental governance literature (Biermann and Bauer, 2004; Ivanova, 2010; Mee, 2005).

Our paper is part of the wider theoretical and conceptual literature in economics and political science on environmental governance and international environmental cooperation. Methodologically, it relates most closely to a strand of empirical literature at the crossroad of economics and political science, which leverages large data sets on IEAs, such as the one we use, to identify empirical patterns of environmental cooperation.

Four studies, which our paper complements, are worth highlighting. Kim (2013) examines a network of IEAs linked through citations and finds an international environmental governance system that is characterized by a cohesive polycentric legal structure. Hollway and Koskinen (2016) apply network analysis to the governance of global fisheries, using and identifying a high degree of social embeddedness in the system. Wagner (2016) uses a structural model of international negotiations to estimate the date when countries ratified the Montreal Protocol as well as the dynamics of trade agreements. Mitchell et al. (2020) discuss the potential, without yet exploiting it, of the International Environmental Agreements Data Base, a similar database to ECOLEX, to better understand the formation of IEAs.

Finally, our paper is also inspired by related literature, which applies network analysis to wider international relations contexts, including trade, financial integration, and technology diffusion (e.g. Smith and White, 1992; Kim and Shin, 2002; Fagiolo et al., 2010; Schiavo et al., 2010; Vega and Mandel, 2018; Htwe et al., 2020; Hafner-Burton et al., 2009).

The remainder of the paper is organized as follows. Section 2 describes the data, the construction of the environmental cooperation network and motivates the subsequent analysis with a set of descriptive statistics. The main results are contained in Sections 3 to 6, each of which studies a different aspect of international environmental cooperation. Section 7 concludes.

## 2. Data and methodology

### 2.1. Environmental treaty data

We use global data on IEAs from ECOLEX (IUCN, FAO, UNEP, 2017), which combines information on environmental laws and treaties from several sources. As in Mitchell (2003), the treaties included in the ECOLEX database are defined as *intergovernmental documents intended as legally binding with a primary stated purpose of preventing or managing human impacts on natural resources.*[1] Our sample comprises 546 environmental treaties signed by 200 countries over the period 1948-2015. Additional details about the sample are provided in Appendix B.

IEAs cover practically all aspects of regional or global environmental concerns (Fig. 1).

In this study, we are interested in the network as a whole, although for some calculations we group IEAs into six categories: sea and fisheries, wild species and ecosystems, waste and hazardous substances, natural resources (e.g., water, cultivated plants, environment genes, food, forestry, land and soil, livestock, and mineral resources), air and atmosphere (e.g., air pollution, ozone layer depletion and climate change), and energy.

There is considerable overlap, with many treaties covering more than one subject area. For example, a large number of treaties on the seas also concern issues of waste (57 treaties), fisheries (38 treaties) or wild species and ecosystems (17 treaties). Independent of the scope, each treaty enters the network only once. However, treaties may be assigned to more than one subject area for the construction of subject-specific networks.

To understand the systemic properties of these treaties, we now turn to network analysis.

### 2.2. Network construction and analysis

The data were initially organized as a country-treaty-year panel, which lists for each country the IEAs it was a member of at the end of each year, and/or for each treaty its signatories at the end of each year. The country-treaty-year data are converted into a sequence of annual environmental cooperation networks in three steps (Appendix C provides additional details about the methodology).[2]

The first step is the construction of annual bipartite networks (Latapy et al., 2008). These are two-mode networks where a link is established between a country and a treaty, if the former has signed the latter, as shown in the left-hand panel of Fig. 2.

In the second step, we convert the bipartite networks into one-mode projections to study cooperation networks among countries. The intuition here is that co-participation can be seen as a sign of a social tie (Borgatti and Halgin, 2011). That is, a cooperative tie between two countries is defined as co-participation in the same treaty. A link is established between any two countries if they have signed at least one common treaty, as shown in the right-hand panel of Fig. 2.

We compute cooperation intensity primarily by considering the number of treaties and their size. Specifically, we quantify the intensity of cooperation between countries by assigning a weight to each link, which is proportional to the number of treaties two countries have co-signed and inversely proportional to the number of signatory countries involved in each common treaty (Newman, 2001b). The intuition here is that two countries which co-sign a treaty together with many other countries have a less extensive cooperation relationship on average than two countries which are the sole signatories of a treaty. This implies that, all else being equal, bilateral treaties contribute more to the intensity of cooperation between two countries than multilateral treaties. In some specifications, we introduce weights that reflect the differing importance of treaties, using media mentions and cross citations between treaties as measures of importance.

The final step concerns statistical validation, that is, the identification of statistically significant links through comparison with an appropriate null model.[3] We adopt the grand canonical algorithm proposed by Saracco et al. (2017), which can be used to obtain a statistically-validated projection of any binary, undirected, bipartite network. The intuition behind this step is that any two countries should be connected if, and only if, they co-signed a significantly larger number of treaties than randomly expected in a corresponding bipartite network with the same number of countries and treaties.

We then use global network metrics to describe the topological structure of the resulting environmental cooperation network. Our chosen metrics include measures of network size (cumulative frequency of nodes and links), connectivity (average degree, average strength), and social cohesion (density, shortest path length, number of components, and clustering coefficient). In addition, the roles of individual countries in the cooperation network are investigated through centrality measures, such as betweenness centrality and closeness centrality. Appendix C provides additional details about the definitions. Further intuitive explanations of the metrics are provided in Table 1.

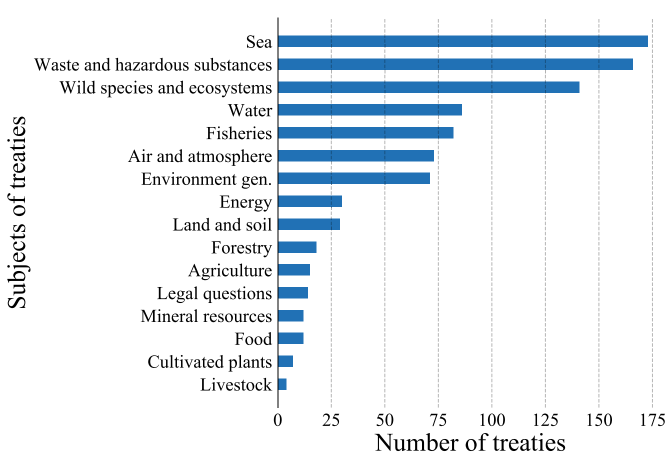



**Fig. 1.** Cumulative frequency of treaties for different subjects in 2015.

## 3. The extent of cooperation

### 3.1. Overview

We first explore what the growth in IEAs means for the emergence and evolution of an environmental collaboration network. The 1972 UN

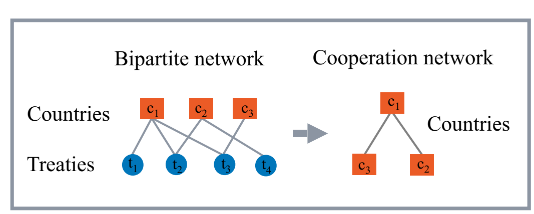



**Fig. 2.** Network construction.

[1] The official definition for international treaties originates from the Vienna Convention on The Law of Treaties (1969). The definition used here has been adapted to treaties on environmental matters.

[2] The Python codes used in this study can be found at https://github.com/jiaoyang2018/Cooperation-network-based-on-IEAs.

[3] The Python codes used for statistical validation can be obtained from https://github.com/tsakim/bipcm.

**Table 1**
Definitions of network metrics.

| Measure | Definition |
|---|---|
| Cumulative frequency of nodes and links | The size of a network can be measured through the number of nodes and links it contains. In a dynamic setting the growth in network size can be measured through cumulative distributions of nodes and links over time. |
| Degree and strength | The degree $k$ of a node is the number of links connected to it. In weighted networks, the metric of node degree is complemented by node strength, $s$, which is the sum of the weights of the links incident upon the node (Barrat et al., 2004). In our cooperation network, the degree of a country indicates the number of partners which this country cooperates with, while the strength accounts for the intensity of cooperation between this country and others. |
| Density | The density of a network is the ratio between the actual number of links m and the maximum possible number of links, i.e., $\binom{n}{2} = \frac{1}{2}n(n-1)$ where n is the number of nodes in the network. Density ranges from 0, when no link is established, to 1, when all possible links have been established. |
| Shortest path length | For a binary network, the shortest path length $d_{ij}$ between node $i$ and node $j$ is the length of the path with the lowest number of links separating the two nodes (Newman, 2018). The weighted shortest path length between any two nodes is the path with the least resistance in terms of exchange costs. However, in our study the weights of links do not represent the cost, but the intensity of cooperation between countries, and therefore we use the reciprocal of weights to identify weighted shorted paths using Dijkstra's algorithm (Brandes, 2001; Newman, 2001b). |
| Components | A component is the largest subset of nodes in a network in which there exists at least one path between any pair of such nodes. The components in a network organize the network into different isolated subgraphs, and the number of components in a network can therefore be used to assess fragmentation and isolation of nodes. |
| Global clustering coefficient | The global clustering coefficient measures the fraction of closed triplets over the total number of open and closed triplets, that is, the degree to which triplets in a network close up into triangles (Opsahl and Panzarasa, 2009; Newman, 2018). A triplet can be defined as three nodes connected by either two (open triplet) or three (closed triplet) links. |
| Local clustering coefficient | The local clustering coefficient quantifies the tendency of a node's neighbors to be connected with each other. For the weighted version, we first use the method proposed by Onnela et al. (2005). This method is based on a node's subgraph intensity, defined as the geometric average of the weights of the links forming all closed triplets centred on the node, where each weight is normalized by the maximum weight globally found in the network. In addition, an alternative method proposed by Barrat et al. (2004) is investigated, according to which the contribution of each closed triplet centred on a node depends on the ratio of the average weight of the two links incident on the node to the average strength of the node (i.e., the node's strength divided by the node's degree). |
| Betweenness centrality | Betweenness centrality measures the degree to which one node lies on the shortest paths between others (Freeman, 1977). In other words, betweenness centrality quantifies the extent to which a node presides over indirect connections between all other nodes in a network (Burt, 2000). |
| Closeness centrality | The closeness centrality of a node is defined as the inverse of the average shortest path length from the node to all other reachable nodes. In social networks, higher closeness centrality, i.e., shorter average distance from other nodes, implies quicker communication at a lower cost (Freeman, 1978). |

Conference on the Human Environment in Stockholm has been described as the beginning of a systematic and potentially universal approach to international environmental policy-making (Falkner and Buzan, 2019). In the ensuing half-century global environmental cooperation has become all but ubiquitous (Mitchell, 2003). Intuitively, one would expect this proliferation of treaties to result in deeper and more intensive environmental cooperation.

The prominence of treaties negotiated under the auspices of the United Nations and UN agencies suggests that the UN played an important role in encouraging this trend. The suite of treaties agreed at the 1992 "Earth Summit" in Rio de Janeiro, in particular, have come to define global environmental cooperation in areas such as biodiversity (Convention on Biodiversity), climate change (UN Framework Convention on Climate Change), and desertification (Convention on Desertification). However, the literature is equivocal about the coordinating and catalytic role played by the UN, pointing out institutional shortcomings and arguing for a stronger anchoring body in global environmental governance (Biermann and Bauer, 2004; Ivanova, 2010; Mee, 2005).

These observations give rise to the following **hypothesis:** *Over the past 50 years, global environmental cooperation has become pervasive, covering virtually all countries. Indeed cooperation is accelerating. This trend has been aided by the UN and its agencies, but the UN is not the dominant platform for environmental cooperation.*

We test the hypothesis using metrics concerned with network size and connectivity. A straightforward way to measure the size of the environmental cooperation network is the number of nodes (countries) and links (through treaties) it contains, and more specifically the cumulative frequency of nodes and links over time. We use two metrics to measure the connectivity of the network, i.e., the average degree and the average strength. The average degree considers the number of partners with which each country cooperates, while the average strength describes the intensity of cooperation of a country with others (Barrat et al., 2004). We use the speed of treaty ratification as our measure of network acceleration.

We find that since the early 1970s countries have been integrated into a network of increasingly intensive environmental cooperation. The growing intensity of global environmental cooperation is reflected in the size of the network, which includes virtually all countries of the world, and a high level of connectivity (high average degree and node strength) between countries. We note that countries do occasionally withdraw from treaties, which weakens the network, but this is relatively rare. Treaty membership is associated with the faster ratification of subsequent IEAs, which suggests network acceleration.

The UN has been an important platform for, but not the main contributor to, the connectedness of the environmental cooperation network. Network properties remain similar with and without the inclusion of UN-sponsored treaties.

The results are robust to alternative calculations that factor in the level of activity under a treaty (by"retiring" dormant treaties) and the relative importance of treaties (as measured by the number of media mentions and citations in other agreements). The results of these extensions are reported in Appendix D.

### 3.2. Network size

A first important observation when assessing the size of the environmental cooperation network is that a statistically significant network only appeared in 1971. From 1948 to 1970, the number of common treaties between any two countries is not significantly different from the number that would be obtained simply by chance, given the involvement of the two countries in the various treaties. That is, before 1970 no pair of countries managed to co-sign a larger number of treaties than would be randomly expected, thus preventing the emergence of statistically significant cooperation links.

However, since 1971 the cumulative frequency of network nodes and network links has grown steadily, both in absolute terms and relative to the number of nation states, which has also grown, as shown in Fig. 3. In the early 1970s many of the newly independent countries in the Global South began to engage with international environmental treaties. The cooperation network became stable in the year 1980, when the growth rate in the number of nodes (countries) fell below 5%. These patterns are consistent with the views of international relations scholars like Falkner and Buzan (2019), who also date the beginning of international environmental cooperation to the 1970s.

The most rapid growth in network links occurred in the 1990s. During this period, 153 new treaties promoted cooperative ties among 192 countries. The growth in links levelled off around the year 2000, when the cumulative frequency of links almost reached the maximum possible.

We next investigate the role of the UN and its agencies[4] as a platform for international environmental cooperation. We do this by filtering out treaties negotiated under the auspices of the UN or a UN agency and reconstructing the network without them. The result suggests that the UN has had a notable impact on the network structure, particularly through its agencies, but it is not the dominant platform of international cooperation, as shown in Fig. 3a. The majority of countries remain engaged, even with the simulated removal of the UN treaties. The number of statistically significant cooperative links decreases without UN treaties but remains substantial.

### 3.3. Connectivity

Over the period of interest, both the average degree and the average strength in the cooperation networks have increased greatly (panel a of Figs. 4 and 5). The growth in connectivity was particularly pronounced in the 1990s. During this period the degree distribution and strength distribution both widened (panel b), suggesting that the growth in connectivity was initially driven by a vanguard of particularly active countries that forged ahead. By 2015, the degree distribution had narrowed again as the laggards caught up and the average number of partner countries reached a maximum. However, the strength distribution continues to be wide. The cooperation network had reached a point in which connectivity did not depend on the average number of partners but was constantly reinforced by the average intensity of cooperation among countries.

We again study the impact of the UN on this pattern by recalculating the metrics for a cooperation network without UN-sponsored treaties. The average degree of the network decreases notably in particular when treaties supported by UN agencies are excluded (Fig. 4, panel a). The exclusion of UN-sponsored treaties also reduces the number of common treaties between countries and consequently the average strength in the network. The effect is particularly pronounced in the second half of the study period (Fig. 5, panel a).

### 3.4. Network acceleration

Past participation in IEAs may create more opportunities for future collaboration and increase a country's readiness to join new treaties when they become available. We explore this possibility by running a simple OLS regression[5] where we regress the speed at which a country joins new IEAs on the extent of past treaty memberships. The regressions include a full set of fixed effects to control for unobserved characteristics at the country, time and treaty levels, that might influence the speed of ratification of a new IEA. We then investigate whether the speed of ratification is associated with memberships in treaties of a certain type, such as UN-sponsored treaties or important treaties with high media mentions or cross-citations.

The full results are reported in Appendix D.3. They suggest that past treaty membership is indeed associated with quicker participation in subsequent IEAs, with salient and UN-sponsored treaties playing a prominent role. We interpret this as a sign of network acceleration.

## 4. The ease of collaboration

### 4.1. Overview

We next study what the proliferation of IEAs implies for the ability of countries to cooperate and the effectiveness with which knowledge and policy are diffused.

IEAs are both the result of environmental cooperation and a facilitator of such cooperation (Bernstein and Cashore, 2012). The shared objectives and agreed actions from environmental cooperation are frequently codified in an IEA, but the IEA then creates the basis for further cooperation by establishing relationships, providing platforms for engagement and setting up organisational structures to share the benefits of cooperation (e.g., Meyer et al., 1997; Bernauer et al., 2010; Sauquet, 2014; Keohane, 1984). Cooperation through IEAs also creates trust, which is key for dealing with both local and transnational environmental issues (Owen and Videras, 2008; Ostrom, 2009; Carattini et al., 2015, 2019; Carattini and Loschel, 2021).

The environmental cooperation network further serves as an information network (Lazer, 2005), where easier information flows can facilitate both learning and imitation (or conditional cooperation). Both are crucial for policy diffusion in the context of transnational and global public goods. Several studies have shown that a shorter distance between nodes leads to faster diffusion of information (Cheng et al., 2014; Goel et al., 2016; Zhang et al., 2016; Newman, 2018). As such IEAs may be an important driver of policy convergence (Busch et al., 2005; Holzinger et al., 2008).

These observations lead to the following **hypothesis:** *The network of IEAs has promoted environmental cooperation, knowledge exchange and information diffusion by shortening the distance between countries and facilitating the emergence of tightly-knit communities and third-party relationships.*

We assess the facilitating functions of IEAs by studying the global and local cohesion of the environmental cooperation network. For the analysis of global cohesion, we refer to the concepts of components, network density, average shortest path length, and global and local clustering coefficients.

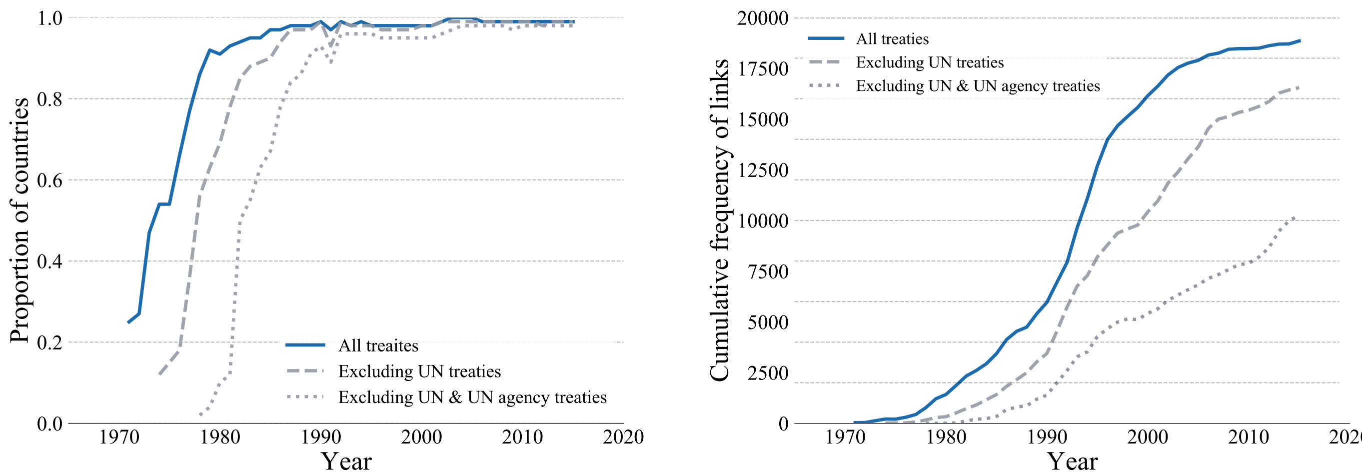
The number of components in a network can be used to gauge the degree of global cohesion across the network, i.e., a network with more components is less cohesive and more fragmented than a network with fewer components. The network density measures the portion of the potential cooperative connections that are actual connections based on co-signing of treaties.

The weighted shortest path between any two nodes is the path with the least resistance between them in terms of costs of communication, coordination and exchange (Brandes, 2001; Newman, 2001b; Newman, 2018). Thus, the average weighted shortest distance describes the ease and cost of cooperation between countries as a result of their structural positions. All else being equal, a network with a small number of components, a high density and a small average shortest distance has a high level of global cohesion and low fragmentation.

It has been suggested that clustering fosters a sense of belonging to a shared group (Portes and Sensenbrenner, 1993), mutual trust, the enforcement of social norms, and the exchange of complex and

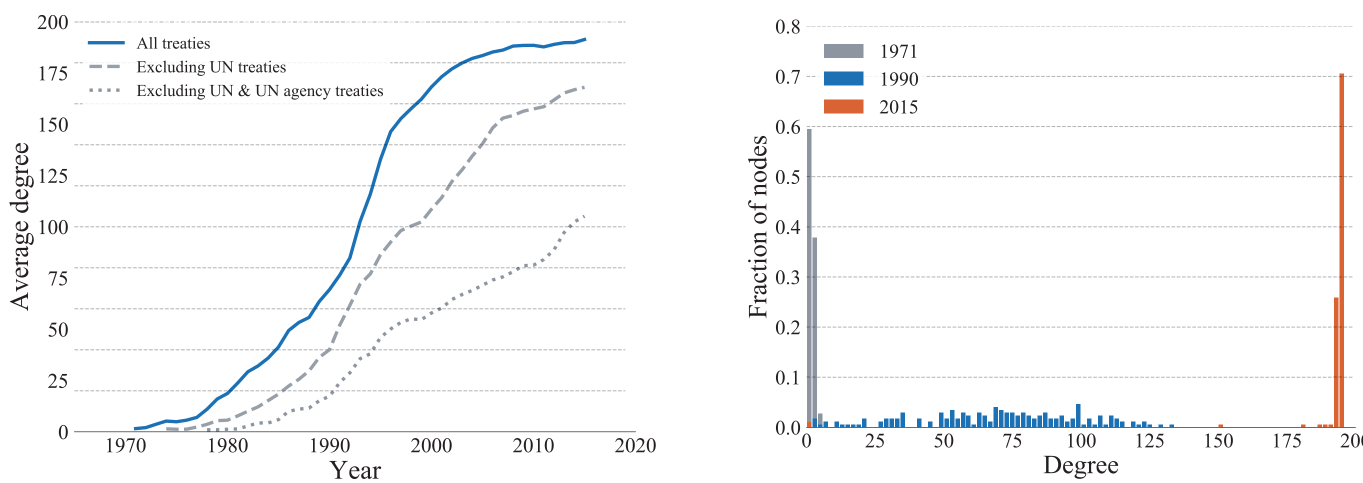
[4] The UN agencies investigated here include, based on the data provided by ECOLEX, Food and Agriculture Organization of the UN (FAO), International Maritime Organization (IMO), International Labour Organization (ILO), United Nations Educational, Scientific and Cultural Organization (UNESCO), United Nations Environment Programme (UNEP).

[5] Despite being in the spirit of some of the empirical methods for networks as discussed in, e.g., Chandrasekhar (2016) and De Paula (2020), this exercise does not consider the process of network formation nor represents a comprehensive analysis of the drivers of speed of ratification. Therefore, results can only be interpreted as suggestive.




(a) Cumulative frequency of nodes (b) Cumulative frequency of links

**Fig. 3.** Cumulative frequency of nodes and links in country networks from 1971 to 2015.




(a) Average degree (b) Degree distribution

**Fig. 4.** Average degree and degree distribution from 1971 to 2015.

proprietary information, which in turn facilitates coordination, cooperation, and collective action (Coleman, 1988). Clustering captures social cohesion both at the global and local levels. The global clustering coefficient detects the degree to which connected triads tend to close up into triangles across the network (Opsahl and Panzarasa, 2009; Newman, 2018). The local clustering coefficient captures the tendency of a node's neighbors to become connected themselves (see Barrat et al., 2004; Onnela et al., 2005; Saramaki et al., 2007, for details on the comparison of different methods). Both measures can be used to uncover closed structures as sources of social capital and in particular the tendency of collaboration to originate from tightly-knit communities (global level) and third-party relationships (local level).

Our analysis shows that, over the past decades, the network of environmental cooperation has become denser, more cohesive, and has produced shorter distances between countries. Countries have become gradually less isolated when dealing with environmental problems. The network ended up consisting of just one component that connects all countries. The combination of high cohesion at both the global and local levels (high density, short path lengths and high clustering) creates a system that can be conducive to policy coordination and the diffusion and exchange of knowledge.

It is worth emphasizing that our results on cohesiveness do not speak to the ambition of treaties, which we do not observe directly. To explore this aspect at least indirectly, we again turn to our alternative specifications that factor in activity levels and treaty importance, as introduced in Section 3 and Appendix D. The hypothesis is that active treaties which continue to attract signatories are particularly good platforms of collaboration, and that significant treaties, which are cross-referenced or enjoy media attention, are especially powerful in facilitating cooperation and knowledge exchange. However, when recalculating our metrics to account for these treaty features, we find that the results are not sensitive to their presence. The ease of international environmental cooperation does not seem to be driven by particularly active or important treaties (see Appendix E for details).

### 4.2. Cohesion

In the early 1970s, when statistically significant environmental cooperation links began to emerge, the network consisted of just 37 countries which formed as many as 12 components. Practically all of the

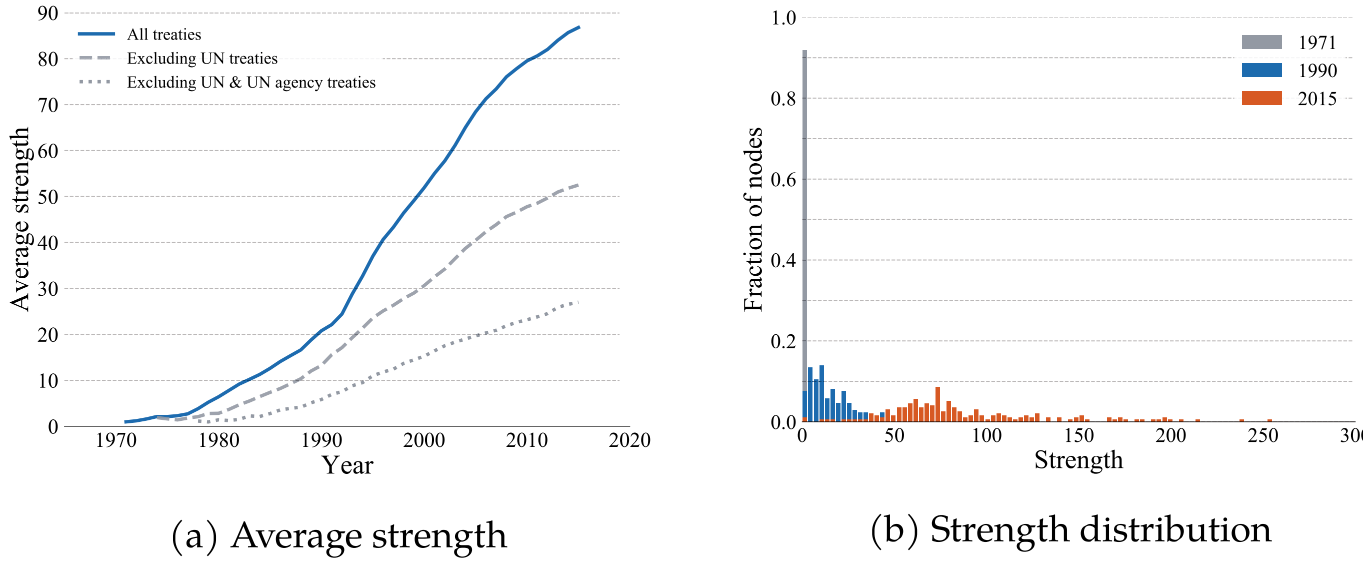



**Fig. 5.** Average strength and strength distribution from 1971 to 2015.

components were regional groups (for example, there was a component of Middle-Eastern countries) and many were bilateral, consisting of just two nodes. The network was small and fragmented.

By the early 1980s, the cooperation network had grown to 157 countries which were integrated into a single component. New components formed in the late 1980s and early 1990s as the countries of Eastern Europe and the former Soviet Union started to engage in environmental cooperation. For example, in 1991, newly-independent Armenia, Azerbaijan, Georgia, Kazakhstan, Tajikistan, Latvia, and Uzbekistan joined the cooperation network as a separate component.

They were absorbed into the largest component in the following year, when the network coalesced again into a single global component. Since 1992 every pair of countries (except Taiwan and later Hong Kong) has been able to reach each other through direct or indirect treaty-based connections.

The density of the cooperation network grew at a similar pace, increasing rapidly through the 1980s and 1990s. At the start of this century nearly every pair of countries had established a significant cooperation relationship (Fig. 6, panel a).

The average weighted shortest distance of the network stayed at a high level in the 1970s, reflecting the growing size of the largest network component, but has fallen steadily since (Fig. 6, panel b). The size of the largest network component remained stable throughout this period, encompassing some 95% of nodes. At the same time new connections appeared and existing connections were strengthened through new treaties, which in turn fostered a reduction in average distances.

These results corroborate the view that the fall of the Soviet Union and the end of the Cold War in the early 1990s created the opportunity for new alliances, encouraging international cooperation and policy diffusion to occur outside the two hegemonic blocs (Yamagata et al., 2017).

The exclusion of UN and UN agency-sponsored treaties leads to a smaller density and a larger average weighted shortest distance, as shown in Fig. 6. Around 1980, the exclusion of UN-sponsored treaties leads to more components and a smaller fraction of countries belonging to the largest component, which results in a lower average shortest distance. However, even without the UN-sponsored treaties, the whole network remains connected from around 1990 to 2015.

Thus, the UN and its agencies have contributed to reducing the distance between countries and provided a framework for inter-state cooperation (in line with Meyer et al., 1997). As noted before, the UN agencies play a more important role in this process than the UN itself.

### 4.3. *Clustering*

The evolution of the global clustering coefficient of the network is shown in Fig. 7. Following a short blip in the 1970s, the clustering coefficient has grown rapidly and steadily through the 1980s and 1990s before levelling off at the beginning of this century. As such, the trend is comparable to that observed for the network size and connectivity metrics. It suggests that, as the cooperation network expanded and new links were created, third-party relationships (i.e., links between countries sharing partners) were formed simultaneously and at the same rate.

Many factors can promote the presence of common partners, such as geographic proximity, affiliation with related regional groups or organizations, a similar economic status, a shared history and trading relationships (Fagiolo et al., 2010; Sauquet, 2014). The presence of common partners is likely to have promoted trust and helped countries establish deeper relationships. As we have observed with other network metrics, the overall trend of the global clustering coefficient changes significantly when both the UN and UN agencies' treaties are removed.

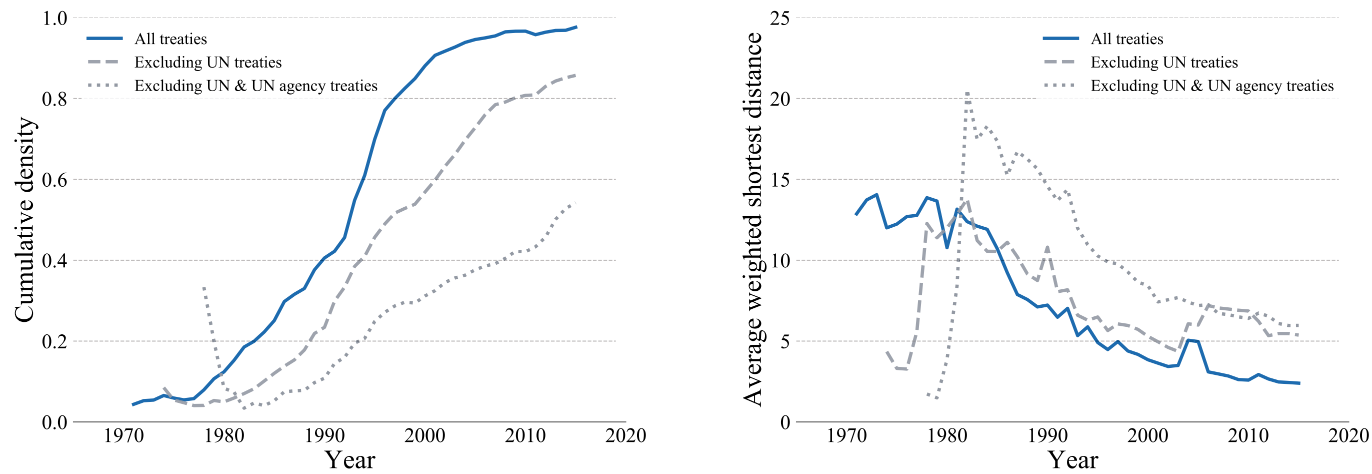
## 5. The role of individual countries

### 5.1. *Overview*

We now turn to the positions of individual countries in the cooperation network. The roles and motivations of different countries are an important subject in the international relations literature, covering angles such as the influence of hegemons (Yamagata et al., 2017) and the changing role of players like the United States (Falkner, 2005; Kelemen and Vogel, 2010) and Europe (Falkner, 2007; Kelemen, 2010; Vogler and Stephan, 2007). A widely held view is that the United States has not played the same dominant role in environmental cooperation as it has in other areas. Instead, international environmental leadership has been provided by the countries of Europe.

We express this observation through the following **hypothesis:** *The major European countries, and not the US, have persistently been the most important players in the environmental cooperation network. Their prominent position has in turn made it easier for European countries to engage in further environmental cooperation.*

To measure the role of individual countries in the network we use the centrality metrics of node strength, betweenness centrality and closeness centrality. To assess the impact of central network positions on further environmental cooperation, we correlate centrality measures with the speed of subsequent treaty ratifications.




(a) Cumulative density    (b) Average weighted shortest distance

**Fig. 6.** Cumulative density and the average weighted shortest distance from 1971 to 2015.

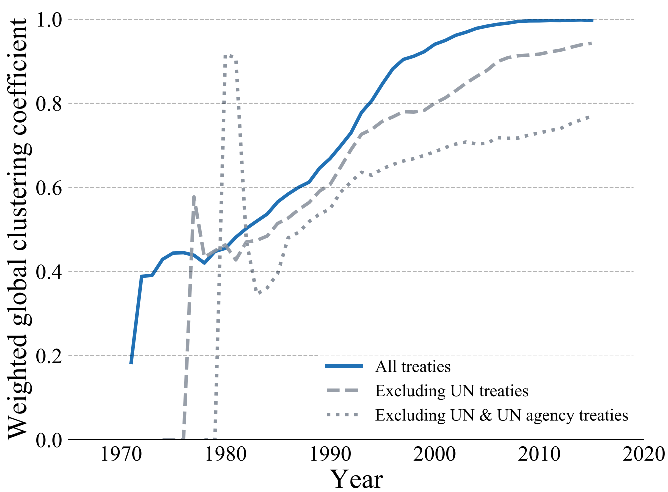



**Fig. 7.** Global clustering coefficient from 1971 to 2015.

Node strength accounts for the intensity of cooperation of a country with others, while betweenness centrality measures the ability of a country to intermediate between others. In other words, betweenness centrality is an indicator of the importance of nodes in participating in networks and influencing the flow of critical resources, such as the spread of information and opportunities across various regions of a social system (Freeman, 1978). Closeness centrality measures the distance of a focal country to the other countries in the network. Higher closeness centrality, i.e., shorter average distance from other nodes, implies quicker communication at a lower cost (Freeman, 1978), and consequently lower potential cost for further cooperation, based on existing treaty connections.

The analysis confirms that the network of environmental cooperation, while fundamentally global, has a noticeable European imprint. In terms of cooperation intensity, betweenness and closeness centrality, the network is heavily influenced by European countries, in particular the United Kingdom and more recently France and Germany. European countries hold these positions in their own right, rather than as members of the European Union.

The position of countries has remained relatively stable over time, although there are important fluctuations. This is in part driven by the fact that a central network position is associated with an increased openness toward further environmental cooperation.

### 5.2. *Centrality*

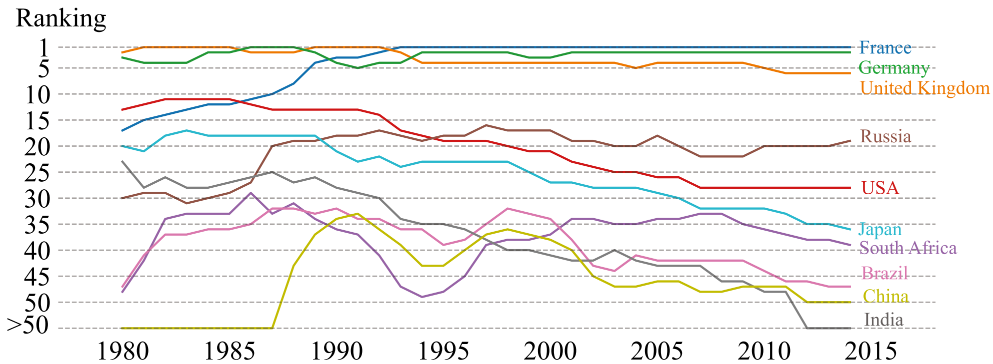
We find strong path dependence in the important role of individual countries in the cooperation network. The countries that topped the centrality rankings at the outset were broadly able to maintain their important positions. This stability is in contrast to other networks, where the centrality of individual nodes is often highly sensitive to changes in the network structure (in our case, the signing of new treaties).

We assess the stability of countries' network position over time by looking at the Kendall-Tau correlation coefficients of country rankings for different centrality measures. The Kendall-Tau coefficient measures the rank correlation for each centrality measure between time $t$ and time $t_{+1}$. The starting point of the analysis is the year 1980, when the number of countries in the network begins to stabilise (see Fig. 3a above) and the rankings of countries are comparable.

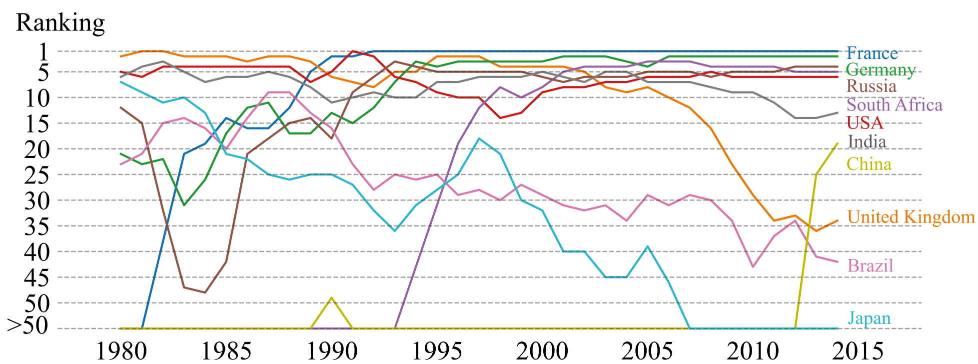
For each centrality measure, we find a statistically significant and positive correlation between country rankings over time. The path dependence is most pronounced in the case of strength and closeness centrality, with Kendall-Tau coefficients of around 0.9. The positive correlation for betweenness centrality is lower but has solidified over time, from 0.65 to 0.85.

Within this stable overall pattern, it is possible to discern some notable trends for individual countries. While our methodology accentuates smaller countries, we are interested in particular in the network positions of major economies. Fig. 8 shows the overall trends of our chosen metrics for 10 major economies: five members of the G7 (Germany, France, United Kingdom, Japan and the US), the four BASIC countries (Brazil, China, India and South Africa), and Russia. The statistics are shown in terms of country rankings since we are interested in the relative positions of countries, rather than the actual centrality scores. The strongest positions in the network are held by European countries, which have both high node strengths and centrality scores. For the past few years, France and Germany were ranked first and second with respect to all three centrality measures. This makes the two countries significant hubs in environmental cooperation, with a high cooperation intensity, significant brokerage power and, thanks to the short network distance to other countries, the ability to influence the cooperation network.

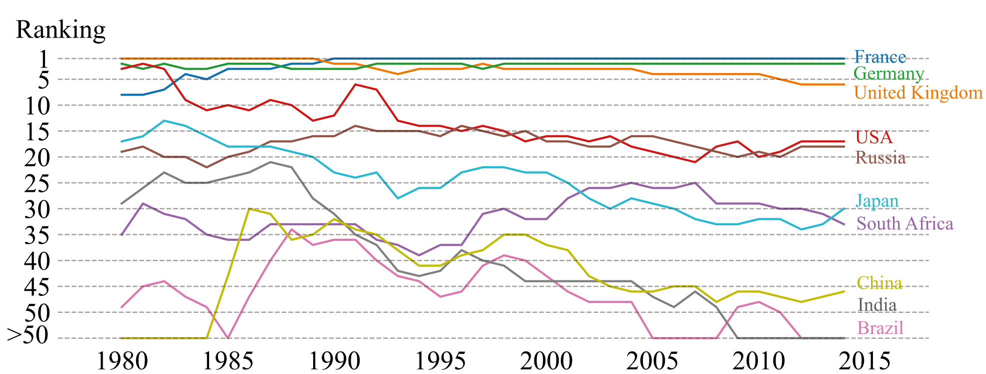
France and Germany are replacing the United Kingdom at the top of the rankings. The United Kingdom played a dominant network role in the 1980s and continues to be a hub in terms of cooperation intensity




(a) Strength of countries




(b) Betweenness centrality of countries




(c) Closeness centrality of countries

**Fig. 8.** Centrality measures. Country rankings from 1980 to 2015.

(node strength). However, its position as a network broker (betweenness centrality) is waning.

The major European countries occupy these positions in their own right, rather than through membership in the European Union. The EU as a body participates in 122 IEAs and sometimes negotiates as a bloc (most prominently perhaps in the international climate negotiations). However, including the EU as an additional network node does not alter the crucial positions in the network by individual EU member states. Additional results, where we include the EU as a network participant in its own right, are reported in Appendix F.1.

Reflecting its recent ambivalence to international environmental cooperation, the network centrality of the United States has decreased notably over the years. The United States still exerts considerable influence over the network, but does not play the dominant role one might expect from a global superpower. The final G7 country, Japan, has also seen its influence wane.

We further note the low centrality of most emerging markets to the cooperation network, including perhaps most notably China's. Until relatively recently environmental issues were not high on the agenda of the Chinese government, either domestically or internationally, although this is starting to change, for example with an increased domestic interest in air quality and a stronger international role on climate change (Green and Stern, 2015).

These rankings corroborate our hypothesis about the leadership role played by European countries, rather than the traditional superpowers.

The rankings also speak to future prospects. The roles of different countries in the cooperation network are both a reflection of their past behaviors in international environmental politics and an indicator of future strengths or weaknesses when seeking international cooperation. In Appendix F.2 we report the results of a simple OLS regression similar to the one introduced in Section 3, where we regress the delay with which a country joins new IEAs on its centrality position. For all three centrality measures - node strength, betweenness centrality and closeness centrality - we find a significant negative correlation. The more central countries are to the network, the faster they are in joining new treaties. This suggests that centrality is not only associated with influence over the current network, but with an increased willingness to pursue further cooperation opportunities.

## 6. Differences across environmental issues

### 6.1. Overview

Our final line of inquiry concerns the cooperation patterns among countries under different treaty subjects. Different environmental problems have attracted international attention at different times and with varying intensities. This reflects differences in the interplay between interests, political power and discourse within and between countries (Mitchell et al., 2020; Mitchell, 2003), as well as the distinct characteristics of different environmental problems (Falkner, 2013a; Meyer et al., 1997). For example, Keohane and Victor (2011) argue that intricate global problems like climate change give rise to more"regime complexity" than more straightforward issues.

Accordingly, we formulate and test the following **hypothesis:** *The dynamics of environmental cooperation are not uniform. Environmental cooperation has distinctly different network features depending on the subject area.*

We analyze environmental cooperation on different treaty subject by constructing separate cooperation networks for the different categories of treaties introduced in Section 2. We use the same metrics as in previous sections, with a focus on network size (number of nodes), connectivity (average degree, strength), and cohesion (density, weighted shortest distance, clustering coefficient). This allows us to describe in topological terms the regime complexity discussed in the international environmental governance literature.

The analysis confirms that environmental cooperation has distinctly different network features depending on the subject area. Specifically, we find that environmental coordination started with the management of marine resources (fisheries and the sea) but is now strongest in the area of waste and hazardous substances. The networks on species, waste and natural resources have a hierarchical structure, where a series of densely connected, small clusters combine into a less dense global network. This feature is absent in the networks on sea and fisheries and air and atmosphere. Despite the high policy salience of the topic, cooperation in the air and atmosphere network appears to be less intensive and the network is less cohesive. Finally, unlike the other networks, the air and atmosphere network is heavily shaped by UN-sponsored treaties.

### 6.2. Network properties by treaty subject

The topic-specific cooperation networks obtained statistical significance at different times. A statistically significant cooperation network first appeared in sea and fishery affairs in 1985, followed by natural resources in 1987[6] waste, and hazardous substances in 1990, wild species and ecosystems in 1994 and air and atmosphere in 2000. Based on our method, the cooperation network for energy treaties does not reach statistical significance, and we, therefore, do not analyze this network.

The topic-specific networks become statistically significant later than the overall network for methodological reasons. When treaties are divided into different categories, each category has a smaller number of treaties, relative to the number of countries. In some of the early country-treaty bipartite networks, the number of countries can be more than four times the number of treaties. When projecting onto the country layer to obtain the cooperation network, this makes it harder for the number of co-signed treaties between countries to be significantly different from the null model. Our interest is therefore in the sequence in which topic networks become significant and not the specific dates.

The different speed at which international cooperation occurred may reflect a number of factors, including the changing salience of different environmental matters over time (e.g., the emergence of climate change as an issue in the 1990s), path dependency (the deepening of links in areas of long-standing cooperation) and potentially an initial focus on subjects where cooperation is easier (Keohane and Victor, 2011).

However, by 2005 most countries had joined all five cooperation networks, suggesting that countries are now collaborating across the full range of environmental issues. In each subject area, nearly all the countries now form a single component.

The relative growth in network size and connectivity is shown in Fig. 9. The cooperation network on waste and hazardous substances ranks first in terms of size (number of nodes), connectivity (average degree, average strength), and global cohesion (density, average weighted shortest distance, and global clustering coefficient).

The cooperation network on air and atmosphere is worth a closer look. Although countries have a high average number of partners in this network, the average cooperation intensity is relatively low. This may be attributable to the fact that there are a number of high-profile treaties with near-global membership such as the 1985 Vienna Convention and the 1987 Montreal Protocol (which explains the high average degree) (Parson, 2003; Falkner et al., 2010). However, compared with other categories, the overall number of air and atmosphere treaties is relatively small (which explains the lower node strength). Moreover, the air and atmosphere network is characterized by a lower density and a higher average weighted shortest distance.

Consistent with the prominence of global treaties, the cooperation relations on air and atmosphere are distributed evenly across the map and do not have an obvious core (Fig. 10). This is in contrast to most other subject areas, which have a prominent core located in Europe.

A further result of note concerns the role of the UN in air and atmosphere treaties. Unlike in the other categories, we cannot construct a statistically significant network when excluding UN-sponsored treaties. In other words, in the area of air and atmosphere, there are no statistically significant cooperation relationships among countries without the support of the UN. The results confirm that the UN has been an effective facilitator in promoting cooperation on issues such as ozone layer depletion, climate change, and air pollution.

### 6.3. Local clustering and node degree

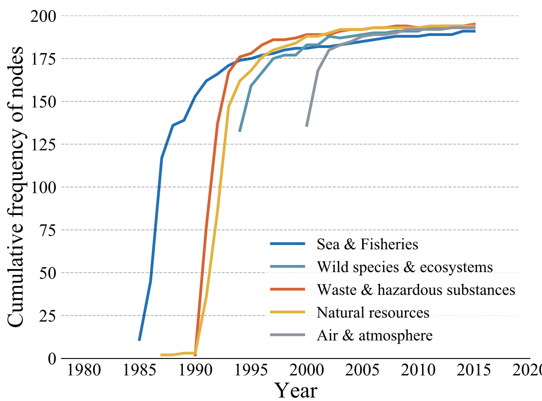
It is instructive to look at the inter-relationship between different network metrics. We first focus on the correlation between unweighted local clustering and degree.

For the cooperation networks on species, waste, and natural resources, countries with a larger degree tend to have a smaller local clustering coefficient: there is a statistically significant and negative Pearson correlation coefficient between degree and local clustering coefficient. This is consistent with a hierarchical structure in which small clusters are densely connected and combine to form larger, but less dense, groups (Ravasz and Barabasi, 2003). Similarly, when coping with these environmental issues, countries with a large number of partners are less involved in interconnected closed triplets.

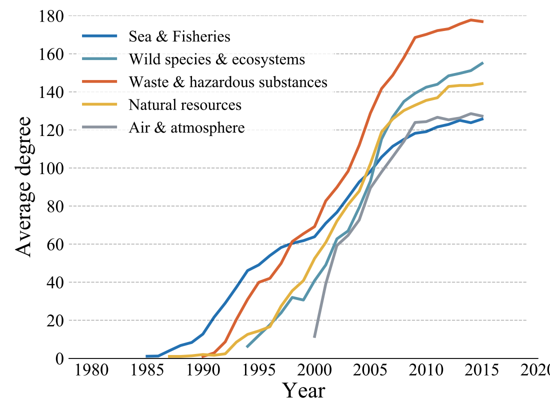
In contrast, neither the cooperation network on sea and fisheries nor the network on air and atmosphere appears to have a hierarchical structure. In these networks, countries with a high local clustering coefficient also have a high degree: the Pearson correlation coefficient between the two metrics is statistically significant and positive.

The positive coefficient observed in the air and atmosphere network is explained in Appendix G. There we show that the members of this

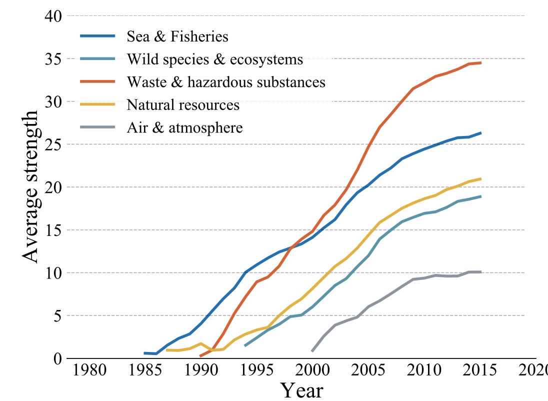
[6] For the category of natural resources, the volatile statistics in initial years are caused by the small number of countries in the network in the initial years.



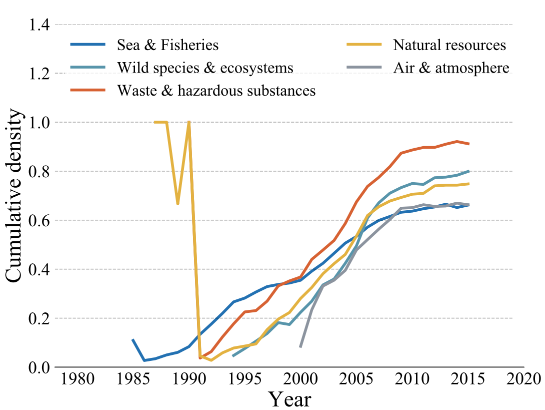

(a) Number of nodes



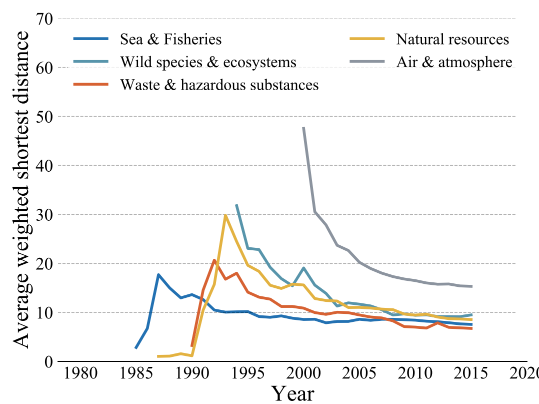

(b) Average degree



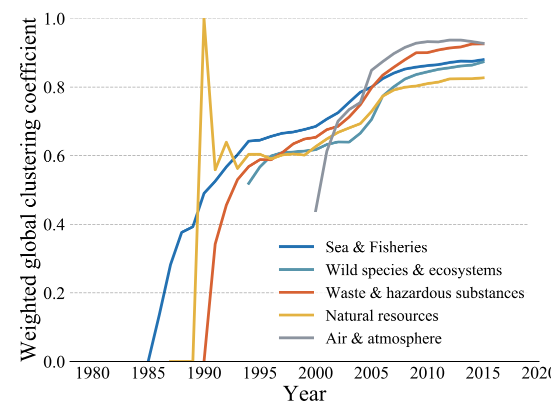

(c) Average strength




(d) Density




(e) Average weighted shortest distance




(f) Global clustering coefficient

**Fig. 9.** Cooperation networks for different treaty subjects.

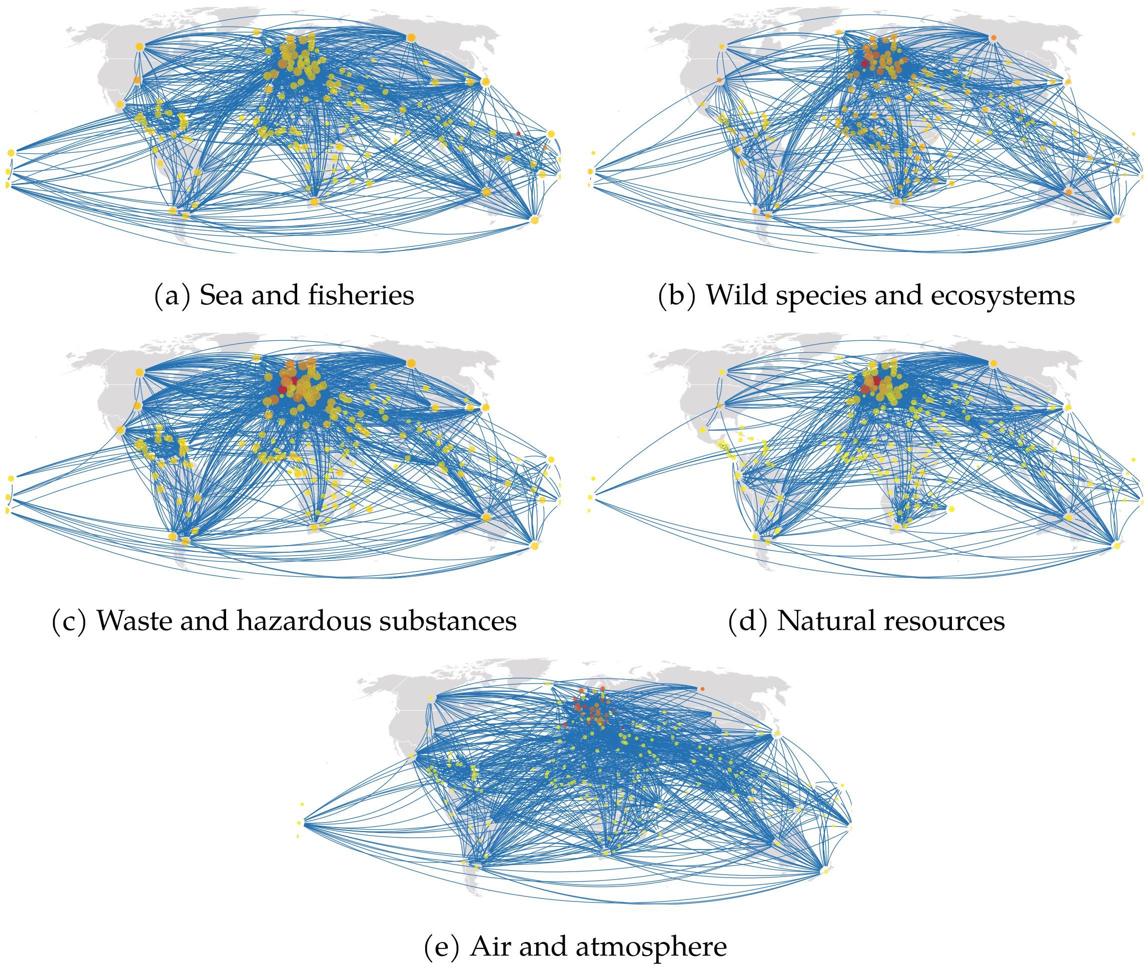



**Fig. 10.** Country networks for different treaty categories in 2015.
Note: For the sake of visualization, the figure only shows the top 10% of links in terms of weight. The size of a node is proportional to its strength, and the color of a node (red = stronger; yellow = weaker) reflects its weighted local clustering coefficient measured using the method proposed by Onnela et al. (2005).

network fall into two distinct groups. First, there is a large number of countries, which have primarily signed large global treaties (e.g., on ozone layer depletion and climate change). Second, there is a smaller group of countries which signed up to a much larger number of treaties. It is the distinctive behavior of these two groups which explains (at least partly) the non-hierarchical organization of these countries and the unusual positive correlation between degree and clustering observed in this network.

### 6.4. Local clustering and node strength

We now turn to the correlation between the weighted local clustering coefficient and node strength. When clustering is computed through the method proposed by Onnela et al. (2005) (see Section 2 and Appendix C), there is a statistically significant and positive correlation between the weighted local clustering coefficient and node strength for each treaty category. This implies that, when copying with environmental issues, countries characterized by many intense collaborative links tend to be connected with other countries that also collaborate with each other. That is, countries at the centre of strong triplets are more likely to be embedded in closed structures, rich in closed triangles, than countries at the centre of weak triplets. This is clearly indicated by Fig. 10, where the larger nodes (i.e., with higher strength) tend to be closer to the red end of the color spectrum (i.e, with higher weighted clustering).

The network on air and atmosphere again deserves special consideration. That network is characterized by a statistically significant and negative correlation between the weighted local clustering coefficient and node degree. Combined with the previous finding on unweighted clustering and degree, this has a twofold implication: (i) when dealing with air and atmosphere countries with many collaborators tend to be included in many triangles (thus resulting in a positive correlation between unweighted clustering and degree); (ii) however, the weights of the collaborative links in these triangles tend to be relatively small (thus resulting in a negative correlation between weighted clustering and degree). Thus, on these issues of air and atmosphere, it is the weaker triads that tend to close up into triangles. Once again, this finding can be explained by the fact that on these issues a very large number of countries tend to co-sign only a small number of very large and popular treaties (Newman, 2001b).

## 7. Conclusions

Global environmental governance has been the subject of academic scrutiny for some time. This paper adds a novel angle to this debate by providing quantitative evidence from network analysis.

Network analysis provides a systematic, quantitative analytical lens that can corroborate or refute evidence, often of a qualitative nature, from the existing literature. Network metrics can help to assess the structure and depth of environmental cooperation and flush out interesting patterns, such as differences by subject areas or the importance of particular countries.

This paper demonstrates the power of network analysis by testing topologically four hypotheses related to salient debates in political science, international relations and economics literature.

The analysis gives rise to a rich agenda for follow-up research. There are intriguing topological differences, for example, between environmental subject areas, which are worthy of further investigation. Other lines of enquiry could move from the predominantly global metrics used here to the *meso* level, investigating for example the tendency of the most well-connected countries to generate exclusive collaborative groups.

Another avenue for future research concerns the dynamic formation of the cooperation network. Pertinent techniques from the econometrics of networks (as reviewed in Chandrasekhar, 2016 and De Paula, 2020) could be used to identify the factors driving the formation of the cooperation network, which in our study we take mostly as given.

Different networks may have to be constructed for different research questions. The network constructed here takes a country-based perspective. Country nodes are connected through treaty links. This is an obvious choice for an analysis interested in the international relations and political economy of environmental cooperation. Other research questions may require a treaty-based perspective, that is, a network in which the treaties are the nodes. In turn, these nodes could be linked through shared signatories, textual citations, content similarity, or geographic proximity (Kim, 2013; Bohmelt and Spilker, 2016; Hollway and Koskinen, 2016).

Through judicious network design, network analysis can account for many of the rich historical, cultural, and economic links that exist between countries, and which go beyond joint treaty membership, potentially including also measures of soft power. More complex network methods could be further leveraged to construct and infer from these networks, such as the K-Nearest Neighbor Graph (K-NNG) construction (Dong et al., 2011).

Our analysis has demonstrated that network analysis has the potential to become a powerful complement to the tools traditionally used in the study of global governance and international cooperation.

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## Declaration of Competing Interest

We have no conflicts of interest to declare.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2022.107670.

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