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Global nanotechnology regulatory governance from a network analysis perspective

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Abstract

Over the last decade, there has been a proliferation of nanotechnology regulatory initiatives, developed to ensure the responsible development of nanotechnology applications. This article examines the emergence and diffusion of environmental, health and safety (EHS) policies dealing with nanotechnology. Drawing on a citation network analysis of global nanotechnology regulatory governance, the article analyzes the role of key organizations at multiple levels and their interplay in initiating and diffusing occupational safety and health policies. It shows that private international standard-setting organizations become "centers of information," which play a strategic role as intermediaries that diffuse national policies globally. Through this process, these centers help to shape supranational policies. Such an understanding of the role of international private standard-setting organizations sheds new light on the current debate over the privatization and internationalization of EHS governance.

Keywords: fragmentation, interactions, nanotechnology regulation, policy diffusion, social network analysis.

1. Introduction

In the last decade, there has been a proliferation of regulatory initiatives that set best practices, rules, or laws to govern conduct related to nanotechnology-based materials, products, or processes and to ensure the responsible development of nanotechnologies. These regulatory initiatives may be an amendment, supplement, or implementation guideline for existing regulatory programs, or an independent initiative.[1] They have been developed by various actors – both governmental and non-governmental organizations – at different administrative levels covering various scopes and using a range of regulatory strategies. These have been developed without direction from international organizations, such as the United Nations Environment Programme (UNEP) or the World Health Organization (WHO), which only recently became involved in the field. This led to the evolution of a dense and polycentric regulatory governance of nanotechnology (Snir 2015).

This phenomenon is not unique to nanotechnology, but has been observed by other scholars in many regulatory fields as part of the *new governance* transformation, which shifts the authority to regulate environmental, health and safety (EHS) problems from formal institutions of the state to self-organizing and interorganizational networks (see e.g. Abbott & Snidal 2009b, p. 542). However, the evolution and internal dynamics of such pluralized systems have rarely been studied empirically. This article contributes to the literature discussing the phenomenon of pluralistic regulatory governance by offering an empirical analysis of the structure of the nanotechnology Occupational Safety and Health (OSH) regulatory field and the dynamics of knowledge flows within it over time. The article examines whether the observed transnational regulatory field is uncoordinated, overlapping, and competitive, or whether it is characterized by self-coordination and collective learning.

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The article uses social network analysis methodology to study the structure and dynamics of global regulatory governance in the field of nanotechnology OSH regulatory governance. This methodology has rarely been used in legal literature.[2] In addition to extracting insights on the particular field, our secondary goal is to explore the potential of social network analysis tools for regulatory analysis.

Social network analysis is a valuable approach as it captures relationships among regulatory elements that cannot be captured using traditional statistical approaches. Such mapping can reveal interaction dynamics that may not be immediately apparent (e.g. small-group dynamics, regulatory-predominance over time, cross-institutional political strategies, and competition vs. coordination dynamics) (Alter & Meunier 2009). Furthermore, the conceptualization of networks as a structure through which diffusion can occur is particularly useful to examine how position within the network affects control (Lazer 2011). Social network analysis models can identify the authoritative leaders, intermediates, and outsiders; the clusters and who is in them; and who is in the core of the network and its periphery (Hanneman & Riddle 2005).

To construct a network of global nanotechnology regulatory governance we mapped citation connections between regulatory initiatives. Citation is a well-established practice that reflects logical reasoning. While no study has investigated citation motives specifically in the context of cross-referencing of regulatory documents, there are similarities to the rationales in scholarly and legal citations, which have been studied extensively. The motives to cite are numerous (see e.g. Brooks 1986; Bonzi & Snyder 1991; Posner 1999, pp. 4–7), and in policy and regulatory citation they may include: self-citation to establish the author's authority in the field; providing an authoritative basis for a statement; indicating the forefront of the work by referencing the latest work of contemporaries; or additional sources of relevant information. Although citation does not always mean agreement with the cited documents (i.e. negative citation), empirical and theoretical work suggests that citations most often indeed signal agreement and that negative references tend to be accompanied by simultaneous positive credit (see e.g. MacRoberts & MacRoberts 1984; Brooks 1986), allowing citation analysis to reveal communities and authoritative sources of knowledge (Shwed & Bearman 2010, p. 820). Thus, it is clear that citation is not a random practice; rather the linkage structure of citation encodes judgment that formulates a notion of authority (Kleinberg 1999, p. 606). This allows citations to serve as a proxy for knowledge interactions (Yan & Sugimoto 2011, p. 1498), revealing social dynamics (such as influence and the diffusion of knowledge) and the rise and decline of *schools of thought* (Posner 1999, p. 3).

The analysis presented in this article is based on a list of all OSH nano-specific regulatory initiatives that were introduced worldwide between 2000 and 2012 – 128 initiatives in total. We analyzed diffusion routes between different types of geographic regions, languages, and institutions. Our analysis shows that international standard-setting organizations have become "centers of information," which play a strategic role as intermediaries that diffuse national policies globally. Through this process, these centers help to shape supranational policies. Such understanding of the role of international private standard setting organizations sheds new light on the current debate over the privatization and internationalization of EHS governance. The following sections of the article include a theoretical overview with hypotheses, methods, results, discussion, and conclusion.

2. From regulatory fragmentation to policy convergence, via private transnational networks

The growing degree of regulatory fragmentation in contemporary global governance is a phenomenon that occupies many scholars of law, international relations, and sociology, who study its causes, consequences, and responses (see e.g. Orsini *et al.* 2013; Zelli & van Asselt 2013). In this article, *fragmentation* refers to the notion of distinct institutions and regulatory arrangements that coexist and operate in the *global governance* of nanotechnology.

A significant portion of the literature on regulatory fragmentation is devoted to the exploration of the diversity of regulatory arrangements and organizations that participate in global governance (see e.g. the concept of *the governance triangle* in Abbott & Snidal 2009a; Abbott 2012; Abbott *et al.* 2012) and to the possible effects of that diversity. Some scholars have emphasized the potential for competing claims of authority and conflicting demands or norms (e.g. Tamanaha 2008; Abbott & Snidal 2009b). Others have pointed to the possible contribution of diversity to the creation of more democratic, tolerant, and creative societies (e.g. Perez 2003; Ostrom 2010).

Less attention has been given to studying how, or if, organizations and regulatory arrangements, which coexist in polycentric regulatory governance, interact in the absence of oversight by a coordinating international organization. Zürn and Faude (2013, p. 120), for example, argue, "it is not fragmentation per se, but rather the *coordination* (or lack of it) of fragmented or differentiated institutions that becomes the most important issue." Therefore, understanding the nature of continuing governance interaction is a key to any assessment of the effects of fragmentation.

This article applies a three-level analysis to study regulatory governance interaction in the domain of nanotechnology OSH. At the macro-level, it examines the regulatory governance structure as a whole and the degree of connectivity among all regulatory arrangements and the organizations that established them. It also considers structural changes that occur over time. At the meso-level, it examines specific structures and patterns of interaction that affect knowledge flows and policy diffusion among organizations and regulatory arrangements. At the micro-level, it identifies the key actors who form and shape global nanotechnology regulatory governance by controlling knowledge flow dynamics within it.

Beginning with the macro-level, scholars have traditionally emphasized the "orchestration deficit" in global regulatory systems, arguing that more directive and facilitative orchestration is needed, inter alia, "to ameliorate excessive multiplicity and reduce forum-shopping and adverse competition;" and "to systematically encourage learning across the system and disseminate, replicate, and scale up the most successful innovations" (Abbott & Snidal 2009b, p. 559). More recently, however, scholars who have focused on the evolution of global regulatory systems demonstrated how their structure has changed over time in the direction of integration, even in the absence of supreme direction.

For example, Morin and Orsini (2013, pp. 42–4) describe the life cycle of regime complexes in four stages: atomization → competition → specialization → integration. Overall, they argue that, over time, "normative conflicts and regulatory competition drive the institutions towards an accommodation even in the absence of a coordinating institution" (Morin and Orsini 2013, p. 44), and, thus, regime complexes tend to become denser and more integrated. Similarly, when studying the evolution of the multilateral environmental agreement system, Kim (2013, pp. 983–4) found that the system has defragmented as it has coevolved. Kim's findings also indicate a stage in which isolated communities were formed before becoming connected to a larger system. However, unlike Morin and Orsini (2013, p. 42), who discussed an integrated structure with equally distributed ties among all elements, the structure Kim (2013, p. 983) found was cohesive and polycentric.

Nevertheless, both studies indicate that, over time, isolated elements of the regulatory system tend to join into communities, which later tend to grow in connectivity with one another. Such evolving structures may suggest some level of regulatory competition at early stages of the regulatory system evolution, which is later overcome by informal global coordination. Therefore, this study tests whether, as the regulatory system evolves, the elements of the regulatory governance system tend to coordinate with one another regardless of the orchestration deficit.

Hypothesis 1: Even in the absence of a coordinating institution, elements in a decentralized regulatory field tend to interact and coordinate with one another over time.

The risks of regulatory competition have troubled many scholars, who have focused on the normative outcome of such competition. Some have been interested in whether, over time, competition over authority yields a "race to the bottom" or "to the top" in terms of policy stringency (Prakash & Potoski 2006, pp. 12–13; Eberlein *et al.* 2014, pp. 12–13). Others have pointed to the importance of timing, suggesting a "first-mover advantage" as the maturation of the emergent field may restrict entry of new contestants. They argue that once the new governance field is established and policy actors adopt existing regulatory arrangements, it is harder for new actors to shape the rules (Smith & Fischlein 2010, p. 520). The connecting idea behind these two hypotheses is that the normative convergence of the system is the result of power struggles and cumulative advantage rather than accommodation, specialization, and integration. This implies that, over time, dominant regulatory arrangements gain more legitimacy and authority by newcomers, which allow the dominates players to control the normative tone of the entire system. Sociologists recognize this phenomenon as the "Price law" (Price 1965) and the "Matthew effect" (Merton 1968). This study tests whether regulatory competition results in a small number of "winners."

Hypothesis 2: Influential actors are likely to gain more influence as new actors join the field over time.

At the meso-level, scholars have tried identifying system-level drivers for regulatory governance interaction that lead to knowledge flows and transnational policy diffusion. For example, one of the assumptions of globalization studies is that, despite regulatory fragmentation, global economy, global culture, and advances in telecommunications and computer technologies, such as the internet, have drastically reduced the barriers to economic, political, and cultural exchange (Drezner 2001, p. 53, p. 56; see generally Friedman 2007). As part of this process, communication and information exchange among countries drive lesson drawing from successful countries, as well as joint problem-solving activities within transactional elite networks (Knill 2005, p. 7). This results in the convergence of policies governing environmental regulation, consumer health and safety, and the regulation of labor (Drezner 2001). Furthermore, some scholars argue that increasing economic integration of the global market has also led to regulatory competition, which drives mutual adjustment of policies across countries (Knill 2005; Holzinger *et al.* 2008). Whether convergence results from emulation, harmonization, penetration, or elite networking and policy communities (Bennett 1991), it implies heterogenic interaction – that is, deterritorialization, actor diversity, and multi-level transnational interaction.

Nevertheless, despite these globalization trends, similar attributes, such as geographical proximity, ideology, culture, and institutional affiliation, may have a greater impact on knowledge diffusion patterns. Studying the spread of pension policy reform, Weyland (2005, p. 266) found that "[M]odels usually spread first in the region in which they originate and only later reach other areas," concluding that proximity prompts imitation. Grossback *et al.* (2004, p. 522) further stress "the importance of ideological similarity between states as a specific factor that can reduce the uncertainty a state may have about a policy and thus induce emulation." Lavie and Drori (2012) show that interorganizational collaboration, such as between universities and nascent industries, have boundary conditions for the benefits of collaboration, which does not present in collaboration between similar organizations. Similarly, Guler *et al.* (2002, pp. 226–7) argue that *role equivalence* in trade generates a competition-based mimicry that increases the diffusion of organizational practices in the global economy. Maoz *et al.* (2006, p. 668, p. 683) add that similarity in patterns of trade with third parties also suggest a common vision of the international political economy, which tends to reduce the likelihood of conflict. Finally, studies on *institutional isomorphism* suggest that organizations tend to mimic other organizations in their nearby environment, because of pressure for favorable public relations (Kanter 1972, p. 154), or as part of their competition for political power and institutional legitimacy (DiMaggio & Powell 1983, p. 150). Taken together, these hypotheses suggest that the development and spread of knowledge and policies occur within defined communities that share some similarities. The study tests whether proximity variables are likely to affect patterns of knowledge flows and policy diffusion in the global regulatory governance of nanotechnology.

> Hypothesis 3: Geographic, cultural, and institutional proximity has a significant effect on the tendency to cite regulatory initiatives.

Finally, at the micro-level, the literature theorizing global governance interaction has traditionally focused on public actors and their regulatory arrangements as the center and driver of international regulatory systems and interactions (see e.g. Keohane & Victor 2011; Orsini *et al.* 2013). However, as private regulatory arrangements proliferate and the regulatory system becomes more global and complex, researchers have started broadening the scope of inquiry looking at how private actors affect the global governance outcome. Barak-Erez and Perez (2013), for example, point to some mechanisms through which private transnational regulation affects national administrative law. Auld and Green (2012), on the other hand, highlight the role of private authority in helping to promote cooperation and overcome path dependencies that public authority may face. In this context, the literature has particularly highlighted the importance of multinational corporations as transnational policy diffusers through their national subsidiaries (see e.g. Bennett 1991; Guler *et al.* 2002). Similarly, Büthe and Mattli (2011) show how international private sector organizations operating as centrally coordinated global networks are recognized by both public and private actors as focal institutions for global rulemaking in their area of expertise. While public-private interdependence and the importance of private actors in public policymaking were established long ago by policy network scholars (see e.g. Laumann & Knoke 1987), these early observations imply a central role for private authority in the development and diffusion of policies in global regulatory governance. Nevertheless, many scholars, especially of regime complex studies, still argue that "states are the most important contributors to and recipients of the norms embedded in regime complexes" (Orsini *et al.* 2013, p. 36). Therefore, the study more systematically assesses private authority influence on global regulatory governance.

> Hypothesis 4: In public-private networks, private organizations tend to be as influential as public organizations in the development and diffusion of policy in global regulatory governance.

By testing these hypotheses, our analytical framework takes a gradual "zooming-in" approach, starting with a fragmentation assessment and examining how interaction over time affects the degree and patterns of connectivity in the regulatory system. It then discusses system-based drivers, such as globalization and isomorphism, which shape interaction patterns and facilitate knowledge flows and policy diffusion. It concludes with the examination of individual actors who control the development and diffusion of nanotechnology OSH norms in global regulatory governance.

3. Methodology

3.1. Dataset compilation

The dataset analyzed in this study comprised all 128 nanotechnology OSH regulatory initiatives introduced worldwide by 92 organizations between 2000 and 2012. The dataset was retrieved from a larger database of Global Nanotechnology Regulatory Initiatives analyzed elsewhere (Snir 2015). Each initiative was analyzed for its citations of other regulatory initiatives, which are represented as a directional link from the citing to the cited initiative. Propriety R (R Development Core Team 2015) scripts was used to transpose the regulatory initiatives network to organizations network where each node represents an organization, and the link signifies that the organization cited at least one initiative from the other organization. The method used to develop the database and the criteria to determine the OHS-related regulatory initiatives group is explained in the online Supporting Information.

3.2. Citation network analysis methods

The connectivity structure of the networks of global nanotechnology OSH regulatory governance is based on the citation patterns within the regulatory initiatives documented, and the edge between one node and another indicates the direction of knowledge flow (Newman 2003, p. 176). The structure of citation networks typically differs from the structure of other social networks in several ways (Leicht *et al.* 2007, p. 75). First, citation networks are directed and, thus, constitute an asymmetric relationship between the nodes involved. This means that diffusion is determined by the direction of the knowledge flow – from cited to citing organization (unlike, e.g. co-authorship networks in which knowledge flows in both directions and diffusion occurs through collaboration). Still, citation can sometimes be a proxy for acquaintanceships and indicates a potential for future mutual relationships. Yan and Sugimoto (2011, p. 1512), for example, found that "once two institutions establish collaborative relations (or citation relations), they have a higher probability of citing and collaborating with one another than absent such relationships." Therefore, there is a justification to also look at citation networks as undirected, to assess the potential for knowledge diffusion within the network. In this article, findings are presented as directed and undirected networks, as appropriate.

Second, citation networks evolve over time as nodes and edges are added to the network, and tend to remain static with changes only at the "leading edge" of the network. A more dynamic activity (more common in World Wide Web networks) can occur if an updated version of a document adds new citations or removes the citations included in an earlier version. Our networks include amendments to documents, which add new links between existing nodes, making the networks more dynamic than typical citation networks. Third, citation networks are typically acyclic as all edges point backwards in time to existing documents, creating an "arrow of time." A closed loop, however, can appear if a document has been updated or it cites a forthcoming document, as periodically occurs in our networks.

In addition, aggregating nodes into higher levels, such as the author unit (i.e. the organization that publishes the regulatory documents), the type of authority (i.e. public, private, or hybrid), or the geographic region (i.e. Europe, North America, Asia-Pacific, or International) of the document, allows an institutional analysis of *importing* and *exporting* knowledge patterns in complex networks (Yan & Sugimoto 2011). In addition, when nodes are aggregated we can count the number of citations between them as a weight of the edges. The weight of edges is commonly used to demonstrate strong connections between two nodes (Liu *et al.* 2005). In a directed regulatory governance network, it may show the authoritative influence one organization has over another, the dynamics of knowledge interaction among different types of authorities, or patterns in transnational policy diffusion.

To analyze the networks we used several tools, mainly nodeXL, Gephi, Pajek, and R environment with igraph and sna packages. All calculations were performed with R, except the authority and hub measurements and the core and periphery mesaurements, which we performed in Pajek. nodeXL was primarily used for network exploration in the early stages of the research. Network visualization was performed using Gephi.

The study uses three levels of analysis: (i) network-level: focuses on the properties of the network as a whole, such as connectivity, geodesic distance, dyad census, and distribution of nodes degree; (ii) group-level: tracks citation patterns between groups of aggregated nodes based on various characteristics; and (iii) node-level: measures the importance or centrality of a node within the network based on its interactions with the other nodes in the network.

4. Results

4.1. Evolution of the nanotechnology occupational safety and health regulatory governance networks structure from 2000–2012

Of the 128 nanotechnology OSH regulatory initiatives and 92 organizations analyzed, 97 regulatory initiatives and 66 organizations made 261 and 201 cross-references to one another (including self-citation), respectively, until 2012. Figure 1 shows four graphical snapshots of the evolution of the two networks (regulatory initiatives and organizations), taken at approximately two-year intervals from 2005–2012.

4.1.1. The growth of networks connectivity

Between 2000 and 2012, the two networks have shown similar patterns of network growth, indicating three phases, as shown in Figure 2.

To assess the system connectivity more specifically (Hypothesis 1), we measured the fraction of nodes that are connected and the structure of knowledge exchange, as appears in the giant component of the network, defined as the largest maximal subgraph of connected nodes (Ding *et al.* 2014, p. 60). We measured percentage of nodes and connectivity topology in the giant components of the observed networks as the networks evolve, to determine whether their structure fits the theoretical expectation. To ensure that the observed networks' structure did not occur purely by chance, we compared it to the average connectivity structure of 1000 possible networks with randomly edge generated configuration with the same number of nodes and edges (Erdos-Rényi model) (Monge & Contractor 2003, pp. 49–50).

Measures of the networks' growth between 2006 (when the first edge appears in the network) and 2012 indicate an increase in the percentage of nodes in the giant component from 23–72 percent in the regulatory initiatives network, and from 18–70 percent in the organizations network, as shown in Figure 3. The drop that occurred in 2008 relates to the establishment of separate small components that reduced the fraction of the giant component as a percentage of the entire network that year. Over the years, the giant components contain, on average, 98 percent of the edges in the networks.

Furthermore, we found that within the giant component, the average number of outward citations per regulatory initiative or organization grew from 2–3.676 and from 1–3.792, respectively. Similarly, the average clustering coefficient, which measures the degree to which the nodes in the networks tend to cluster together, increased from 0–0.31 in the regulatory initiatives network and from 0–0.42 in the organizations network. This further indicates an increase in connectivity and knowledge exchange over time. A dyad census (Holland & Leinhardt 1970) also found an increase in the number of reciprocal ties in the observed networks, from 0–7 in the regulatory initiatives network and from 0–12 in the organizations network. This indicates an ongoing dialogue between some of the organizations and the regulatory initiative as they are amended, and suggests a reciprocal learning and self-coordination process. Together, these findings show that the evolution of the observed networks contains the theoretically hypothesized property, which assumes an increase in connectivity, self-coordination, and knowledge exchange among the elements of the regulatory system, even in the absence of central direction.

We found that, until 2009, the connectivity structure of the observed networks is not statistically different from the average structure found in the 1000 random networks. However, since 2009, the observed networks demonstrate a different structure to that of the random networks, with a much smaller percentage of nodes in the giant component. For example, the analysis shows that in 2011, only 66.4 percent of the regulatory initiatives and 67.8 percent of the organizations connected with one another in the giant components of the observed networks,

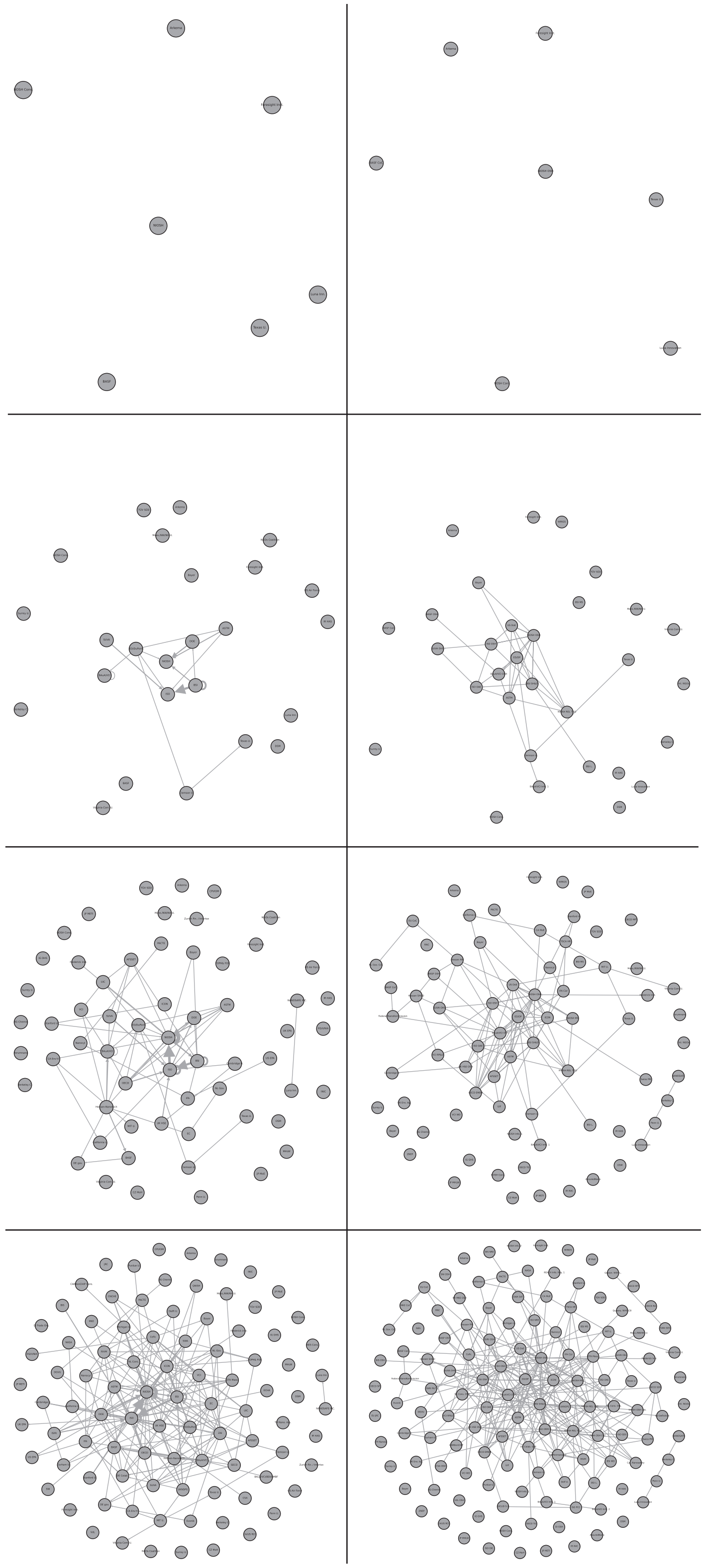


Figure 1 Graphical representation of the evolution stages of regulatory initiatives (right) and organizations (left) in 2005 (top), 2007, 2009 and 2012 (bottom), using a Fruchterman–Reingold layout algorithm.

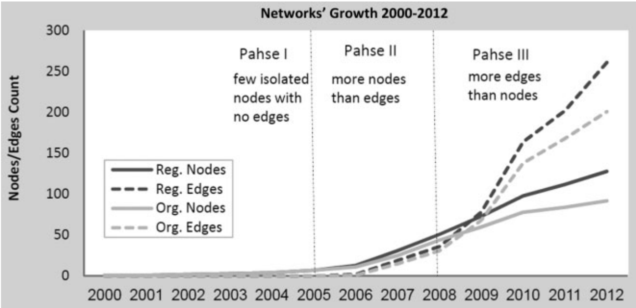


Figure 2 Cumulative increase in numbers of developed regulatory initiatives, participating organizations, and respective cross-references between 2000 and 2012. Org., organization; Reg., regulatory.

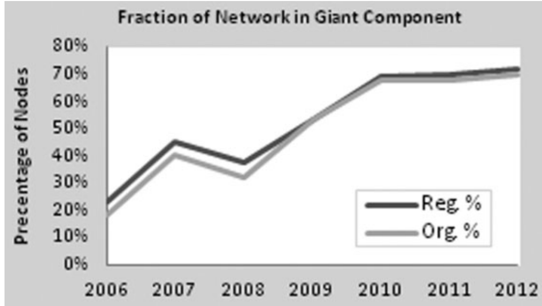


Figure 3 Fraction of the nodes in the giant component between 2006 and 2012. Org., organization; Reg., regulatory.

compared with 97 percent with a standard deviation of 0.015 and 98.1 percent with a standard deviation of 0.01 in the random networks, respectively. These differences are statistically significant, with a $P < 0.000$ confidence interval.

Furthermore, we found that in the random networks, the average clustering coefficient is 0.03 and 0.04, on average 8.7 and 9.5 times smaller than the clustering coefficient of the observed networks. Similarly, comparing the dyad census results to that of the random networks indicates that, since 2009, there have been more reciprocal ties in both networks than would otherwise be formed by chance. These findings support the argument that the structure of the citation network is not random; rather it is formed by logical reasoning and, thus, reflects judgment. Furthermore, it implies that although smaller, the giant components in the observed networks enjoy higher density (more edges connecting a small number of nodes), higher clustering, and more reciprocal interaction compared with random networks. Therefore, there is a greater potential for knowledge diffusion and transnational coordination within the connected regulatory initiatives and organizations than would otherwise occur by chance.

4.1.2. Small-world network

Another indicator for the assembling of the nanotechnology OSH regulatory system is the networks' proximity to the *small world* phenomenon. The *small-world network* is a phenomenon in which most nodes are not connected to one another, yet each can be reached by any other in the network by a small number of steps, despite the large size of the network (Watts & Strogatz 1998). In small-world social networks, information can travel efficiently throughout the network, supporting knowledge exchange (Latora & Marchiori 2001). For this phenomenon to exist in a network, the network must meet two cumulative conditions regarding the average of shortest paths and clustering coefficient (>10), as described in Ravid and Rafaeli (2004), and shown in Table 1.

Table 1 Small world fitness for nanotechnology occupational, safety and health regulatory initiatives and organizations networks between 2006 and 2012

Year	Regulatory Initiatives Network			Organizations Network		
	L/L random	CC/Cc random	SW Index	L/L random	CC/Cc random	SW Index
2006	0.96			1		
2007	0.84	7.38	9	0.74	8.52	11
2008	0.76	12.63	17	0.80	11.84	15
2009	0.49	10.37	21	0.45	10.56	23
2010	0.30	8.60	29	0.35	7.50	22
2011	0.36	10.03	28	0.38	7.90	21
2012	0.54	9.53	18	0.49	8.79	18

L, average shortest path; CC, clustering coefficient; SW, small-world.

4.1.3. Peripheral attachment and scale-free network

To test the influence constellation within the networks (Hypothesis 2), we measured the in-degree distribution over time. In-degree measures the number of times a single regulatory initiative or organization has been cited by others (i.e. inward citation). The larger the in-degree, the "more important" the node is in a network. In 2012, for example, we found that seven percent of the regulatory initiatives and five percent of the organizations received 50 and 48 percent of all inward citations in the observed networks, respectively. This indicates that the networks contain a few highly influential actors, while the majority has very little influence over the production of knowledge in this field.

To determine whether current influential actors are likely to maintain their influence, we tested whether the observed networks are scale-free. A *scale-free* network demonstrates a power law distribution of its degree. This means that regardless of how large the network grows over time, current influential actors will maintain their position in the network and become even more influential. Barabasi and Albert (1999) found that *scale-free* networks occur through two mechanisms: one, the network expands continuously through the addition of new nodes (as presented above); and two, new nodes attach preferentially to already well-connected nodes. Consequently, the network is governed by robust self-organizing phenomena that go beyond the particulars of the individual system.

We estimated the power law parameters using the igraph R package (Csardi & Nepusz 2006), which implements Newman (2005) and Clauset *et al.* (2009) algorithms. We found that, since 2007, the networks' degree distribution is a power law distribution; hence, the networks can be termed "scale–free" (see Table in Supporting Information). This means that in nanotechnology OSH regulatory governance, the current most influential regulatory initiatives and organizations have maintained this position over the last few years and are likely to maintain it in the future.

Still, given the relatively small size of the networks, interpretation of the results demands some caution. Therefore, to support the conclusion that Hypothesis 2 is correct, we also tested whether there was a correlation between the number of citations received by a regulatory initiative or organization in two consequent years. A correlation indicates a pattern based on which it can be expected that over the years influential actors will become more influential. We found that both networks demonstrated a linear relationship, with a regression coefficient of 1.22 (adjusted $R^2 = 0.92$) in the regulatory initiatives network, and 1.21 (adjusted $R^2 = 0.923$) in the organizations network, every two subsequent years between 2006 and 2012 (Fig. 4). This finding clearly supports the hypothesis. We further elaborate on which regulatory initiatives and organizations were found to be the most influential in the Key Actors section.

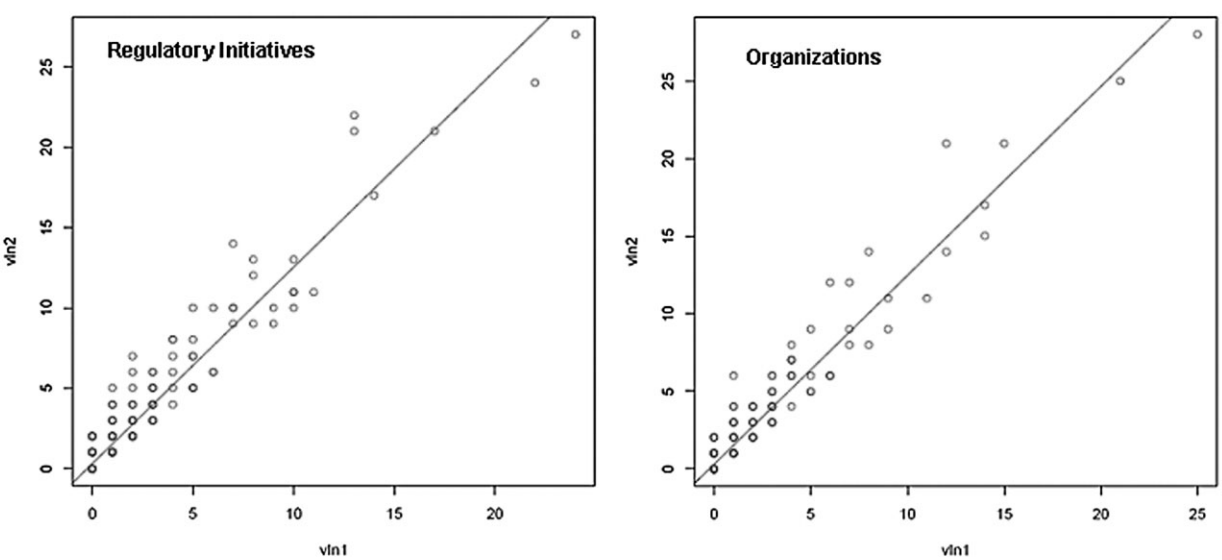


Figure 4 Number of citations received in later periods as a function of the citations in the former period.

4.2. Knowledge flow dynamics and the effect of proximity

To assess the effect of proximity on policy diffusion through the network (Hypothesis 3), we applied a group-level analysis, which measures out-degree distribution of citations between groups of nodes based on the following affiliation categories: geography – the region and national country in which the regulatory initiative was developed; culture – the native language of the organization that established the regulatory initiative (regardless of the language in which the regulatory initiative was published); and institution – the sector and the regulatory role of the actor. We used crosstab tables to examine the distribution of citation links between different categories of data. Each cell counts the number of times a regulatory imitative was cited from (row) to (column) and compared to the expected value by chance (distribution according to the share in the population). We tested differences using a chi-square test (see e.g. Table 2 bellow). (Additional tables are available online in Supporting Information.)

The analysis starts in 2009 (as prior to that the network was too small and unstable and it is hard to determine a statistical pattern in its ties.). A geographic proximity test shows that nanotechnology OSH regulatory initiatives are developed and diffused mainly in three regions (Table 2). Europe is the largest player with the majority of inward and outward citations, followed by North America, while International players are only third. The fourth region, Asia-Pacific, which includes Australia, New Zealand, and Asian countries, only became involved in the field in 2010 and is still relatively small. The effect of geographical proximity is most significant in Europe and North America. In the International region, there is a strong tendency to also cite North America and Asia-Pacific, besides the International. Asia-Pacific is the only region affected by heterophily with a strong tendency to cite the International region.

At the country level, however, we found that 152 out of 261 citations in the network (58%), are exchanged between four country categories: the United States (US), Germany, the United Kingdom (UK) and Multinational. Eleven countries cite the remaining 42 percent, while eight countries make no links with other countries. These results show a statistically significant geographic proximity effect in the network compared to a random network. The proximity effect is much stronger in the US and Germany, while in the UK and Multinational it is accompanied by a mixed knowledge flow from the Multinational to the UK and from the US to Multinational.

Cultural proximity, which presents the distribution of citations by most popular language, shows that 210 out of 261 citations in the network (80%) are exchanged between three language categories: English, German, and Multilingual. The remaining 20 percent are cited by five other languages: Dutch, French, Persian, Korean, and Indonesian, and another five languages make no links with other languages. The results show that lingual proximity affects citation choices. Exceptionally, we found a higher tendency in Asian languages to cite multilingual initiatives – more than any other language.

Institutional proximity, which presents the distribution of citations among public, private, and hybrid sectors until 2012, shows that there is a high tendency to cite more regulatory initiatives from the same sector than any other sector. Additionally, it is interesting to note that, by 2012, the number of inward and outward citations of each sector is approximately the same, with a total share in the network: private (51%), public (43%), and hybrid (6%). This may suggest that all sectors take an equal role in both developing and diffusing knowledge in the network, relative to their size.

Table 2 Citation distribution by region in 2012

From	To				
	Europe	North America	International	Asia-Pacific	Total
Europe	90 (64)	28 (46)	22 (27)	1 (4)	141
North America	10 (26)	36 (19)	10 (11)	2 (2)	58
International	14 (21)	18 (15)	11 (9)	3 (1)	46
Asia-pacific	4 (7)	3 (5)	8 (3)	1 (1)	16
Total	118	85	51	7	261

$\chi^2 = 63.34$; df = 9 sig < 0.000. Cells in shade indicate where there was a higher tendency of citation then would be expected by chance based on the share in the population. The shaded cells highlight the proximity effect found in the network.

However, the distribution of citations based on regulatory roles reveals mixed dynamics. While the proximity effect is evident in almost all parties, citation patterns are also affected by heterogeneity. Most interesting is the reciprocal pattern between second party public and third party, which indicates strong collaboration between the two.

4.3. Key actors

The results of the evolution of the networks growth indicate that a small number of key actors dominate the nanotechnology OSH regulatory networks. Additionally, group level analysis found that private actors are the largest group in the networks, and import and export more than 50 percent of the knowledge in the networks. We used a node-level analysis to identify the key organizations and regulatory initiatives within the networks and the role that influential private organizations play (Hypothesis 4).

Several centrality parameters are used to measure the importance of actors in social networks. One is *Authority and Hub* (Kleinberg 1999), which is used to identify the strongest authoritative sources in the network. The authority score depends not only on how many cited the source (i.e. in-degree score), but also on the importance of those who cite it. The authority rank of private regulatory initiatives and organizations is an important indication of their level of influence on the development of policies in the networks. Tracking authority scores over time may also reveal strong consistent leadership, as well as shifts in authoritative influence.

Figure 5, which compiles all organizations and regulatory initiatives with authority scores above 0.02, shows the relative influence of each group on the networks over time. The findings show that, while in earlier years the public sector was more influential, since 2009, as the networks became more stable and significant in size, public and private actors as a sectorial group have gained a similar level of influence within both networks. The graphs show that the majority of organizations and regulatory initiatives in each sector are within a similar range (1st-3rd quantile) with only minor fluctuations over the years, and that each sector has a few actors above that range. The hybrid sector is too small (the graphs include one organization and two regulatory initiatives) to compare its influence with that of the other sectors. However, relative to its share in the entire networks' population, it is more influential than would be expected in a random network. In addition, we found that in absolute numbers, the group of private organizations and regulatory initiatives is the largest in the top 10 percent of the networks. However, when comparing the

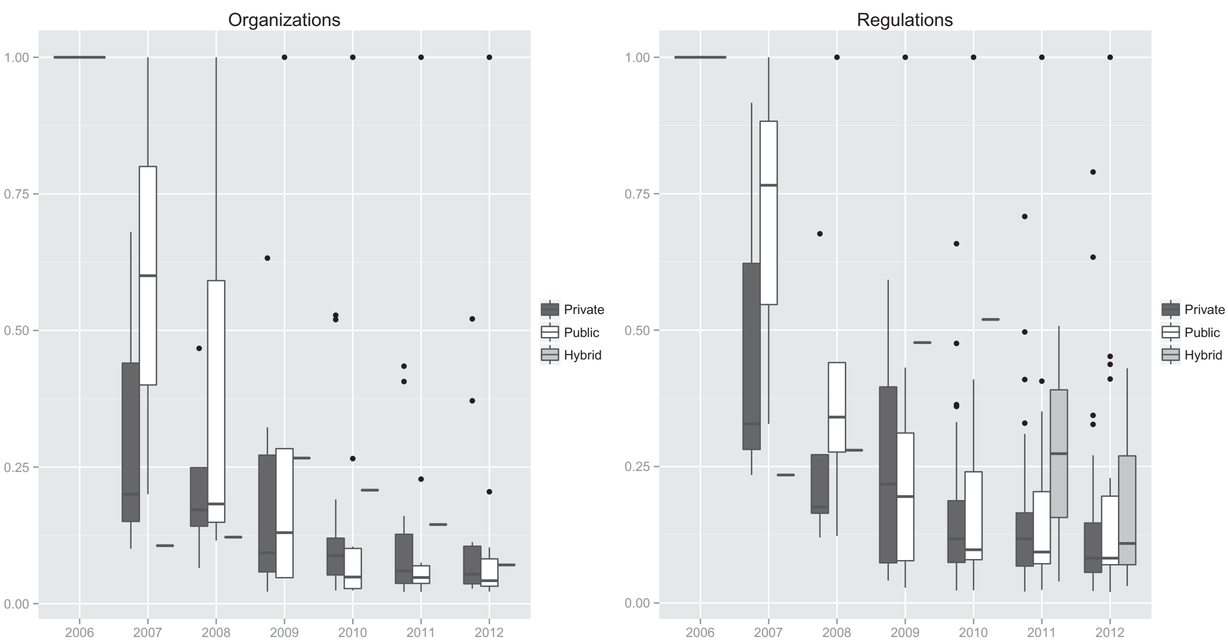


Figure 5 Authority ranks based on actors' sector in the organizations (left) and regulatory initiatives (right) networks between 2006 and 2012, using Kleinberg's hyperlink-induced topic search algorithm. Public (white), private (dark gray) and hybrid (light gray).

numbers to the relative share of each sector in the networks, there is a larger portion of the public and hybrid sectors in the top 10 percent. Still, given the small size of the group we cannot confidently state that this finding is statistically significant.

More specifically, Tables 3 and 4, which list the top four ranked authorities in both networks between 2006 and 2012, show which organizations and regulatory initiatives are most influential. Despite some fluctuation during the early years, only four organizations have maintained their position, thus becoming the strongest authorities in the network. Ranked at the top is the US National Institute for Occupational Safety and Health (NIOSH) (public), followed by the International Organization for Standardization (ISO) (private). The British Standard Institute (BSI) (private), and the German partnership between the Federal Institute for Occupational Safety and Health (BAuA) and the Chemical Industry Association (VCI) (hybrid) alternate between third and fourth places. Tables 3 and 4 also highlight organizations that have lost their top position over the years, such as the American Society for Testing and Materials (ASTM) International (private), the U.S. DOE (public), and the Swiss National Accident Insurance Fund (public).

Table 3 Top ranked authorities in organization networks between 2006 and 2012

Rank	2006	2007	2008	2009	2010	2011	2012
1	NIOSH	NIOSH	NIOSH	NIOSH	NIOSH	NIOSH	NIOSH
		ISO					
2		BAuA/VCI	ISO	ISO	ISO	ISO	ISO
3		ED/DP	BAuA/VCI	BAuA/VCI	BSI	BSI	BSI
4		BSI	BSI	BSI	BAuA/VCI	BAuA/VCI	BAuA/VCI
		ASTM	ASTM	ASTM			
		US DOE	US DOE	US DOE			
		Texas U.	SUVA	SUVA			

Public (white), private (dark gray), and hybrid (light gray). ASTM, American Society for Testing and Materials; BAuA/VCI, Federal Institute for Occupational Safety and Health/Chemical Industry Association; BSI, British Standard Institute; ED/DP, Environmental Defence/DuPont; NIOSH, National Institute for Occupational Safety and Health; SUVA, Swiss National Accident Insurance Fund; Texas U., Department of Engineering at Texas A&M University; US DoE, United States Department of Energy.

Table 4 Top ranked authorities in regulatory initiatives networks between 2006 and 2012

Rank	2006	2007	2008	2009	2010	2011	2012
1	NIOSH OSH	NIOSH OSH	NIOSH OSH	NIOSH OSH	NIOSH OSH	NIOSH OSH	NIOSH OSH
	NIOSH REL TiO2	ISO OAE					
2		NIOSH REL TiO2	ISO OAE	BSI SH&D ISO OAE	BSI SH&D	BSI SH&D	ISO OSH BSI SH&D
3		BAuA/VCI OSH	NIOSH REL TiO2	BAuA/VCI OSH	ISO OSH	ISO OSH	NIOSH REL TiO2
		ISO OSH	BAuA/VCI OSH		ISO OAE		ISO OAE
		BSI SH&D			BAuA/VCI OSH	BAuA/VCI OSH	BAuA/VCI OSH
4		US DOE	BSI SH&D	ISO OSH	US DOE	ISO OAE	NIOSH MS
		ED/DP	US DOE			US DOE	US DOE
		ASTM	ASTM		ED/DP	ED/DP	ED/DP
		Texas U.	SUVA OSH				

Public (white), private (dark gray), and hybrid (light gray). ASTM, American Society for Testing and Materials; BAuA/VCI, Federal Institute for Occupational Safety and Health/Chemical Industry Association; BSI, British Standard Institute; ED/DP, Environmental Defence/DuPont; ISO, International Organization for Standardization; NIOSH, National Institute for Occupational Safety and Health; OAE, Occupational Aerosol Exposure; OSH, Occupational Safety and Health; REL, Recommended Exposure Limit; SH&D, Safe handling and Disposal; SUVA, Swiss National Accident Insurance Fund; Texas U., Department of Engineering at Texas A&M University; TiO2, Titanium dioxide; US DoE, United States Department of Energy.

The picture in the regulatory initiatives network is slightly more complex. Still, some patterns have emerged, especially in later years as the network became more consolidated. The strongest authoritative source is clearly NIOSH guidance on *Approaches to Safe Nanotechnology* (National Institute for Occupational Safety and Health 2005, 2009). Other high-ranked initiatives with similar regulatory objectives (i.e. OSH risk management best practices) are: ISO technical report on *Health and Safety Practices in Occupational Settings Relevant to Nanotechnologies* (International Organization for Standardization 2008); BSI Guide to Safe Handling and Disposal of Manufactured Nanomaterials (British Standard Institute 2007); BAuA and VCI *Guidance for Handling and Use of Nanomaterials at the Workplace* (Federal Institute for Occupational Safety and Health/Chemical Industry Association 2007); and DOE guidance on *Approach to Nanomaterial ES&H* (Department of Energy 2008). These regulatory initiatives could potentially compete with one another over the supranational supremacy of regulatory practices in this specific area. However, this will require additional qualitative text analysis that is beyond the scope of this research.

Another centrality parameter is *betweenness* (Brands 2001), which measures how often a node appears on shortest paths between nodes in the network. It is used to identify nodes that serve as bridges between disconnected clusters in the network (Freeman 1977). High betweenness nodes are often critical to collaboration and to maintaining the spread of new knowledge throughout the network. Therefore, they have an important role as intermediary actors facilitating policy diffusion. The same analysis conducted for the authority score shows a similar range of betweenness for all sectors in both networks, except in 2012, when some differences appear in the regulatory initiatives network. This is explained by the size of groups and the range between the lowest and highest score of each group, which significantly widened in 2012 compared with earlier years. In absolute numbers, however, we found that, overall, the group of private organizations and regulatory initiatives is the largest in the top 10 percent of the networks. When comparing the numbers to the relative share of each sector in the networks, there is a larger portion of private and hybrid sectors in the top 10 percent. However, given the small size it is not possible to state that this finding is statistically significant. Furthermore, the lists of the four organizations and regulatory initiatives with the highest betweenness score also show that private actors play a dominant role in the diffusion of policies. They further show that the same key organizations and regulatory initiatives that received the highest authority score also had top betweenness scores (Figures and Tables available online in Supporting Information).

Finally, the *core and periphery* (Pajek's Blockmodeling algorithm) (De Nooy *et al.* 2011), which groups nodes into clusters and determines the relations between these clusters, was used to ascertain whether a network structure consists of sources that are tightly connected to each other (the core), and sources that are connected to the core but not to each other (the periphery). Where it exists, this type of structure provides the core with the opportunity to control the flow of information (De Nooy *et al.* 2011). In a regulatory governance network, this would mean some level of coordination that sets the regulatory tone for the entire network.

Running the algorithm on both networks between 2007 and 2012 reveals a steady core of four actors, of which at least 50 percent are private. As demonstrated in Figure 6, the core in the organization network consists of NIOSH, ISO, BSI, and ED-DuPont, and the core in the regulatory initiative network consists of NIOSH OSH, ISO OSH, BSI SH&D, and US DOE. Interestingly, three out of the top four authorities in the organizations network are part of the core (NIOSH, ISO, BSI), while the German partnership of BAuA and VCI is not. This may suggest some level of collaboration between NIOSH, ISO, and BSI on their recommended policy for OSH risk management best practices, while BAuA/VCI may take a different approach. Additional content analysis could determine whether this is the case.

5. Discussion

The data analyzed in this study represents the first 12 years of nanotechnology OSH regulatory initiatives development worldwide. While it is preliminary and allows us to investigate correlation rather than causality, initial observations suggest the following.

First, the *small world* properties of the networks support the first hypothesis that although the elements of the observed regulatory system are interdependent, information is efficiently exchanged among them. This means that the regulatory system is self-organized and that its norms tend to converge over time, even in the absence of intergovernmental organizations' central direction. Its evolution, however, does not follow Morin and Orsini's (2013) life cycle process of atomization → competition → specialization → integration. Rather, it more closely resembles Rogers' (1995) process of diffusion of innovation.

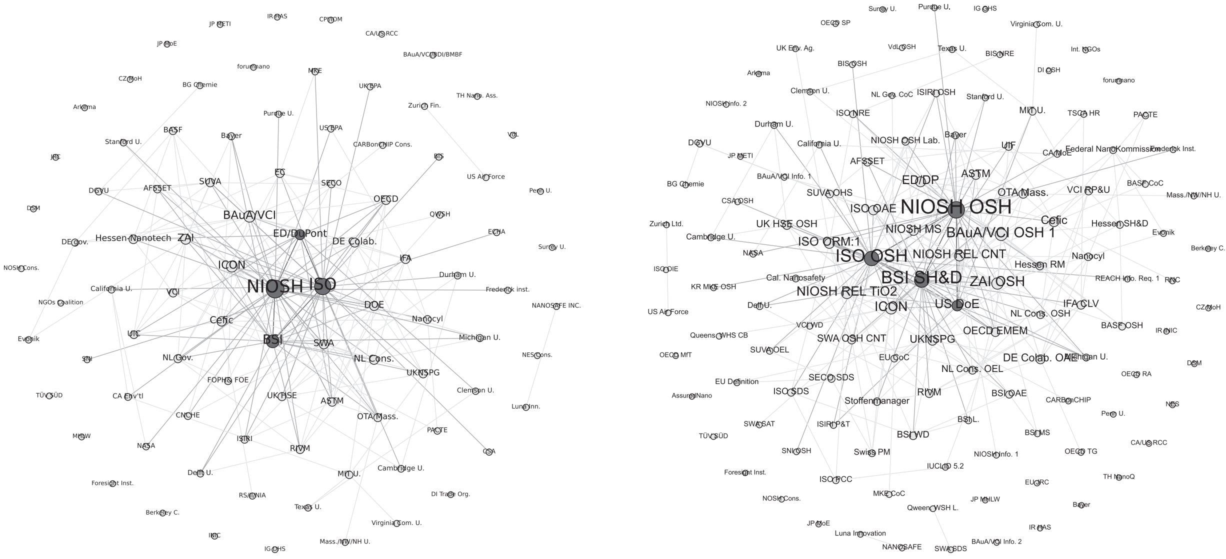


Figure 6 Core and periphery in the organizations (left) and regulatory initiatives (right) networks in 2012. Core (dark) and periphery (light), using a Fruchterman-Reingold layout algorithm.

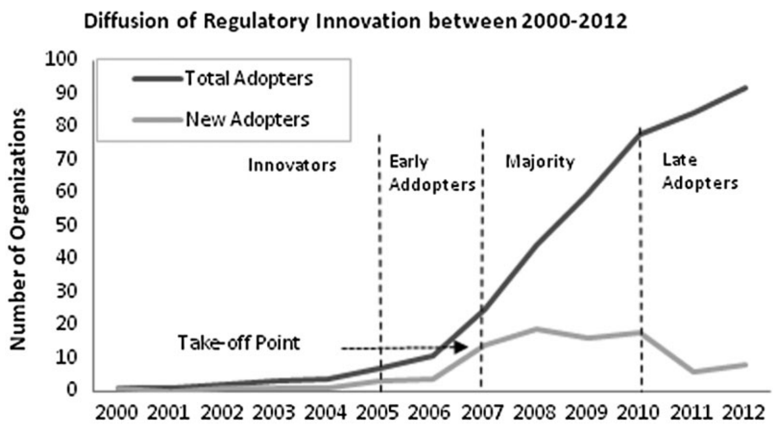


Figure 7 Diffusion of regulatory innovation among organizations between 2000 and 2012. Total number of adopters per year (black) and new adopters annually (gray).

The polycentric governance observed in this field seems to result from the widespread adoption of the new understanding that nanomaterials require specific OSH risk management practices. Although it is difficult to determine the exact phases as the field continues to evolve, as Figure 7 shows, it seems reasonable that between 2000 and 2005 a small group of innovators introduced the new regulatory concept and proved that it works. Between 2006 and 2007, early adopters who foresaw the future development of the field then decided to adopt the concept. According to Rogers' theory, this group has the highest amount of opinion leaders, and these serve as trendsetters. Indeed, our analysis found that regulatory initiatives first established in 2007 are the most cited in the network. This was followed by the entry of the majority of adopters, who, between 2008 and 2010, tripled the number of organizations involved in the field and led to a nine-fold increase in connectivity among them. This meant less independent innovation and more diffusion of existing knowledge. Between 2011 and 2012, this trend continued while the number of new organizations entering the field each year began to decrease and the connectivity increased further. This suggests that late adopters hardly innovate and mainly contribute to consolidation of the field.

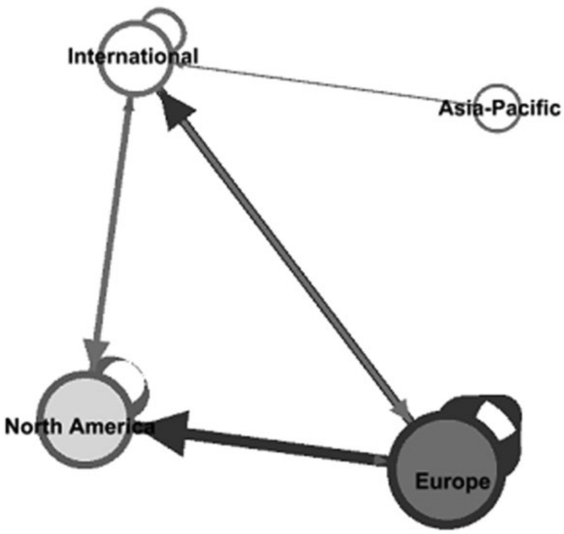
Second, the network structure shows that the regulatory system is characterized by high connectivity in the core of the network and that ties are not distributed equally. This supports the argument that the consolidation of the regulatory system entails "winners" and "losers" and is not the result of specialization and integration. The *network* *free-scale* and *peripheral attachment* properties further suggest that over time the "rich get richer," and that a small group of actors formed during the innovation and early adoption phases control the development and diffusion of regulatory practices years later. While the maturation of the field does not restrict entry of new actors, it is much harder for them to shape the widely adopted regulatory practices (Smith & Fischlein 2010), institutionalizing the "first-mover advantage."

One reason for this phenomenon could be the scientific uncertainty nature of the field and the common need for regulatory clarity and legitimacy. According to Dimaggio and Powell (1983, p. 156) "in fields characterized by a high degree of uncertainty, new entrants, which could serve as sources of innovation and variation, will seek to overcome the liability of newness by imitating established practices within the field." This leads to isomorphism after short "ideologically motivated experimentation." Thus, in the strive for legitimacy, uncertainty encourages imitation of an already established practice in the field. Over time, first mover organizations with established authority in certain policy issues (e.g. OSH risk management best practices) have the advantage of drawing more followers to their new policies in related issues (e.g. occupational exposure limits [OELs]), based on the path dependency that has been established in the network. As North (1990, p. 99) argues, "once a development path is set on a particular course, the network externalities, the learning process of organizations, and historically derived subjective modeling of the issues reinforce the course."

Third, citation patterns in the network show significant proximity effect on knowledge flow dynamics. This supports the third hypothesis that, despite globalization drivers, similar geographic, cultural, and institutional attributes have greater impact on choices related to policy models. However, our odds-ratio analysis of citations between different groups shows only the tendency to cite with single variable consideration. The interplay between the attributes and the relative tendency between them cannot be determined at this stage. Further investigation, mainly with exponential random graph models, could help decipher the complexity of the data. Still, the proximity effects in general may suggest interesting insights about the diffusion mechanisms of policies in this field. Given the early stage of this regulatory field and the lack of validated policy implementation experience or lessons-learned, proximity effects are more likely to suggest a mimetic process of institutional isomorphism, rather than a learning process. As Gabbay *et al.* (2001, p. 145) showed, institutional isomorphism "does not happen randomly and in a social structural vacuum" and the tendency is to mimic models in the immediate surroundings.

Citation patterns in the network, however, also show other strong heterophilic tendencies, which, as argued by Rogers (1995, p. 19), are crucial for facilitating the process of innovation diffusion and the spread of new ideas within the network. A good example is the strong tendency of international regulatory initiatives to cite North American regulatory initiatives, as well as the strong Asia-Pacific tendency to cite international regulatory initiatives. These tendencies may be explained by the influence North American actors have in initiating and negotiating international regulations, and by the political desire Asian actors may have to show conformity with international norms as global players. Nevertheless, as shown in Figure 8, which illustrates knowledge flows between geographic regions and their relative weighted in-degree and betweenness centrality, while Europe is the largest player in the field, the international players are better positioned on the path between the Atlantic and the Pacific and, therefore, are more influential in transpacific policy diffusion. Together, these patterns reveal how regulatory innovation is spread around the world and policies initiated in North America may find their way into the Asia-Pacific region through international intermediation. Furthermore, while the strong effect of geographic proximity in Europe and North America could result in transatlantic policy divergence, it is less likely in this field because of repeated reciprocal ties, which indicate significant exchange of information and possibly coordination between the two regions that also facilitate the progression of the field.

Similarly, the reciprocal ties between second party public and third party reveal the ongoing dialogue between the public sector and third party, particularly private standard-setting organizations. As shown in Figure 9, which illustrates knowledge flows between the regulatory parties ranked by their relative betweenness centrality and weight in-degree in 2012, the structure also indicates the authoritative shift that established new centers of information and facilitated the diffusion of policies. Our findings do not suggest that third parties, such as private standard-setting organizations, replace the traditional venue for regulatory decisionmaking, but they do show the decentralization of these venues. They also show the collaboration between the venues, which supports Auld and Green's (2012) argument that private authorities help promote cooperation and overcome path dependencies that public authorities may face. The reciprocal information flow between the regulators and the regulated further show how knowledge



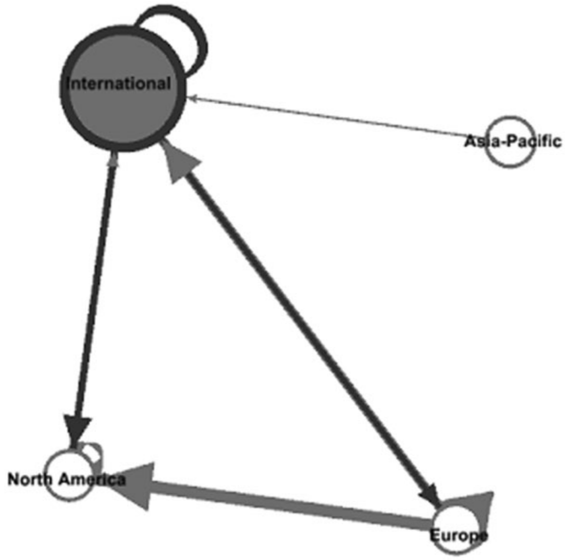
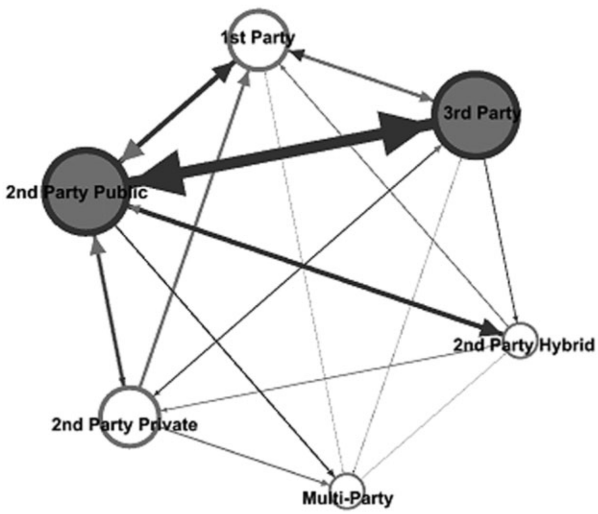


Figure 8 Knowledge flows between regions with at least eight repeated occurrences of citations from one region to another in 2012 ranked by weight in-degree (left) and Brandes betweenness centrality (right), using a Fruchterman-Reingold layout algorithm.



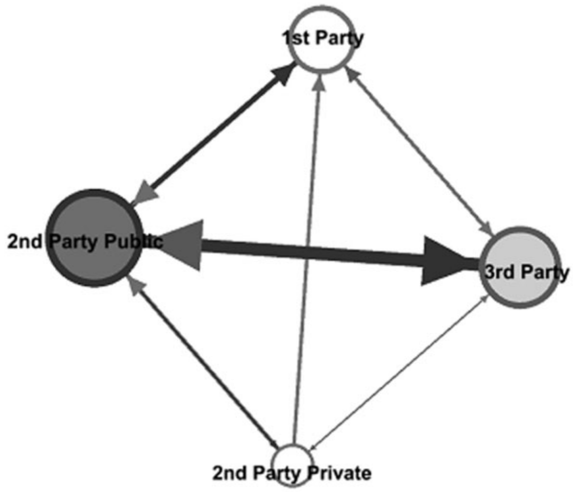


Figure 9 Knowledge flows between regulatory parties in 2012, ranked by Brandes betweenness centrality algorithm (left) and, filtered to show at least nine repeated occurrences of citations from one party to the other and ranked by weight in-degree (right), using a Fruchterman-Reingold layout algorithm.

is repeatedly exchanged between first, second, and third parties, who co-produce the regulatory norms. Thus, it stresses the importance of both public and private actors to advancing regulatory innovation.

Finally, the analysis of key actors in the network supports Hypothesis 4, that the private sector has significant influence on the development and diffusion of policies in the field of nanotechnology OSH. A closer examination of the key actors in the networks further shows the interrelation between public and private actors in regulatory innovation, and the role of intermediary organizations. NIOSH, which is the single most influential actor in the network overall, was among the innovators and early-adopter organizations. It started publishing guidance drafts in 2005, which, although only officially published in 2009, received many citations beforehand. NIOSH is not a typical public sector regulatory agency; it is the US federal agency responsible for conducting research and making recommendations for the prevention of work-related injury and illness, which, as a non-regulatory agency, has no mandate to set regulatory requirements. NIOSH's reputation as apolitical, scientifically rigorous, and independent (Bisom-Rapp 2009, pp. 17–8) allows it to posit itself as a "neutral" scientific expert and gain the trust of both the public and private sectors nationally and internationally. Rather than setting hard law regulations, it uses new governance techniques, such as collaborative problem-solving, and acts as a public intermediary (Bisom-Rapp 2009, p. 53).

The ISO, the second most important organization, established its Technical Committee (TC 229) on nanotechnology in 2005, and BSI (third in level of importance), which was the motivating force behind TC229's establishment, administratively manages it. Both are third party organizations that have been part of the early adopters group, and began publishing guidance documents in 2007. The chairmanship of ISO Working Group 3 on *Health, Safety and Environmental Aspects of Nanotechnologies* is held by the US delegation, and Project Group 1, which developed the flagship technical report on *Health and Safety Practices in Occupational Settings Relevant to Nanotechnologies*, is led by a NIOSH representative. This administrative relationship could potentially explain the collaboration between these organizations in the core of the network.

Furthermore, our analysis provides additional insight into the underlying dynamics of the reciprocal ties between second party public and third party organizations. It supports Büthe and Mattli's (2011) argument that both public and private actors recognize international private organizations as focal institutions for global rulemaking in their area of expertise, and shows that their consensus-based standards build a framework that provides government agencies with confidence to issue guidance for new technologies. By doing so, these private organizations enhance international collaboration and transnational governance integration faster and more effectively than traditional intergovernmental organizations, such as WHO (Snir 2015, p. 157).

The analysis may also suggest that by going through private international decisionmaking venues, national regulators can strategically diffuse their regulatory approaches to other countries. While this hypothesis requires additional research, preliminary findings suggest that the close relation between NIOSH and ISO helped to posit NIOSH and its regulatory approach to nanotechnology OSH risk management practices in the center of the global network. As also acknowledged in NIOSH's progress report *on Filling the Knowledge Gap for Safe Nanotechnology in the Workplace*, "[R]ecommendations given in the document have provided the rationale and basis for guidance documents developed by the Organization for Economic Cooperation and Development (OECD), the International Standards Organization (ISO), National Institute of Occupational Safety and Health Japan, and Safe Work Australia" (National Institute for Occupational Safety and Health 2012, p. 24). If this hypothesis is correct, the same pattern will be witnessed in the near future with regard to the regulatory approach to the development of OELs for nanomaterials. Currently, several countries (including the US, Germany, and the Netherlands) and private corporations have developed their own method (Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung 2011; NIOSH 2011, 2013; Social and Economic Council 2012), but more recently, the ISO has started developing a *General Framework for the Development of Occupational Exposure Limits for Nano-objects and their Agglomerates and Aggregates* (International Organization for Standardization 2013). A NIOSH representative leads the ISO project group and its list of experts includes, inter alia, 10 US experts and only one each from Germany and the Netherlands. Time will tell which of the national approaches have "won" in the international negotiation process.

6. Limitations

It is important to note some limitations to the dataset. First, possible additional initiatives may have been excluded as a result of language or access barriers. Second, the Global Nanotechnology Regulations database (from where the data set was derived) only indicates when the initiative was first introduced and does not reflect continuity over time; therefore, the evolving network does not show "aging" regulatory initiatives. Third, focusing on only one regulatory domain (i.e. OSH) leaves knowledge diffusion between other regulatory domains out of the analysis. Some organizations may also vary in importance within the narrow network compared to the broader regulatory governance network. However, this study focuses on their respective role in the process of OSH policy innovation in the nanotechnology field. Finally, content analysis of each reference may reveal some citations that do not reflect flow of influence as suggested in the introduction.

7. Conclusion

Network analysis is a useful tool for understanding regulatory governance relationships among organizations and regulatory initiatives. Network structure topology shows that although regulatory practices are developed interdependently by many organizations globally, few organizations significantly influence the formation of the norms and are responsible for their diffusion to the rest of the network. Network analysis is also useful to identify patterns in knowledge flows, which helps to understand the path of policy diffusion around the world. It also empirically shows the informal dialogue between public and private actors that advance regulatory innovation in the field and the importance of private actors, particularly third party organizations, in the development and diffusion of new regulatory norms. Finally, network centrality measurements can identify the *elite* group of actors in the network based on their position, and focus the attention on a small number of key organizations and regulatory initiatives. Additional qualitative investigation involving text analysis and in-depth interviews can support network analysis methods in identifying whose norms gain supranational supremacy.

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Notes

1 “Regulatory initiative” does not refer to literature reviews of best practices or policy statements, which do not have a normative call; nor does it refer to existing regulatory programs that may cover nanomaterials under their regulatory umbrella but have not been specifically adapted or used to address nanomaterials, as they do not contribute to the regulatory innovation in the field.

2 Studies on legal citation networks have mainly focused on analyzing citation patterns of court cases to measure the influence of individual judges or follow the diffusion of precedents and legal doctrines among jurisdictions (see e.g. Chandler 2007; Leicht *et al*. 2007). In related areas, few studies have analyzed citations in academic articles to follow the diffusion of scholars’ understanding regarding the nature of regulation (see e.g. Malloy 2010; Short 2011). However, scholars have rarely examined other legal documents (including legislations, regulations, voluntary programs, and self-regulations), and their citation linkage to study policy diffusion among organizations. Exceptions are Hamdaqa and Hamou-Lhadj 2009 and Kim 2013.

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Supporting information

Additional Supporting Information may be found in the online version of this article at the publisher's website:
Appendix S1 includes: The method used to develop the database and the criteria to determined the OHS-related regulatory initiatives group; A table presenting the Power law distribution fitness for Nanotechnology-OSH regulatory initiatives and organization networks between 2006 and 2012; Tables presenting citation distribution by country, language and regulatory role; Figure showing Betweeness ranks based on actors' sector in the organizations and regulatory initiatives networks between 2006 and 2012; Tables presenting top ranked betweeness in the organizations and regulatory initiatives networks between 2007 and 2012.

