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Systemic vulnerabilities of the global urban-industrial network to hazards

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Abstract

Systemic impacts such as global supply chain failures can spread among urban areas through social and economic linkages. Urban vulnerability to hazards has been studied from the perspective of individual cities, but global vulnerability to systemic impacts at the network scale has not been assessed. Here we analyze the structure of global industrial supply chains as a lens to examine how impacts might spread across the global system of cities. We generate a novel urban risk network that describes industrial flows among 1686 urban areas. In contrast to the prevailing view of the global urban system dominated by the largest, wealthiest cities, we show that the functionality of the network is evenly spread across urban areas. These findings suggest that the network is more vulnerable to multiple simultaneous hazards than to singular impacts to urban areas with the highest nodal strength. We also find that clusters of the most strongly connected urban areas transcend administrative boundaries, increasing the possibility for systemic impacts to spread transnationally. These results illuminate the potential for linkages between city-scale vulnerabilities to climate change impacts and systemic vulnerabilities that emerge at the global network scale.

1 Introduction

Anthropogenic climate change will profoundly impact natural and social systems over the coming century as natural hazards become more frequent and intense (Barros et al. 2014). These impacts will disproportionately affect inhabitants of urban areas, where natural hazards such as hurricanes (Comfort 2006), sea level rise (McGranahan et al. 2007), and extreme heat events (McCarthy et al. 2010) will be most pronounced. Urban areas account for more than half of the global population and 80% of the global GDP production (Grubler et al. 2012). As a

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result, societal sustainability under climate change critically depends upon the capacities of urban areas to mitigate and adapt to climate change impacts.

Hazards are more likely to be clustered temporally (for example, within a hurricane season) and geographically due to the increased frequency of hazards anticipated as a result of climate change. Clusters of hazards may stress cities more than the sum of individual hazards. For example, critical infrastructure systems compromised by recent prior hazards may have less capacity to recover from subsequent hazards. Conventional approaches to assessing hazards do not consider potential coupling among discrete hazard events (Turner et al. 2003). The effects of clustered hazards are neglected within frameworks that discretize hazards and, as a result, may underestimate the nonlinear impacts of climate change.

Recent worldwide supply chain failures highlight the role of increasingly global material chains in shaping systemic impacts that spread among urban areas through industrial interdependencies. Disruptions to material supply chains propagate through global networks as price shocks, material supply shortages, and reduced demand (Otto et al. 2017). Following massive flooding in Queensland, Australia, in 2010–2011, the global price of coal spiked (Queensland Treasury 2011), subsequently suppressing global steel production (Levermann 2014). Flooding in Thailand the same year resulted in worldwide shortages of computer components as well as disruptions to the automotive industry (Chongvilaivan 2012). These kinds of systemic impacts have primarily been studied through post hoc analyses of regional economic impacts. Forensic analyses of this type describe the magnitude and distribution of systemic supply chain impacts; however, this accounting has not generated insight into how these regional and global failures emerge from the structure of relationships underlying them.

Systemic impacts due to climate change have not been studied despite the demonstrated capacity of urban linkages to spread the socioeconomic effects of natural hazards, illuminated by phenomena such as supply chain failures. Conventionally, climate change impacts are studied at the site scale through case studies or at aggregate national and regional scales. Studies that estimate climate damages at the global scale (e.g., Hinkel et al. 2014) are designed to accumulate impacts but are not capable of accounting for the relational dependencies between urban areas that give rise to systemic impacts. Characterizing systemic impacts of climate change requires not just an increase in scale but also a new analytical framework to describe inter-urban dependencies.

2 Model motivation

Our approach represents the global urban-industrial system as a network. Systemic failures of networks depend on the structure and dynamics of relationships between nodes which govern how shocks spread through a system. We leverage insight from network analysis to characterize structural vulnerabilities of the urban-industrial system to the propagation of impacts among cities.

The application of network analysis to global urban networks has been limited by the lack of relational data. The structures of proxy networks are often studied in place of direct relationships between urban areas. Examples include networks of cities that are connected by global corporations (Sassen 1994), NGOs (Taylor 2004), or architecture firms (Knox and Taylor 2005). These networks consider a limited geographic scope because they depend on where these actors are located, and typically exclude industrial cities, megacities, and those in developing countries (Robinson 2002). Most urban inhabitants live in small- and medium-

sized cities (UN. 2014) so network data that describe only the largest cities excludes a significant portion of the urban system from analysis.

Geographic sampling biases have been overcome in the case of synoptic shipping network datasets such as air passenger travel (Guimera et al. 2005) and maritime freight (Ducruet and Notteboom 2012). However, the strength of relationships in the network may be influenced by economic or spatial constraints rather than the relationships between the urban areas they occupy (Derudder and Witlox 2005). This complicates their utility as proxies for the structure of functional urban relationships. For example, airport hubs may develop for logistical expediency, and not because the particular city occupied by the hub is hierarchically related to the spoke cities it connects. This analytical gap between network-scale structure and local urban processes limits the potential for these data to describe how the spread of systemic impacts across a shipping network would ultimately impact the urban areas in which it is situated.

Global industrial flows represent one mode of functional interdependency among urban areas (Decker et al. 2000). These transnational inter-industrial linkages are represented at the national scale by multi-regional input-output (MRIO) tables (Wiedmann et al. 2011). MRIO data have advanced our understanding of not just where environmental emissions occur but where the demand for these embodied impacts is generated. This has shifted our conceptualizations of how responsibility for environmental change is shared among both producers and consumers (Bergmann 2013). Disruption to these industrial linkages can spread economic impacts among connected places through the emergence of global supply chain failures (Bierkandt et al. 2014; Otto et al. 2017); however, the examination of supply chain failures with MRIO methods has primarily remained at the national scale. Vulnerability and exposure are heterogeneous subnationally among urban areas, limiting the potential to couple national-scale industrial networks with natural hazards at local spatial and administrative scales.

In this paper, we present a novel empirical network that advances the study of global urban climate impacts by bridging the gap between relational and attributional urban research across scales. Our network, UrbaN Industrial Connectivity Risk Network (UNICORN), quantifies functional industrial connections between urban areas. We characterized the robustness of the network by analyzing the intersection between network structure and the exposures of urban areas to hazards. Our qualitative analysis generates insight into which places are likely to generate or be affected by systemic impacts that emerge from natural hazards.

3 Methods

We analyzed the structural vulnerabilities of industrial linkages between urban areas. We focus on the systemic vulnerability of the global industrial network because the underlying capital dependencies of this system permit a conceptual bridge between the industrial flow network and local impacts to economic activity in and livelihoods of people in the urban areas it connects. Disruptions to industrial flows can spread economic impacts to both suppliers and purchasers by suppressing inputs to production or demand for outputs, respectively. These fluctuations in the flow network impact local economic and social systems through suppressed industrial activity and labor markets (Higuchi et al. 2012), providing a structural understanding of how natural hazards might spread among urban areas through inter-urban linkages.

We developed methods to generate the UNICORN dataset by combining several types of models to rescale national MRIO data to the urban scale (Fig. 1). The methods
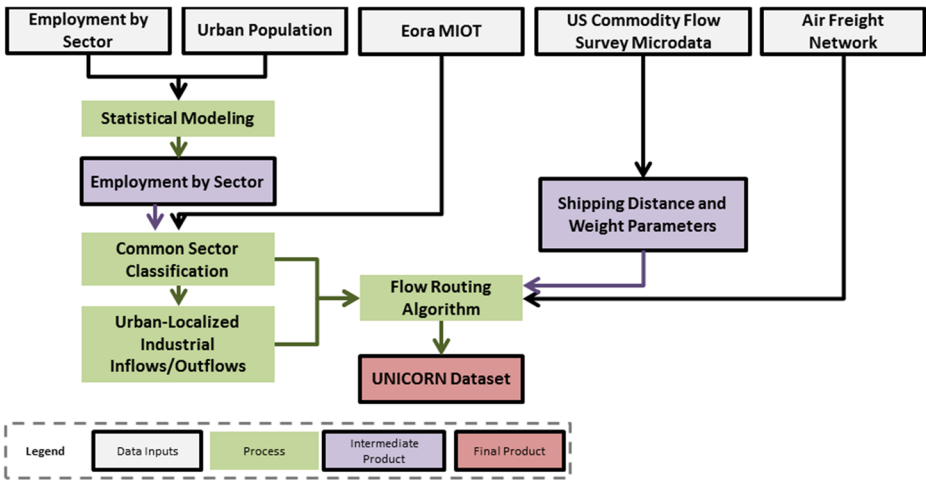
Fig. 1 Schematic of data inputs and workflow used to estimate the network. Processes (green) are described in the Methods section

are combined into two main modeling activities: (1) attributing industrial output by sector from the national to urban scale (Section 3.1) and (2) simulating a network of flows between urban areas that satisfies industrial output and input quantities allocated to each urban area (Section 3.2). We use input-output methods to quantify the magnitude of industrial production, inputs, and outputs within each urban area. This provides an attributional description of production within each urban area but does not describe the network of relationships between urban areas. We develop a simulation methodology that combines insight from gravity modeling—in which trade flow between two places is inversely related to distance between them—and empirical air freight network data.

The output network represents all urban areas with more than 300,000 inhabitants for a total of 1686 nodes. Edges between nodes represent flows of industrial inputs weighted by annual value (USD) and are directed from suppliers to purchasers. Each of 16 industrial sectors is represented as a layer.

3.1 Industrial output allocation

Proxy variables such as population or GDP are typically used to allocate national industrial output to subnational regions (e.g., Wenz et al. 2014). Multipliers estimated from these proxies represent the fraction of industrial output for each subnational region. We use sector-specific counts of employees (following Rosado et al. 2014) as a proxy for industrial output (see S1.2). The advantage of sectoral employment as a proxy is that unlike other data that do not distinguish between sectors (e.g., population), UNICORN represents differential allocation of industrial output within a country.

To estimate the outflow s of sector i in urban area r, we multiply the national outflow by the share of employees for sector i located in area r, E_{ir}:

$$s_{ir}^{\text{out}} = \frac{E_{ir}}{\sum_r E_{ir}} s_i^{\text{out}}, \tag{1}$$

And the analogous calculation is performed for inflows of inputs from sector j to r:

$$s_{jr}^{in} = \frac{E_{jr}}{\sum_r E_{jr}} s_j^{in}. \tag{2}$$

The quantity of inputs to each sector follows fixed recipes at the national scale and varies by country as a function of technology.

Employment estimates are drawn from national accounts and a Proquest International dataset compiled from national accounts. These data include values for at least one year for 35% of the cities included (representing 45% of the urban population). Missing data are estimated by regression (see S1.4) using national population, urban population, and the known distribution of industrial activities across urban areas and years. Eora and employment data do not conform to a single standardized classification of industrial sectors. In order to harmonize sectoral classification across data sources so that they could be combined, we developed a 16-sector common classification to which all employment and industrial data are converted (see S1.3).

3.2 Network wiring simulation

The simulation generates likely network configurations to describe the flows of industrial inputs between urban areas that correspond with industrial output localized to urban nodes (see S1.1). In order to reduce the solution space from which network configurations are drawn, two additional constraint datasets are added to the simulation. Eora data constrains sectoral flows between country-country dyads and air freight network data captures a portion of industrial flows at the airport-airport scale. Air freight data capture all air freight shipments that originate or terminate in a US airport. Additional proprietary freight data could be incorporated to further constrain the simulation such as maritime freight data.

The simulation takes the form of a discretized augmented gravity model. We use simulation to generate network configurations because the multi-scale constraints are not amenable to analytical solutions without incorporating additional simplifying assumptions. The simulation operates by moving discrete parcels of industrial output from supplier to purchaser node sectors. The simulation proceeds until all output and inputs have been satisfied.

We represent two modes of routing parcels between node sectors: through a generic gravity mechanism which is a function of distance, or through air freight network pathways which depend on distance and weights of links in the network. Air freight network data is incomplete and does not account for all industrial flows. In order to account for industrial inputs and outputs not represented in the air freight data, we also represent the generic routing mechanism. We do not assume that flows through the air freight network move between the urban areas and their nearest airports, which means that we do not determine in advance the quantity of output from each urban area that moves through the transit network. We represent both the generic and transit routing mechanisms simultaneously to allow the determination of shipping method to occur ad hoc. The sensitivity of shipments to distance is estimated from US freight microdata (BTS 2016) for each sector for the average across all transit modes and for the average across air freight shipments.

Air freight data describe the quantity of shipments by mass. These data do not describe if origin and destination airports represent airports of embarkation and disembarkation, or if freight is reshipped. To avoid restrictive assumptions about embarkation and disembarkation, we represent movement through the air freight network as a multi-step process in which

parcels have probability of being reshipped as a function of distance traveled weighed against the increased distance of reshipment.

Our model describes likely configurations of the network that satisfy all of the data constraints, but the model incorporates some stochasticity as flows are routed, so we run the model 100 times and describe the average characteristics of the network over these configurations. We generate network configurations for each year between 1990 and 2012, which is the range over which Eora MRIO data is available.

4 Results

4.1 Network structure and fragility

General structural properties of the network indicate how systemic impacts are likely to be generated and to spread. The network generated is sparse, with the ratio of edges to the square of number of nodes ranging from 0.06 to 0.16. UNICORN is best described as a small-world network (Watts and Strogatz 1998)—it has a short characteristic path length $\langle l_{char} \rangle$ relative to a random network l_{rand} and has a higher clustering coefficient C than a random network C_{rand} (complete network statistics in Table S3). Small-world networks are characterized by clusters of nodes with dense in-cluster connections and sparse between-cluster connections. This structure makes small-world networks more fragile to cascading failures than either scale-free or Erdos-Renyi random graphs because the capacities of nodes in the same cluster are more likely to become overloaded (Xia et al. 2010).

An increase in mean degree $\langle k \rangle$ reflects an increase in the number of nodes across which systemic impacts could spread and dampened. Increased connectivity is also illustrated by a reduction in the mean characteristic path length $\langle l_{char} \rangle$ which represents that the distance between nodes decreased. These increases in connectivity are generally associated with increased network robustness but the magnitude of the effect on vulnerability depends on the dynamics of failure propagation in the network.

The potential for a node to generate a systemic impact depends on the distribution centrality, degree, and strength across the network. In homogeneous networks of similarly central and strong nodes, all nodes are equally likely to generate systemic impacts. In contrast, systemic impacts are only likely to be generated in the most central or strong nodes of highly heterogeneous networks (i.e., scale-free; Xia et al. 2010). We found that the distributions of these variables in UNICORN are relatively homogeneous (Fig. 2). The distributions are right-skewed but are not as heterogeneous as a scale-free network. This suggests that systemic impacts are more likely to result from simultaneous impacts across nodes than from single impacts in critical central nodes. This suggests that the average urban area is relevant to the generation of systemic impacts and not just the largest cities such as New York and London.

4.2 Spread of systemic impacts

We identified functional clusters of urban areas in UNICORN using a weighted Louvain clustering algorithm (Blondel et al. 2008). The clusters defined by this process represent sets of nodes among which the magnitude of within-cluster ties is maximized relative to the magnitude of between-cluster ties. The 1990 network is best described by 58 functional clusters and the 2012 network by 37 clusters (Fig. 3). Between the two years, cluster consolidation is most
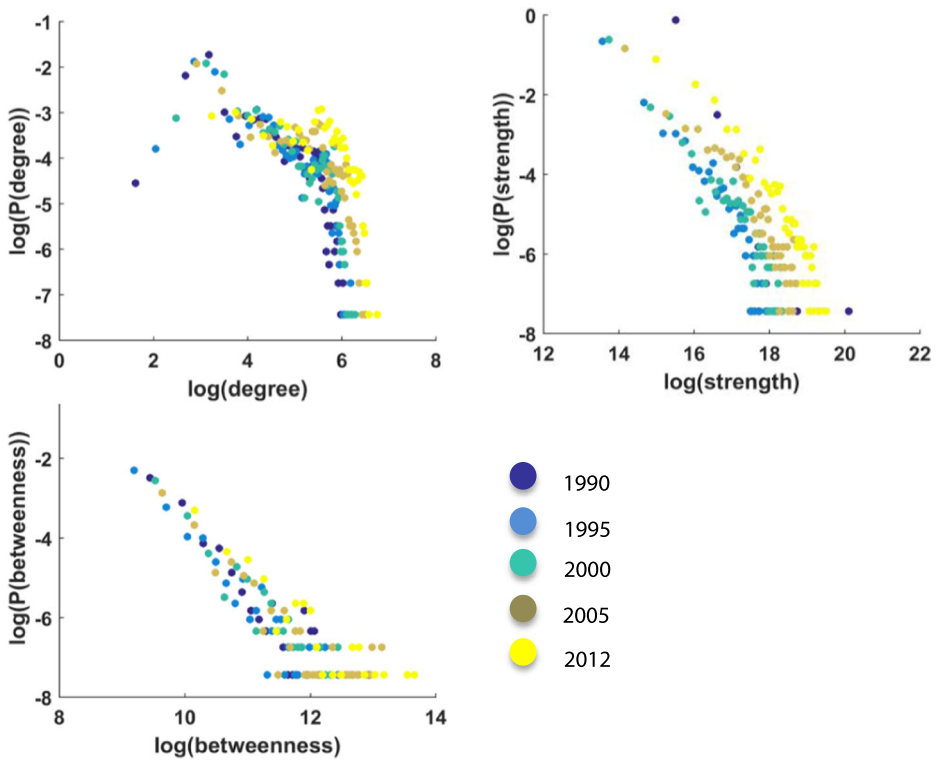
Fig. 2 Distribution of node strength, degree, and betweenness centrality

notable in East Asia, North America, and Southern Africa. The consolidation of clusters corresponds with increased connectivity strength between the two merged clusters. While increased connectivity increases the robustness of the network overall, it also results in more expansive clusters. These expansive clusters could result in a larger set of cities through which
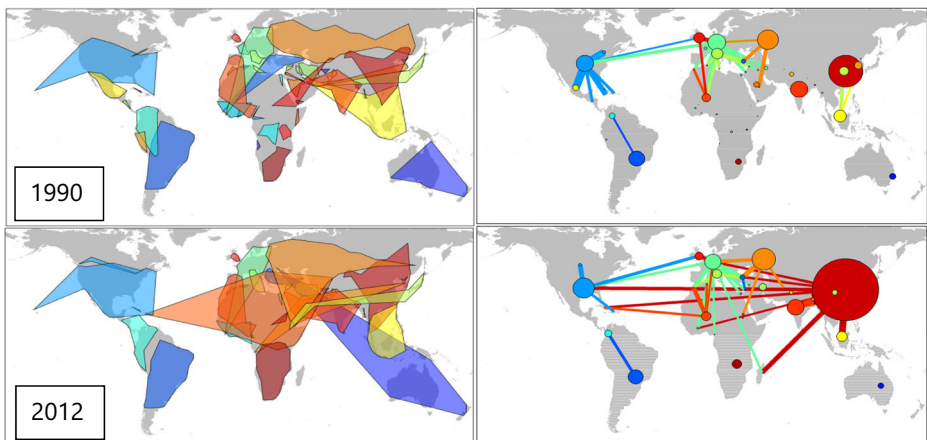

Fig. 3 Polygons bounding constituent cities for each cluster (left). Cumulative strength of urban areas in each cluster (circles, right). Edges represent inputs ≥2% of total inputs into receiving cluster and thickness is proportional to fraction of inputs

a systemic failure is likely to spread by virtue of their strong interdependencies. However, the net result on systemic impacts of these countervailing effects of connectivity cannot be directly inferred from the structural characteristics of UNICORN (Babaei et al. 2011).

The geographic situation of functional clusters indicates where systemic impacts are likely to spread globally. The geographic footprint of systemic impacts will determine which communities are most exposed and the relevant scale for mitigation and adaptation. We identified the overlap between functional clusters and national boundaries as a first-order measurement of how the footprint of clusters corresponds with the administrative footprint of countries. Qualitatively, the clusters tend to contain spatially proximal urban areas. We represented the overlap between functional clusters and administrative boundaries as a normalized mutual information (NMI) index. The NMI index describes the similarity between the two data partitions defined by the functional clusters and administrative boundaries.

In 1990, the national boundary and functional cluster partitions shared 92% information. By 2012, the information shared by the partitions statistically significantly decreased to 87%. This indicates that functional clusters are largely contained within national boundaries, but that a substantial portion of functionally clustered cities transcend national borders. As a result, the spread of systemic impacts through functional clusters is also likely to spread the impacts transnationally.

4.3 Global pathways and distribution of systemic impacts

We examined the strongest industrial linkages among clusters to identify regional interdependency patterns that might shape pathways for the global spread of systemic impacts. We focus on the cluster scale to highlight regional interdependencies, which are obscured in the node-level network because the strongest between-node linkages are distributed within geographically local clusters. In 1990, the strongest inter-cluster linkages stem from clusters in North America and throughout Europe (Fig. 3). Clusters in these regions are linked among themselves as well as with clusters in Northern Africa, the Caribbean, and the Middle East. By 2012, clusters in East Asia were the predominant sources of inter-cluster linkages. Clusters on the receiving end of these inter-cluster linkages are primarily located in Northern Africa, the Middle East, and the Caribbean across years.

An uneven distribution of inter-cluster linkages may lead to differential patterns of exposure to systemic impacts at global scales. Systemic impacts are more likely to spread among clusters with strong interdependencies. Clusters that receive inter-cluster linkages are likely to be affected by the spread of systemic impacts from clusters that generate the linkages through supply shortages. The strongly inter-linked clusters in North America, Europe, and East Asia are likely to both generate and receive systemic impacts mediated by these linkages. By contrast, the clusters in the Middle East, Northern Africa, and the Caribbean are unlikely to generate systemic impacts because few clusters have dependencies on them, but are likely to receive systemic impacts because they have dependencies on highly embedded clusters.

4.4 Urban network exposure to hazards

The geographic space occupied by urban areas is inhomogeneous physiographically as well as socially and politically. The likelihood that the urban network will be affected depends on the intersection between these geographic domains and the spatial situation of the urban areas through which the system functions. We calculated the aggregate normalized strength—the weight of industrial flows through a node—of urban areas within each world region as a first-

order approximation for where network functionality is located and the overall exposure of the network to hazards.

Regional changes in strength partially reflect trends in urbanization, with Asia urbanizing the most rapidly on average (UN 2014). A majority of the network strength is situated in North America and East Asia in 2012 (Fig. 4). Nodes in East Asia increased most in strength relative to other region between 1990 and 2012. Changes over time in all regions are statistically significant across simulation runs (Fig. 4).

We overlaid the network with historic exposure to flooding, drought, and cyclones to identify how the regional functionality of the network intersects with natural hazards. Exposure represents the proportional GDP loss risk generated by historic hazards between 1981 and 2000 for a 2.5-min-resolution global grid (CHRR 2005; Dilley et al. 2005). Relative proportional economic impacts for each hazard are represented as deciles, and we group deciles into low exposure (deciles 1–3), moderate exposure (deciles 4–7), and high exposure (deciles 8–10). We found substantial overlap between high-exposure areas and normalized network strength. For example, most of the network strength in East Asia, Eastern Europe, and North America is situated in cities with high or moderate exposure to flooding. This pattern intensified between 1990 and 2012 with an 11% increase in the urban strength exposure to a high risk of flooding.

The geographic proximity of most nodes within functional clusters (Fig. 3) suggests that some clusters may be disproportionately likely to generate systemic failures. Exposure to natural hazards is also geographically clustered, for example, of the type illustrated with our regional overlap analysis. Exposure to multiple nodes within a cluster has a greater likelihood of generating such an impact than a diffuse exposure across nodes that are less strongly
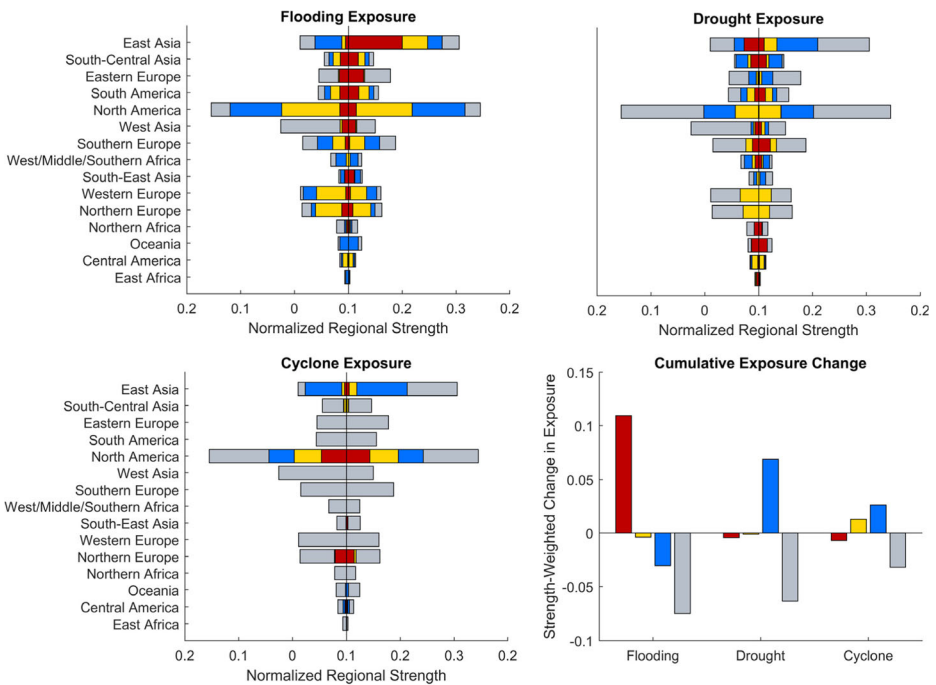

Fig. 4 Cumulative normalized nodal strength of cities within each region in 1990 (left) and 2012 (right). Cumulative normalized nodal strength within high exposure (red), moderate exposure (yellow), low exposure (blue), and unexposed (gray) locales for each region

connected because of the potential to overload the capacities of those clustered nodes (Xia et al. 2010). High exposure to flooding across Asia and Europe and clustering of cyclone exposure in East Asia and North America increase the likelihood that these exposures could precipitate systemic impacts within functional clusters centered in these regions.

Clusters with a large share of network strength, high exposure to natural hazards, and dependencies from other clusters pose a particularly high risk of generating and spreading systemic impacts globally. For example, the East Asian cluster is the most strongly embedded by 2012. This geographic region is also generally the most exposed to flooding hazards historically. This illustrates the roles of both network structure and geography in the generation of systemic impacts, and the potential for increasingly intense and frequent natural hazards due to climate change to unevenly affect urban areas in the network.

The vulnerability of urban areas to climate change impacts depends on myriad local factors including wealth, institutional resources, and social networks. Smaller cities generally have fewer material and social resources available than large cities, making them more vulnerable to
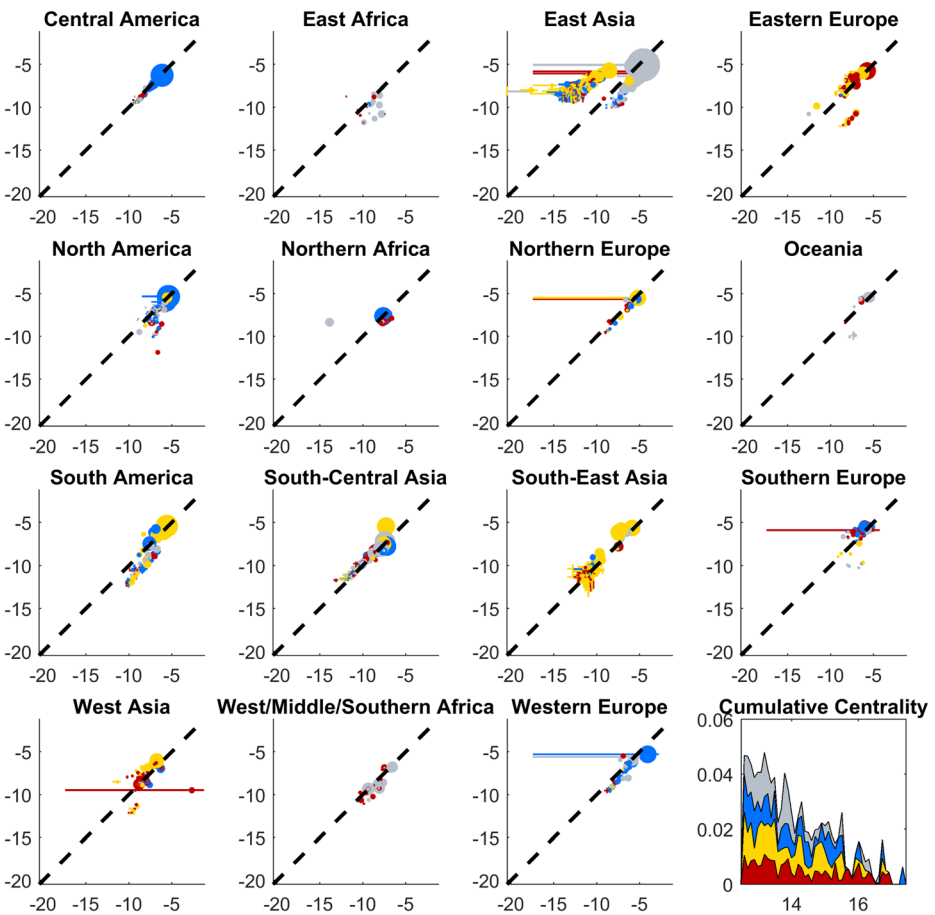
Fig. 5 Regional plots of log(normalized strength, 1990) vs log(normalized strength, 2012). Each point represents one city with size proportional to the population in 2012. Color represents exposure to flooding. Cumulative normalized strength plots log(population, 2012) vs log(normalized strength, 2012). The colored area represents the cumulative exposure by risk category for flooding

climate exposures on average. However, we found that half of the strength in the network is situated in small cities—those with fewer than 1 million inhabitants. Globally, small- and medium-sized cities are the most predominant (UN 2014) and the magnitude of strength situated in these smaller cities reflects this prevalence. Smaller urban areas in East Asia, for example, are also proportionally more exposed to hazards than larger cities (Fig. 5). These features suggest that small cities in high-exposure regions are both more likely to be directly affected by climate change impacts and to generate systemic impacts at aggregate scales due to their predominance in the system.

5 Discussion

We found that small cities play a bigger role in the functionality of the global urban-industrial network than previous studies of urban networks have suggested. Conventional studies of urban networks focus on a theoretical core comprised of major cities such as London and Tokyo. However, we found that most of the strength in the urban industrial network is situated outside of these "global" cities. The structure of UNICORN challenges prevailing expectations about the role of "global" cities in the world system by demonstrating the functional contribution of smaller urban areas—accounting for half of the network strength—and of urban areas in the developing world. Our results provide a new perspective on the global network in which small urban areas substantively participate. Whereas global climate change impact analyses have primarily focused on the wealthiest, largest cities, our results show that these cities are not uniquely critical to the emergence of systemic impacts.

The structure of the network indicates how more frequent and intense hazards due to climate change impacts are likely to spread among urban areas. Strong linkages among groups of urban areas lead to the emergence of functional clusters; and systemic impacts are most likely to spread within these clusters. Our analysis illustrates differential overall exposure to hazards across these clusters due to their geography. Urban areas that are highly exposed to climate change impacts are also likely to be affected by systemic failures because of this overlap between structure and exposure. For example, urban areas in East Asia have relatively high exposure rates to flooding. This physiographic pattern of exposure is likely to be amplified by systemic failures because these urban areas are also strongly connected within a functional cluster. This finding points to a new way of understanding how direct and systemic impacts could nonlinearly reinforce each other at intermediate scales and might intensify patterns of climate change impacts.

At the global scale, systemic impacts are likely to spread unevenly among clusters based on the strength of inter-cluster dependencies. Clusters in the Global North generate most of the inter-cluster industrial dependencies among all clusters. Climate change impacts in urban areas in this world region are structurally poised to spread to urban areas in other clusters through supply disruptions. By contrast, climate change impacts in urban areas in the Global South are more likely to be contained locally because there are fewer global industrial dependencies on these clusters. This illustrates how urban areas will be differentially affected by systemic failures as a result of their position in the global structure—independent of local exposure conditions. Systemic impacts play a role not just in amplifying but also in redistributing climate change impacts as a result of this structural unevenness.

The structure of the global urban network provides new insight into how climate change might exacerbate the emergence of systemic failures. An even distribution of node strength

indicates that all urban areas could participate in the generation of systemic failure. In an alternative hypothetical network dominated by a few urban areas, the network would be highly sensitive to failures in those urban areas with the highest nodal strength, but unaffected by failures in all others. While the hypothetical network would be most affected by an increase in the intensity of climate change impacts in the urban areas with the highest nodal strength, UNICORN suggests the urban network is more likely to be critically affected by simultaneous climate change impacts across multiple urban areas. This suggests that the increasing frequency of climate change impacts will be more relevant to systemic failure generation at the network scale than increases in intensity. Previous studies of urban climate change impacts primarily focus on the intensity of climate change impacts, but the timing and frequency of impact have generally not been studied. Climate change impact studies typically take a city-by-city approach and are not capable of accounting for temporal dynamics mediated by network structure through which climate change impacts could interact. UNICORN provides a new analytical framework for examining fragility that emerges at the network scale. This approach represents a radical departure from the existing paradigm for studying urban-scale climate change impacts toward illuminating effects at the global urban scale.

We found that administrative boundaries only partially overlap with functional clusters in the network. This suggests that systemic impacts are likely to spread transnationally among urban areas through strong intra-cluster feedbacks, and not exclusively through relatively weak inter-cluster linkages at the national scale. Recent hazards demonstrate how systemic impacts spread transnationally between directly connected locales. For example, the 2011 tsunami in Japan caused automotive supply chain shortages that reduced output in the USA by as much as 400,000 units (Canis 2011). Automotive production was reduced for several weeks in Louisiana, Kentucky, Texas, and Indiana, where GM and Toyota factories are located (Stein 2011). Our analysis suggests that inter-urban systemic impacts like these that transcend national boundaries are not irregular, but result from the increasingly transnational structure of the urban industrial network. This indicates inherent limitations of national governments to address systemic climate change impacts—even a comprehensive national strategy for mitigating climate change impacts would not be sufficiently expansive to capture all of the urban interdependencies related to systemic impacts.

Our model generates synoptic estimates of functional linkages between urban areas globally. Previous studies of urban networks describe complex measured or inferred social relationships. The effects of perturbations on social networks with complex linkages cannot be inferred from their structure because the content of the flows is unobserved. The systemic impacts resulting from a failure in such a social network depend on the particular function of the failed node, which is not directly represented in the network data. By contrast, UNICORN is an economic network that describes unambiguous capital flows. These flows have direct effects on the productivity of the urban areas they connect. The other significant innovation of UNICORN is the incorporation of a global sample of cities. Our model merges multi-scale datasets which enables it to incorporate all available data about the system. This allows us to estimate flows in the network not just the portions situated in cities with available data (which often only include the largest, wealthiest cities) but also for cities in which only regional- or national-scale data is available.

Our analysis draws a network analytic approach, focusing on how patterns of exposure, such as how interactions among geographically and temporally clustered hazards resulting from climate change, may produce global outcomes characteristically distinct from the aggregate of individual hazards. This approach provides insight into the effects of changing patterns of exposure, such as the increase in intensity and frequency of hazards anticipated as a result of climate change, on

global systemic impacts. Hazard research is typically agnostic to geographic patterns in exposure because connections among places are not considered. Our network approach allows us to examine the effects of geographic and structural exposure patterns on global vulnerabilities; however, network analysis does not permit a causal relationship between any individual hazard and its subsequent systemic impacts. As a result of this trade-off, the UNICORN framework is more amenable to analyzing patterns of hazards at global scales, such as those associated with increasing frequency due to climate change, rather than an individual hazard.

Our analysis utilizes the functional relationships described by UNICORN to draw new insights into how urban areas are connected and generic failure properties of this network. Measures such as strength and degree are well constrained by the model and have limited variance. This makes the network suitable for structural analysis including the analyses we have presented; however, there is significant variance on the weight of some individual edges in the network. This variance limits the amount of confidence in the estimated weight of any particular edge. This could be improved by the inclusion of more city-scale and network data, such as additional urban-scale employment estimates or the inclusion of additional shipping network data (e.g., maritime freight data). Our analysis advances the study of climate change impacts by developing a network framework to describe global-scale urban dependencies.

6 Conclusion

Linkages among clusters with the highest historical exposures to natural hazards suggest the structural potential for the systemic impacts from more frequent and intense hazards due to climate change to spread globally. Uneven linkages between urban clusters may bias the global spread of these impacts toward urban clusters in the Global South. This result highlights the potential for the structure of relationships to affect the geographic distribution of systemic climate change impacts, which may compound existing inequities in the distribution of climate change impacts.

The network framework operationalized here provides an avenue for further examination of systemic climate change impacts and their dynamics. Our results indicate the potential for interaction among systemic impacts that are spatially and temporally clustered. This has implications for systemic vulnerability resulting from increasingly frequent climate change impacts over the coming century. Our results draw new hypotheses about how these impacts might spread, but the magnitude and geographic expanse of these effects will depend on the dynamics underlying the spread of systemic impacts. Additional work coupling dynamics to the structure of UNICORN would provide insight into the potential for systemic impacts to amplify and redistribute climate change impacts, or to precipitate catastrophic hyper-risks to society.

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