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The Technological Resilience of U.S. Cities

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JEL codes: O33, R11, L65, D83

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The Technological Resilience of U.S. Cities

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Abstract: We study the resilience of cities by analyzing their capacity to sustain the production of technology when facing adverse events. Patent applications for 366 U.S. Metropolitan Statistical Areas, spanning the period 1975 to 2002, are used to analyze the vulnerability and response of cities to technological crises. Crises are defined as periods of sustained negative growth in patenting activity. We find that the frequency, intensity and duration of technological crises vary considerably across American cities. We examine how the technological knowledge bases of cities, their network openness and institutional environment condition resilience. Econometric analysis suggests that cities with knowledge bases that are diverse, flexible and proximate to technologies in which they do not currently possess comparative advantage tend to avoid technological crises, have limited downturns in patent production and recover faster from crisis events.

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1. Introduction

For much of the last forty years, the cities in the old manufacturing core of the United States have found themselves in a persistent downward slide, shedding jobs, investment and much hope for the future. Over the same period, many cities in the South and West of the country have experienced considerable growth. This simple Snowbelt-Sunbelt division captures the relatively broad-scale spatial logic of regional uneven development in the U.S., at least since the early-1970s, but it fails to identify those cities whose fortunes differ in significant ways from that of their regional neighbours. A small number of Snowbelt cities have experienced growth at rates above the U.S. median since 1975, while some cities in the Sunbelt have declined substantially. Why is it that some cities and regions have failed to maintain their historical rates of growth while others have passed them by? Why are some cities more resilient than others, escaping repeated slides in performance or at least limiting the intensity of short-run shocks that weaken competitors? Still other cities appear capable of repeated re-invention over the long-run, abandoning obsolete sectors, modes of work organization and institutional practice, and avoiding the lock-in that may bring gains that are all too often short-lived.

Economic geographers have recently embraced the concept of regional resilience, though the resulting debate suggests they are far from a common understanding (Christopherson et al., 2010; Pendall et al. 2010; Pike et al. 2010; Simmie and Martin 2010; Fingleton et al., 2012; Martin 2012). What is clear is the tendency to refute equilibrium-based approaches, in which resilience is analyzed as a short-term response to external shocks and a move back to a steady state. In place of equilibrium, scholars have advocated an evolutionary approach to regional resilience that focuses on the long-term capacity of regions to reconfigure their economic and institutional structures to develop new growth paths (e.g. Christopherson et al., 2010; Simmie and Martin 2010; Bristow et al. 2012).

However, the concept of regional resilience is still underdeveloped (Boschma 2014). First, there is a need to unite independent literatures that focus either on the short-term capacity of regions to absorb shocks, or on the long-term capacity of regions to develop new growth paths. Second, there is a misleading tendency in much existing work to equate resilience with the avoidance of path dependence. We argue that the legacy of the past has a strong imprint on regional resilience, as it sets the scope for re-orientating skills, resources, technologies and institutions within different geographical units. Recent empirical work has demonstrated that pre-existing resources and capabilities in regions are often rejuvenated and redeployed in new combinations that shape new growth paths in regions (Neffke et al.

2011; Rigby 2013; Boschma et al., 2014a). Third, the existing literature has been criticized for ignoring key dimensions of resilience, like technological relatedness, network structures and institutions.

The objective of this paper is to account for these critiques when explaining the technological resilience of U.S. cities over the period 1975 to 2002. We focus on cities as centres of knowledge production, and we view resilience as the capacity of cities to maintain their levels of knowledge creation over the long-run. We explore how the flexibility of urban knowledge cores, the openness of city networks and the institutional structure of cities impacts resilience. Three dimensions of resilience are analyzed: the capacity of U.S. metropolitan areas (1) to withstand periods of technological slowdown or crisis, (2) to limit the intensity of crises, and (3) to shorten the duration of crisis events. Econometric analysis suggests that cities with knowledge bases that have high levels of relatedness to the set of technologies in which they do not yet possess comparative advantage have a higher tendency to avoid crises and a greater capacity to limit the intensity and duration of crisis events. The institutional character of cities and the position of cities within the U.S. urban network are more varied in their impacts on resilience.

The structure of the paper is as follows. In Section 2, we briefly discuss the regional resilience literature and offer a simple conceptual frame that allows us to explore how resilience might be operationalized. Section 3 turns to questions of data and identification of episodes of technological crises confronting cities. Section 4 provides descriptive statistics concerning the dynamics of knowledge production across the U.S. city system since 1975. In Section 5, a model of the technological resilience of cities is presented, that model is estimated and results discussed. Section 6 offers a short conclusion.

2. Regional resilience

The resilience of regions has recently generated much interest within economic geography and related fields (Swanstrom et al., 2009; Bristow 2010; Christopherson et al., 2010; Hassink, 2010; Pendall et al. 2010; Pike et al. 2010; Simmie and Martin 2010; Treado, 2010; Wolfe, 2010; Cooke et al., 2011; Fingleton et al., 2012; Hill et al. 2012; Martin 2012; Diodato and Weterings 2014; Martin and Sunley 2015). A recurrent concern within this literature is the fuzziness of the concept of resilience (Pendall et al. 2010; Martin, 2012). Economic geographers have tended to refute engineering-based approaches that view regional resilience as the ability of regions to return to a pre-existing stable equilibrium state after a shock (Rose 2004; Fingleton et al. 2012). This definition fails to reference long-run changes in the structure and function of regions (Martin 2012). Understandings of resilience inspired by ecology (e.g. Reggiani et al. 2002; Swanstrom et al. 2009; Zolli and Healy 2012) have also been criticized for failing to capture structural changes and the role of human agency and institutions in directing regional dynamics (MacKinnon and Driscoll Derickson 2013).

An evolutionary approach to regional resilience has been proposed instead (Christopherson et al. 2010; Clark et al. 2010; Pike et al. 2010; Simmie and Martin 2010; Cooke et al. 2011; Bristow et al. 2012). This approach focuses on the long-term evolution of regions and the ability of economic agents to adapt and reconfigure their industrial, technological, network and institutional structures within an economic system that is in constant motion (Swanstrom 2008). These dynamics are twinned to processes of capitalist competition that continually reorder the competitive standing of technologies, modes of organization and institutions and, in aggregate, the firms and regions within which they are embedded.

However, the evolutionary perspective on regional resilience remains underdeveloped for four reasons (Boschma 2014). First, the evolutionary literature has focused on the capacity of economic agents in regions to induce structural change and develop new growth possibilities in terms of path creation and path renewal (Pyka and Saviotti, 2004; Garud et al 2010). By doing so, it has successfully criticized the resilience literature for ignoring how shocks affect long-term regional competitiveness and for ignoring the ability of regional actors to create new growth paths (Boschma, 2014). Still, these evolutionary claims remain rather disconnected from the core focus of the resilience literature, namely, the capacity of regions to absorb shocks, and the speed with which they can recover from them. This implies that an evolutionary approach to regional resilience has to make explicit what characteristics of regional economies help them avoid shocks, what local characteristics and processes limit the intensity of shocks once they occur, and how the duration of shocks may be limited.

Second, there is a tendency in the literature to equate regional resilience with the avoidance of path dependence, as if path dependency causes only problems of adjustment, and as if regions need to escape from their historical legacy to develop new growth paths (Ebbinghaus 2009; Magnusson and Ottoson 2009; Henning et al. 2013; Boschma 2014). We argue instead that the legacy of the past has a strong imprint on regional resilience, as it sets the scope for re-orienting skills, resources, technologies and institutions in regions. A large body of empirical studies has shown that pre-existing geographies of resources and capabilities tend to shape new regional growth paths (Rigby and Essletzbichler 1997; Bathelt and Boggs 2003; Glaeser 2005; Klepper 2007; Belusssi and Sedita 2009; Buenstorf and Klepper, 2009; Treado 2010). New key technologies tend to branch from and recombine local resources and capabilities (Tanner 2011; Boschma et al. 2014b; Colombelli et al. 2014), and new industries tend to emerge from existing related sectors (Klepper and Simon 2000; Neffke et al. 2011; Van der Wouden 2012; Boschma et al., 2013; Essletzbichler 2013; Muneepeerakul et al. 2013; Rigby 2013). It is also important to understand how institutional structures within regions provide opportunities and set limits on the types of new growth paths that can be developed (Amable 2000; Hollingsworth 2000; Hall and Soskice 2001; Thelen 2003; Streeck and Thelen 2005; Ebbinghaus 2009; Strambach 2010). In sum, developing new growth paths in regions does not necessarily mean breaking with the past, for the resilience of regions depends to a considerable degree on their history.

Third, the regional resilience literature has given little attention to the role of networks (Martin and Sunley 2007; Swanstrom et al. 2009; Pendall et al. 2010; Bristow et al., 2012; Bristow and Healey 2014). What seems to matter for regional resilience is the internal structure of a region's knowledge network (Fleming et al. 2007; Vicente et al. 2011; Balland et al. 2013; Crespo et al. 2013), and the connectivity and openness of those networks to knowledge developed elsewhere (Asheim and Isaksen 2002; Bathelt et al. 2004; Moodysson 2008; Dahl Fitjar and Rodríguez-Pose 2011), and the ability of regions to efficiently absorb external knowledge inputs (Cohen and Levinthal 1990). The structure of a region's knowledge acquisition network is critical in terms of preserving the quality of technological information exchanged and mitigating problems of knowledge acquisition, especially when network links are broken and when processes of search are uncertain (Hagedoorn and Duysters 2002; Nooteboom and Gilsing 2004). Watts and Strogatz (1998) examine a continuum of network types characterized by different degrees of clustering and path length. They establish the importance to knowledge production of small-world networks, characterized by high local clustering and low path length, a function of trust generated in local clusters (Granovetter 1985) and preservation of the fidelity of knowledge flowing along short paths (Verspagen and Duysters 2004; Fleming et al. 2007). It is also important to recognize that network structure is itself an emergent property of a set of interacting agents and behavioural routines that are distributed across the economic landscape (Kogut 2000). Thus, networks evolve and may themselves get "locked-in", preserving certain types of regional ties, and limiting the creation of variety and resilience (Vonortas 2009). Different network architectures enhance or retard network flexibility, the capacity of agents within the network to alter linkages and redraw network structure.

Fourth, the regional resilience literature has neglected the role of institutions (Swanstrom et al. 2009; Bristow 2010; Hassink 2010; Wolfe 2010; Pike et al. 2010; Davies 2011; Wink 2012; MacKinnon and Driscoll Derickson 2013). Alongside the technological capacity to generate and accumulate knowledge, resilient spaces are more likely to have dynamic institutional structures that acknowledge the benefits of heterogeneity, of technological and other kinds, that promote knowledge production, recombination and application, and which are themselves mutable. In his early work on institutions, Douglas North (1995, p. 26) argued, "…the key to continuing good performance is a flexible institutional matrix that will adjust in the context of evolving technological and demographic changes". Davis (2010) built on these claims to outline a growth model driven by increasing returns to institutional learning where greater specialization offers gains the realization of which may be threatened by existing institutional constraints. Using national economic data, he presented compelling evidence that the evolution of institutions is more important than static institutional quality for long-run economic growth. Saxenian (1994) and Storper (1993) present similar claims at the regional level. Within the context of rapidly changing economic environments, especially those driven by new knowledge systems, the co-evolution of institutional structures has been examined by Setterfield (1993) and Van de Ven and Garud (1994). The dangers of institutional stasis are exposed by Grabher (1993), and the power of new technologies to overturn existing institutions is highlighted by Hargadon and Douglas (2001).

In the rest of this paper, we aim to tackle these critiques on the regional resilience literature. We propose a comprehensive view of urban resilience in which we assess how the local knowledge base, the local institutional structure and the position within the U.S. urban knowledge network influence the capacity of cities to avoid technological crises and limit their intensity and duration.

3. Data & Methodology

In this section, we discuss characteristics of U.S. patent data that are used to develop our empirical arguments about the relationship between technological resilience and the structure of knowledge within metropolitan areas. In the absence of survey data, patents provide, perhaps, the only reliable method of identifying the knowledge base of regions. Early efforts to characterize the technological character of U.S. cities relied upon proxies such as the distribution of output across industrial classes or the distribution of workers across (creative) occupations or educational classes (Hall and Markusen 1985; Markusen 2001; Florida 2002). Unfortunately, these proxies provide little information about different types of knowledge or technology and thus they fail to cast much light on variations in the structure of knowledge. The advantages of patent data for mapping the changing character of knowledge production over space and time are clear. First, patents provide detailed information about the nature of knowledge claims or technology. Second, patents reveal where new knowledge is created by referencing the geography of inventors (and co-inventors, where applicable), and they indicate the year in which this knowledge was produced. Third, there are a number of well-known methods for measuring the relatedness between different technological classes listed on patents (Engelsman and van Raan 1994, Jaffe 1986; Teece et al. 1994; Rigby 2013). These measures enable us to characterize the structure of knowledge generated within U.S. cities and to track how that structure has evolved since 1975.

3.1 Data

This paper uses data on utility patents granted by United States Patent and Trademark Office (USPTO). Digital records for U.S. patents originate in 1975, and hence this year marks the beginning of our period of study. Analysis ends in 2002 because of right-truncation in the patent series. We are interested in the timing of new knowledge creation and so focus on the application year of the patent rather than the grant year because of the time-lag between the dates of creation and formal recognition. Upon review, individual patents are placed into one or more distinct technology classes that are designed to reflect the technological characteristics of the underlying knowledge base that they embody. By the end of 2010, there were 438 classes of utility patents in use by the USPTO (Strumsky et al. 2012). Investigation focuses on U.S. patents defined as those produced by an inventor located within the United States. In the case of co-invention, patents are located by the address of the first-named, primary inventor. We discard patent records if the primary inventor is not located in one of the 366 U.S. metropolitan areas.

3.2 The Growth of Invention

It is well known that the number of patents generated in the United States has increased over time (Hall et al., 2001). Figure 1 shows the annual number of utility patents granted each year in the United States. The contribution of foreign patents (those generated outside the United States) seeking U.S. patent protection is also highlighted. The rate of knowledge production is inconstant over time, with periods of relatively slow and more rapid growth punctuated by abrupt shocks. Downturns in the pace of invention are not randomly distributed, but appear connected to important historical events that shaped the creation of technological knowledge. Figure 1 reveals a first period of growth from 1900 to 1916, interrupted by the First World War. Between 1916 and 1920 the total production of patents in the U.S.

dropped by about 16%. Patent production rebounded in the 1920s, pacing the rapid growth of the U.S. economy until the onset of the Great Depression. After 1932, patent production in the United States began a long, fifteen year slide, only briefly interrupted by the start of the Second World War. Between 1932 and 1947, the rate of domestic invention in the U.S. fell by almost 60%.

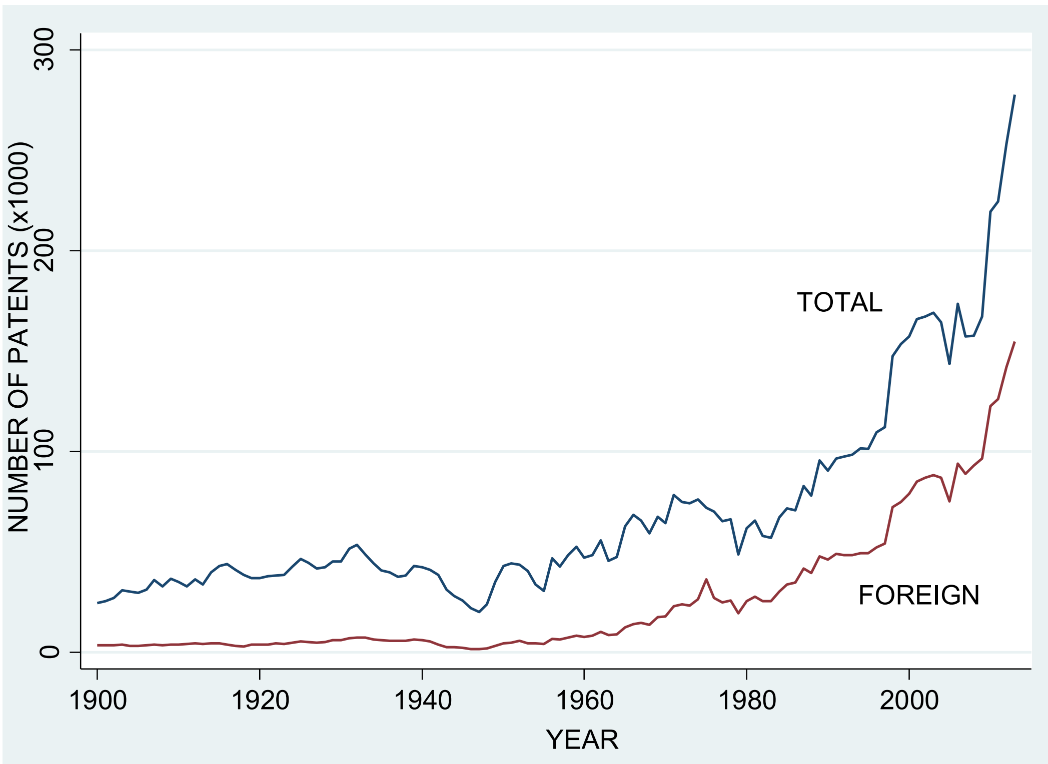

Figure 1. The Rise of Patenting in the United States[1]

The post-war economic boom in the United States helped sustain a long period of rapid growth in patenting. This ended dramatically in the early-1970s with a deteriorating financial climate related to the costs of the Vietnam War and a sharp rise in international competition. The OPEC[2] oil embargo of 1973 sent shockwaves through the U.S. economy, triggering a period of economic instability that was to last almost a decade. Indeed, between 1971 and 1983, the number of patents granted each year dropped by 27%. From the mid-1980s until 2000, annual patent production in the U.S. enjoyed almost uninterrupted

[1] This figure is based on the table of Annual U.S. Patent Activity Since 1790 provided by the USPTO: http://www.uspto.gov/web/offices/ac/ido/oeip/taf/h_counts.htm. We use the count of utility patents granted as the overall measure of invention. Foreign patents include plant and design inventions as well as utility patents.

[2] Organization of Arab Petroleum Exporting Countries

growth, though as the dot.com technology bubble burst in 2000, U.S. domestic knowledge production contracted. Rates of U.S. patenting turned sharply upwards, once more, after 2005.

3.3 Identifying events of technological crises

It should be clear from Figure 1 that the dynamics of U.S. invention, at least as they are captured by annual variations in patent production, are complex. We define technological crises as sustained periods of negative growth in patenting activity. More formally, a time series recording yearly patenting activity can be defined as a continuum of local maxima (peaks) and minima (troughs) that divide the series into periods of technological growth from trough to peak and technological crisis from peak to trough. A hypothetical example of peak, trough and technological crisis is displayed in Figure 2.

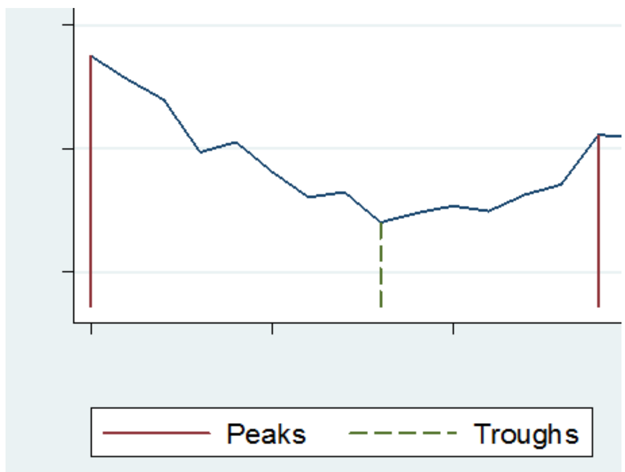

Figure 2. Peak, trough and technological crisis

The time series of U.S. domestic and foreign patent counts is noisy. Periods of growth and crisis are interrupted by odd years of gains and losses in knowledge production. Key to analysis of complex time series is to define turning points (peaks and troughs) in such a way that only significant series variation is captured and noise is excluded. To achieve this, we make use of an adapted version[3] of the algorithm originally developed to detect business cycles by Harding and Pagan (2002). This algorithm identifies potential turning points as the local minima (trough) and maxima (peak) in the series. Let P_t be an annual patent count series. A trough is identified as $(p_{t-j},\dots,p_{t-1})>p_t^{trough}<(p_{t+j},\dots,p_{t+1})$, while a peak

[3]The stata programme can be found here : http://fmwww.bc.edu/repec/bocode/s/sbbq.ado

follows the condition that $(p_{t-j},\ldots,p_{t-1})<p_t^{peak}>(p_{t+j},\ldots,p_{t+1})$. Because of data truncation (before 1975 and after 2002), we allow crisis events to start with a peak/trough in 1975 and end with a peak/trough in 2002. The algorithm defines turning points in such a way that a peak must be followed by a trough and a trough followed by a peak. To avoid series noise, candidate years for peaks and troughs must satisfy two conditions: the phases (technological growth or crisis) should be at least two years long, while complete cycles (period between two peaks or between two troughs) should be at least five years long.

4. Descriptive statistics

The main objective of this paper is to study the relative capacity of cities to maintain the production of technological knowledge over time, particularly in periods of economic adversity. In order to identify peaks and troughs in patent production at the city level, we run the algorithm identified above for all 366 U.S. Metropolitan Statistical Areas (MSAs) from 1975 to 2002. Analysis reveals that the probability of an individual MSA being in a period of (patenting) crisis varies dramatically across U.S. cities. Similarly, the depth and duration of crisis events are markedly different between cities.

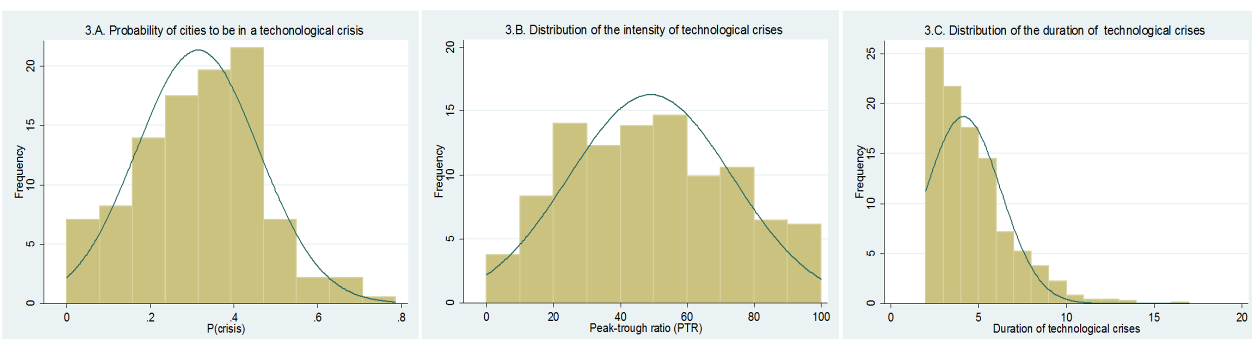

Figure 3. Frequency, intensity and duration of technological crises

Figure 3A shows the probability distribution of a city being in a period of technological crisis in a single year from 1975 to 2002. On average, the probability of occurrence of an annual city-crisis event is approximately 0.3, corresponding to about eight years in total. Only 20% of cities spend less than six years in crisis over the study period, while the majority of cities spend between six and twelve years in this condition. A surprisingly large share of cities spend between twelve and eighteen years in crisis (30%) while only about 5% of cities are usually classified in crisis mode (more than eighteen years).

Figure 3B reports variation in the intensity of crisis events between cities. To calculate the intensity of a crisis, we compute the peak-trough ratio (PTR), the share of patents produced in a given trough year compared to the number of patents produced at the previous peak. Thus, if a city produces 1000 patents at a peak in $year_t$ (beginning of a technological crisis) and only 500 at the next trough in $year_{t+n}$ (end of the crisis event), the PTR equals 50%. On average across all cities and crisis events, the PTR equals 49%. As Figure 3B reveals, some technological crises have more dramatic consequences in term of patent loss. About 4% of crises lead to a PTR of less than 10%, while the majority generates PTRs of 20 to 60%. About 30% of crises are very destructive, associated with a PTR of more than 60%.

The distribution of crises by duration is mapped in Figure 3C. Most of the crises in patent production tend to be relatively short. On average, crises last for about four years, with the modal length being two years (26% of the events). Only about 35% of the technological crises last for more than five years. Figure 4 illustrates the dynamics of knowledge production across a set of U.S. cities, showing periods of peaks, troughs and technological crises (periods from peak to trough).

5. Empirical analyses

To model the resilience of cities, we focus attention on three dimensions of resilience:

1. Vulnerability – why some cities enter technological crises while others are less vulnerable?

2. Crisis intensity – why some cities suffer more from technological crises?

3. Crisis duration – why some cities recover more quickly from technological crises?

5.1. Modeling the technological resilience of cities

Econometric specifications

We regress measures of each of the three dimensions of resilience on the technological, institutional and network flexibility of cities. The general econometric equation to be estimated is:

$$resilience_{c,t} = \beta_1 tech_{flexibility_{c,t-1}} + \beta_2 inst_{flexibility_{c,t-1}} + \beta_3 net_{flexibility_{c,t-1}} + \beta_4 adverse_{events_t} + \boldsymbol{\beta}_k \boldsymbol{city}_{k\,c,t-1} + \varepsilon_{c,t} \quad (1)$$

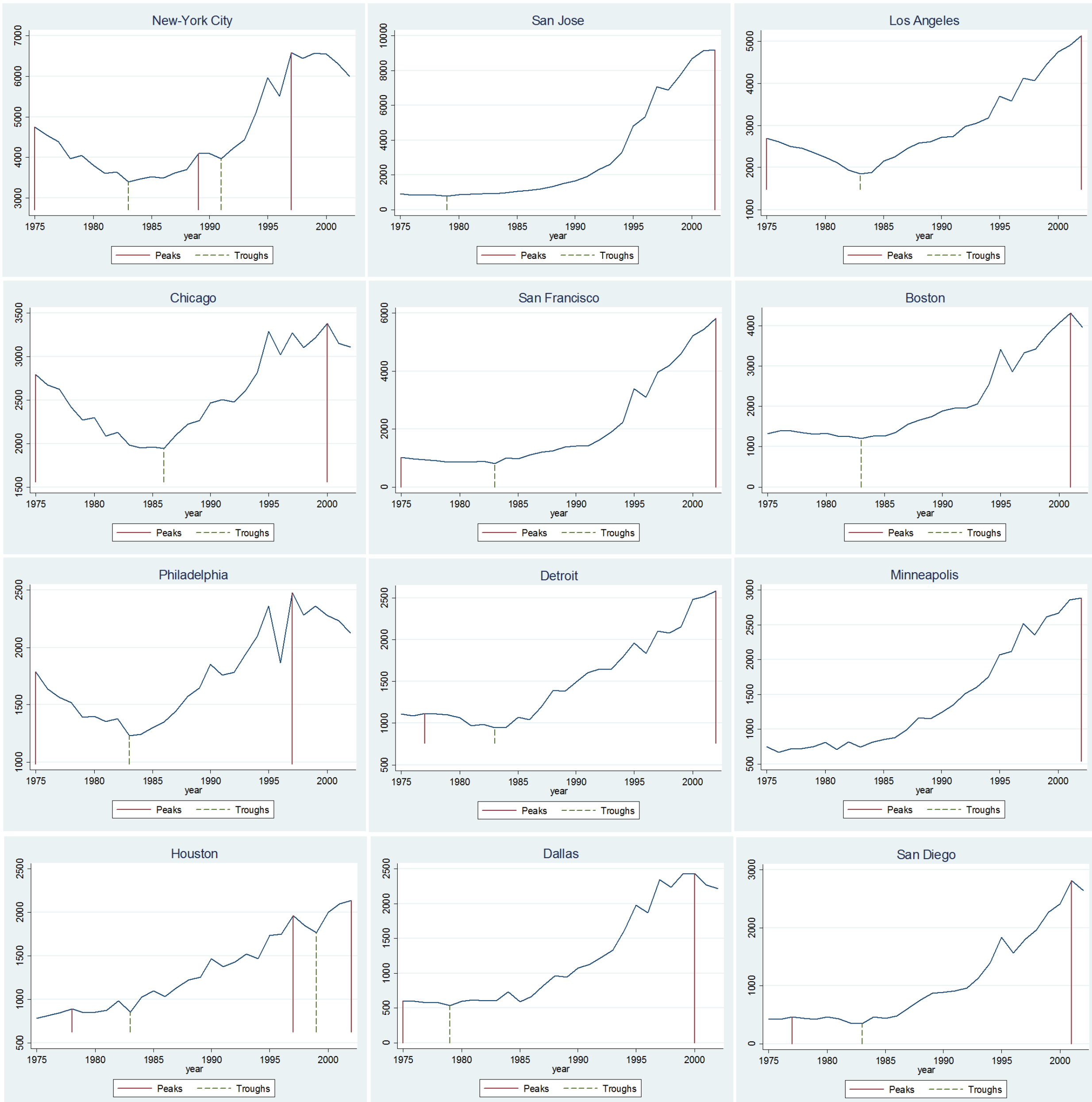

Figure 4. Peak, trough and technological crises across U.S. cities

We do not properly capture the complexity of the resilience concept in a single dependent variable $resilience_{c,t}$, but instead we use three alternative dependent variables: (1) the probability of a city falling into crisis $(crisis_{c,t})$, our measure of vulnerability (2) the peak-trough ratio

$(peak\_trough_{c,t})$, our measure of crisis intensity and (3) the length of the crisis $(duration\_crisis_{c,t})$, our measure of crisis duration. The same set of independent variables is employed to account for the variance across each of the three measures of resilience. The dependent variable $crisis_{c,t}$ is by nature binary, and equals 1 if a city that was not in crisis enters a period of sustained negative technological growth (from peak to trough), and 0 otherwise (i.e. if the city continues to avoid being in a crisis the next year). Therefore, we model a city's movement into technological crisis with our first dependent variable. We use a logistic regression model to account for the binary nature of the dependent variable.

Our second specification uses the dependent variable $peak\_trough_{c,t}$ that captures the intensity of a crisis event. As introduced above, $peak\_trough_{c,t}$ is the ratio between the number of patents produced by a city the year before entering a crisis (number of patents at the peak) and the lowest number of patents produced by a city at the trough of the crisis. By construction, this ratio ranges between 0 (if the number of patents at the peak equals the number of patents at the trough) and 100 (if the city produced patents at the peak but does not produce any patents in the trough). The higher the $peak\_trough_{c,t}$ value, the more intense the crisis. Here we use an OLS linear regression to explain the variation in crisis intensity.

The third regression specification uses the dependent variable $duration\_crisis_{c,t}$, to measure how many years a city remains in a given crisis event, the number of years between peak and succeeding trough. We presume that resilient cities tend to recover more quickly from crises. To evaluate the duration of crises, we adopt Cox's proportional hazards model for our regression relationship. Since some cities are still in crisis at the end of our period of observation, survival times are by construction right-censored, as we do not know when these cities will get out of technological crises.

Measuring the flexibility of cities

Technological flexibility is a city-level measure that reflects the structure of the knowledge base of a city (Boschma et al., 2014a; Rigby, 2013; Kogler et al., 2013). Inspired by the work by Hidalgo et al. (2007) on product space, we define a knowledge space as a network where nodes are the primary technology classes (*n=438*) into which patents are placed. In this network, the links indicate the degree of relatedness between any two technological classes. We measure relatedness between classes by looking at how often two technology classes co-occur on the same patent. These co-class counts are normalized by the product of the number of patents found in each of the technology co-classes, assuming a simple probability calculus (Van Eck and Waltman, 2009). Our technological relatedness measure $\varphi_{i,j,t}$ indicates whether two technology classes *i* and *j* co-occur on individual patents more often than what can be expected by chance under the assumption that individual occurrences of patents in class *i* and in class *j* are statistically independent.

Combining this measure of relatedness between classes with information on the technological portfolio of a city (the set of technology classes in which patents in a city are located) at time *t*, we compute the technological flexibility of each city as the average relatedness of the patents present in the city to all technological classes that are not yet in the city. Technological flexibility characterizes the structure of the knowledge base of cities. More formally, the technological flexibility of a city *c* in time *t* is given as

$$tech\_flex_{c,t} = \frac{\sum_{i \notin c} \left(\frac{\sum_{j \in c, j \neq i} \varphi_{ij}}{\sum_{j \neq i} \varphi_{ij}} \times 100 \right)_{i,c,t}}{\sum_{i \notin c} i} \tag{2}$$

where *i* and *j* are technological classes.

Let us assume that class *m* and class *n* are the only classes absent in the portfolio of city *c* in year *t*. And let us further assume that the degree of relatedness between class *m* and the technological portfolio of city *c* is 100%, and that the degree of relatedness between class *n* and the technological portfolio of city *c* is 50%. This means that all the classes that are related to *m* in the knowledge space can be found in city *c*, while only half of the classes related to *n* can be found in *c*. Therefore, the technological flexibility of city *c* at time *t* is 75%. Technological flexibility provides a measure of the potential reconfiguration of local technological assets, a measure of the relative ease with which a city might adjust or adapt its technological portfolio in the face of shocks that might render parts of that portfolio less competitive. We use the moving average (3 years) of this measure in our estimations to take account of potential persistence in the knowledge structure of cities.

For each city, we also develop an indicator of institutional flexibility based on the enforceability of non-competition agreements. Non-competition agreements are legal contracts that prevent the workers of one firm from joining a rival firm, including spin-offs that they might form themselves. As a result, non-competition agreements can reduce labor mobility and knowledge flows within cities. We expect cities that have a more open and flexible institutional environment, cities within states that don't enforce non-competes, to be better able to avoid crises and to adapt more easily to crisis events. To measure institutional flexibility we used the inverse of the non-competition enforcement index developed by Garmaise (2011) for U.S. states. This index is based on an extensive survey by Malsberger (2004), who identifies 12 key dimensions of non-competition law in the United States. These dimensions takes the form of questions such as *"Who has the burden of proving the reasonableness or unreasonableness of the covenant not to compete?"*. Garmaise assigned one point for each question in which a state enforces a dimension of non-competition law. For this question for instance, states in which the burden of proof is placed on the employee score 1. As a result, states non-competition enforcement index can potentially range from 0 (low enforcement) to 12 (high enforcement), but in practice the index goes from 0 (California) to 9 (Florida). A complete list of questions and state totals is given in the Appendix of Garmaise (2011). To generate an institutional flexibility score, we use the inverse of this index, so a low score of enforcement means high institutional flexibility. When MSAs are split across different states, we locate the city in the state where its footprint is largest.

The network flexibility of cities is measured each year as the betweenness centrality score from an inter-urban network identified from patent co-inventor linkages that tie U.S. cities to one another. The weight of the co-inventor linkages between a pair of cities is given simply by the number of patents that list at least one inventor in each of them. We use the moving average (3 years) of this measure in our estimations to take account of potential persistence in the ties between inventors.

Control variables

While we are primarily interested in the relationship between technological, institutional and network flexibility and the different dimensions of resilience, we recognize that resilience may be influenced by a range of other variables. $\boldsymbol{City}_{kc,t-1}$ is a vector that captures a range of city characteristics. We develop controls for the specific economic context of the city using *employment growth*, the number of inhabitants in the city by square meters (*population density*), the number of patents in a given city (*inventive capacity*), the growth rate of the number of patents (*technological growth rate*), and the *technological specialization* of each city. The latter covariate is calculated using a Herfindhal index. For each city, we also include a competition index (the ratio of firms to employees, following Glaeser et al. 1992), the ratio of inventors to employees, the share of independent inventors, the number of firms and a dummy for being in the Sunbelt or the Snowbelt. There are clear theoretical priors for inclusion of these variables, though we do not review all related literature here.

In our base model specification, $adverse\_events_t$ is a vector that summarizes a range of important events that might have negatively impacted the U.S. economy during the period of investigation. We use dummy variables for each of the periods covered by these events. For instance, the variable *oil crisis* = 1 for the years 1975 to 1983 (also capturing the slowdown associated with the deep recession of the early 1980s), while the variable *gulf war* runs from 1990 to 1991 and the *dot com bubble* accounts for the internet crisis from 1999 to 2001. We expect all these events to affect the likelihood of a city entering a crisis, but also to increase the intensity and duration of crisis events. Our panel consists of data for 366 cities (MSAs) examined annually over the period 1975-2002. Table 1 provides summary statistics of the variables used in the econometric analysis.

Variable		**Obs.**	**Mean**	**Std. Dev.**	**Min**	**Max**
Resilience (dependent) variables						
Crisis		7987	0.118943	0.323742	0	1
Peaktrough		585	49.23624	24.45894	3.215591	100
Duration_crisis		950	3.345263	2.293702	1	17
Main variables of interest						
Technological flexibility		9150	12.38585	14.75754	0	83.55173
Institutional flexibility		10248	-4.42701	1.927631	-9	0
Network flexibility		9150	888.07	6087.9	0	93000
City characteristics						
Employment growth (%)		9882	2.063726	3.022189	-15.03574	66.49197
Inventive capacity (log)		9882	3.287253	1.891504	-4.60517	9.119979
Population density		9882	233.7206	284.4223	2.9599	2765.112
Tech. specialization		9882	0.12	0.17	0	1
Tech. growth rate		9752	.1420715	.304235	-.619047	5.61111
Competition index		9046	.0445672	.0250041	.0071901	1.140337
Inventor ratio		9882	.0004447	.0004995	0	.0079516
Ratio independent inventors		9423	.3603598	.2432031	.01	1
Number of firms		9050	13201.07	32113.05	0	498341
Sunbelt		10248	.6229508	.484671	0	1
Adverse events						
Oil crisis	*[1975-1983]*	10248	0.321429	0.467048	0	1
Gulf war	*[1990-1991]*	10248	0.071429	0.257552	0	1
Dot com bubble	*[1999-2001]*	10248	0.107143	0.30931	0	1

Table 1. Summary statistics of the dependent and independent variables

5.2 Does flexibility lower the probability of entering a technological crisis?

We first investigate what leads cities to enter a technological crisis. We identify 950 crises out of 7,987 event possibilities (years when cities are not in crisis and are thus possible candidates to enter one), that leads to a rate of new technological crises of about 11.89 % (see Table 1). Table 2 presents the results of estimating equation 1, using a logistic regression model with $crisis_{c,t}$ as the dependent variable. Note that all our independent variables have been lagged one period to dampen concerns with endogeneity. We turn, first, to the influence of our three different measures of flexibility at the city-level, technological flexibility, institutional flexibility and network flexibility. The coefficient for technological flexibility is negative and significant. Thus, as technological flexibility (average relatedness to new technologies) increases, the likelihood that a city enters a crisis falls. The coefficient for institutional flexibility is negative and significant at the 0.1 level, suggesting that cities with greater institutional flexibility are also less likely to fall into technological crises. The coefficient for network flexibility is positive though insignificant, so there is no clear relationship between the centrality of a city in the U.S. city system and crisis avoidance. Turning to the city-level control variables, two variables seem to be important in explaining the vulnerability of cities to crises. Both employment growth and the growth rate of technology are significantly associated with a lower probability of entering a technological crisis. Cities that patent a lot in the previous year (positive and significant coefficient for inventive capacity) and cities from the Sunbelt are more at risk, but also cities that are very specialized, cities with a high number of firms and many inventors working independently. The population density, inventor ratio and measure of competition are not significantly associated with crisis events. We find general evidence that U.S. cities tend to fall into technological crises during periods of overall national economic stress such as the oil crisis and the gulf war (the dot com bubble also shows a positive sign but it is not statistically significant). Overall, our results show that an increase in the flexibility of the knowledge structure of cities and an increase in the institutional flexibility of cities significantly lower the risk of entering a technological crisis.

Dependent variable is : crisis$_{c,t}$	**Coefficients**	**Robust Std. Err.**	**P-value**
Technological flexibility	-0.11893	0.01154	0.00000
Institutional flexibility	-0.03471	0.01867	0.06298

Network flexibility	0.00001	0.00001	0.16136
Employment growth	-0.06556	0.01431	0.00000
Inventive capacity (log)	1.02229	0.11425	0.00000
Population density	-0.00003	0.00027	0.90946
Tech. specialization	1.60083	0.50048	0.00138
Tech. growth rate	-0.69559	0.27125	0.01034
Competition index	-2.34360	1.54424	0.12911
Inventor ratio	25.83415	89.86623	0.77375
Ratio independent inventors	0.48590	0.21150	0.02160
Number of firms	0.00001	0.00000	0.00064
Sunbelt	0.27688	0.08155	0.00069
Oil crisis	0.72554	0.09268	0.00000
Gulf war	0.31413	0.14351	0.02860
Dot com bubble	0.18313	0.12568	0.14510
Constant	-4.83123	0.38037	0.00000
Observations		6,431	
Pseudo R-squared		0.0587	

Notes: The dependent variable crisis$_{c,t}$ equals 1 if a city (n=366) that was not in crisis in t enters a crisis event defined as sustained negative technological growth (from peak to trough) in t+1, and 0 otherwise. Standard errors are clustered by city.

Table 2. Probability of entering a technological crisis

5.3 Does flexibility reduce the intensity of technological crises?

Technological crises vary considerably in terms of intensity. As Table 1 shows, the peak-trough ratio ranges in value from 3.2% to 100%. Table 3 presents the results of estimating equation 1 when the dependent variable is $peak\_trough_{c,t}$ our measure of crisis intensity. The peak-trough ratio is computed in the year of the trough, while the values of the independent variables are computed for the year before crisis entry. Observations are limited to the cities that experience crises (n=950). Of the 950 crisis events, some are censored (if the technological crisis continues through 2002, we cannot observe a trough) so the intensities of crises are not always known. Nonetheless, we can exploit information on 527 peak-trough ratios of crisis intensities for cities over the period 1975-2002.

In this model, the coefficient for technological flexibility is again negative and significant, meaning that cities with a more flexible knowledge structure experience less intense technological crises. Institutional flexibility and network flexibility also have the expected negative sign, but they are not statistically significant. This result might be explained by the low number of observations. In terms of city characteristics, there is a strong size effect, as the level of invention tends to dampen the intensity of technological crises. Urban density and technological growth rate are associated with more severe crisis events. Most of the other city controls (employment growth, specialization, competition, inventor ratio, ratio of independent inventors, number of firms, Sunbelt) are insignificant. When turning to the impact of adverse events, the effect is also much less clear than when looking at the probability of crisis entry. Only the oil crisis is significantly associated with more intense crises (positive coefficient), while the dot com bubble (positive coefficient) and the gulf war (positive coefficient) variables are insignificant. Overall, there is a significant negative effect of the flexibility of urban knowledge structures on crisis intensity, while institutional and network structures have no significant influence.

Dependent variable is : peaktrough$_{c,t}$	**Coefficients**	**Robust Std. Err.**	**P-value**
Technological flexibility	-0.46220	0.21646	0.03355
Institutional flexibility	-0.08392	0.44303	0.84989
Network flexibility	-0.00001	0.00021	0.97165
Employment growth	-0.28789	0.28185	0.30786
Inventive capacity (log)	-9.11003	2.56809	0.00045
Population density	0.00929	0.00452	0.04076
Tech. specialization	26.05740	19.80034	0.18917
Tech. growth rate	9.97786	2.97598	0.00090
Competition index	77.43708	108.61691	0.47644
Inventor ratio	-480.19330	2,201.49585	0.82748
Ratio independent inventors	-1.02989	5.06545	0.83902
Number of firms	0.00003	0.00004	0.44369
Sunbelt	-1.25805	1.91229	0.51112
Oil crisis	11.13402	1.92716	0.00000
Gulf war	0.52637	2.41380	0.82752
Dot com bubble	1.38082	2.69221	0.60840
Constant	72.37400	11.20091	0.00000
Observations		508	

R-squared	0.48292

Notes: The dependent variable $peak\_trough_{c,t}$ *is the ratio between the number of patents produced by a city the year before entering in a crisis (number of patents at a peak) and the lowest number of patents produced by a city during a crisis (number of patents at a trough). Standard errors are clustered by city.*

Table 3. Intensity of technological crises (peak-trough ratio regressions)

5.4 Does flexibility limit the duration of technological crises?

Crisis events vary also in terms of duration. During our period of observation and across the 366 U.S. cities, crises can be as short as 1 year or as long as 17 years. This section explores whether the technological flexibility of cities is associated with the duration of crisis events. Table 4 presents the results of estimating equation 1 when the dependent variable is $duration\_crisis_{c,t}$. In this model, we estimate the hazard of exiting a crisis using the Cox proportional hazard model allowing for repeated events. It is important to note that a coefficient greater than 1 means that the probability of the hazard occurring (the likelihood of exiting the crisis) increases. So, contrary to the logistic (probability of entering in crisis) and OLS specification (intensity of crisis), we expect in the duration model a coefficient greater than 1 for our key variable of interest, technological flexibility. In the hazard model, we are able to use information on all 950 crisis events since this model does not omit observations on crises that have not ended by the year 2002. Indeed, hazard models consider censored events as arising out of the same distribution as those events that have been observed to end (Hausmann et al., 2006).

The hazard ratio for technological flexibility is above 1 and significant, indicating that the technological flexibility of cities increases the likelihood of exit from a crisis. The hazard ratio on technological flexibility suggests that a 1-unit increase in flexibility increases the probability of exiting a crisis by about 1%. The economic context of a particular city, captured by employment growth, is also important in explaining why some cities exit technological crises more quickly than others. Surprisingly, this is not the case for institutional and network flexibility, inventive capacity and inventor ratio. Specialization is strongly associated with longer crises, while most of the other control variables (population density, technological growth rate, competition, ratio of independent inventors, number of firms, Sunbelt) are insignificant. Unfortunately, since we use a Cox proportional hazard model with time-varying independent variables (interacted with time), we cannot test the effect of adverse events. Alternative model specifications with time-constant independent variables suggest that the oil crisis period, in particular, lowered the recovery speed of cities.

Dependent variable is : duration before exiting crisis	**Hazard ratio**	**Robust Std. Err.**	**P-value**
Technological flexibility	1.01000	0.00159	0.00000
Institutional flexibility	0.99363	0.00391	0.10468
Network flexibility	0.99999	0.00000	0.00161
Employment growth	1.00776	0.00284	0.00604
Inventive capacity (log)	0.90461	0.01692	0.00000
Population density	1.00005	0.00003	0.10621
Tech. specialization	0.84205	0.06829	0.03402
Tech. growth rate	1.04078	0.02973	0.16177
Competition index	7.89408	10.40096	0.11685
Inventor ratio	0.00000	0.00000	0.07620
Ratio independent inventors	0.94358	0.03641	0.13231
Number of firms	1.00000	0.00000	0.09856
Sunbelt	0.91280	0.12924	0.51930
Observations		944	
Wald chi2(13)		140.42	
Prob > chi2		0.0000	

Notes: The dependent variable duration_crisis$_{c,t}$ indicates the number of years spent in a technological crisis. Standard errors in parentheses. We report hazard ratios from Cox proportional hazards model with time-varying variables.

Table 4. Duration of technological crises

6. Discussion and Conclusion

In this paper. we tackled a number of issues that have not yet been fully addressed in the regional resilience literature. Instead of merely focusing on the ability of a city to absorb shocks, as is common in the conventional concept of resilience, we redefined regional resilience in terms of how shocks affect the long-term capacity of regions to develop new technological knowledge. We regard knowledge production as a critical indicator of the ability of regions to remain competitive in the long run, and this is captured by our concept of technological resilience. This is the first study that has investigated resilience as the capacity of regions to maintain their levels of knowledge creation over the long-run in the context of technological crises. Moreover, we have made efforts to incorporate history as a key input to our understanding of regional resilience. This is most visible in our notion of technological flexibility which refers to features of the regional knowledge base that defines the potential of regions to adapt their technological assets in the face of shocks. We also proposed a comprehensive view on regional resilience in which the role of regional institutions and open network structures are included, two key dimensions that have been largely ignored in the regional resilience literature so far. In that respect, we proposed the notion of institutional flexibility to grasp the potential of regional institutions as enablers of local knowledge transfers and interactions alongside our measure of network flexibility.

We analyzed the technological resilience of U.S. cities from 1975 to 2002 by documenting their relative capacity to sustain the production of knowledge in the face of adverse events. We found that the frequency, intensity and duration of technological crises varied across American cities. We examined whether the technological knowledge base of cities, their network centrality and institutional environment conditioned their resilience to crisis events. Our findings showed that U.S. cities with a knowledge base that has a high degree of relatedness to technologies that are not yet present in the city were better able to avoid technological crises, to limit serious downturns in patent productivity, and to speed recovery from crisis. The influence of network centrality and the institutional environment of cities exerted little overall impact on urban technological resilience.

There remain a series of issues that should be taken up in further research. First, we defined resilience as the capacity of cities to maintain levels of knowledge creation when technological crises occur. An interesting next step would be to extend the analysis of urban resilience to the capacity of cities to develop new technology growth paths. We know relatively little about the transfer of regional resources from obsolescent to emerging knowledge domains, and about how novel forms of technology are related to the existing structure of knowledge within a region. Second, it is possible to further refine the network measures, by not only looking at the intensity of knowledge linkages between cities, but by exploring the nature of these linkages, the types of external knowledge flow into the city and to what extent such inflows are related to the local knowledge base. In addition, the resilience of local network structures themselves to adverse shocks represents a key line of research (Fleming et al. 2007; Crespo et al. 2013). Third, we assessed the effect of institutions on urban resilience by means of the non-competition enforcement index that we take as representing an open and flexible institutional environment. It would be interesting to develop further this institutional dimension to urban resilience by investigating the extent to which local institutional structures are open to (radical) change, are capable of responding swiftly to adverse shocks, and enable institutional change to support new growth paths (Boschma 2014). Finally, there is a need to complement our quantitative approach by case studies of U.S. cities that will yield insights on urban resilience, such as the role of key local agents, practices and policies that are unlikely to be captured in quantitative studies (see e.g. Glaeser 2005; Treado 2010).

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