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Article (Accepted version)
(Refereed)

Original citation:
Ahlfeldt, Gabriel M. and Wendland, Nicolai (2013) *How polycentric is a monocentric city?: centers, spillovers and hysteresis.* Journal of Economic Geography, 13 (1). pp. 53-83. ISSN 1468-2702 DOI: 10.1093/jeg/lbs013

How Polycentric is a Monocentric City? Centers, spillovers and hysteresis[1]

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Abstract: We assess the extent to which firms in an environment of decreasing transport costs and industrial transformation value the benefits of proximity to a historic CBD and agglomeration economies in their location decisions. Taking a hybrid perspective of classical bid-rent theory and a world where clustering of economic activity is driven by between-firm spillovers, Berlin, Germany, from 1890 to 1936 serves as a case in point. Our results suggest that the average productivity effect of a doubling of between- firm spillovers over the study period increases from 3.5% to 8.3%. As the city transforms into a service-based economy, several micro agglomerations emerge. Their locations close to the CBD still make the city look roughly monocentric. This is in line with a hysteresis effect in which second-nature geography drives the ongoing strength of a historic city center even though the importance of the originally relevant first-nature geography has vanished.

Keywords: *Transport Innovations, Land Values, Location Productivity, Agglomeration Economies, Economic History, Berlin*

JEL classification: *N7, N9 R33, O12*

Version: *May 2012*

[1] We thank the German Science Foundation (DFG) for funding large parts of this project. We furthermore thank Kristian Behrens (the editor), Stefan Goldbach, Christian Hilber, Volker Nitsch, and three anonymous referees for valuable comments and discussions.

1. Introduction

The traditional models of urban economics view cities as aligned around a single, exogenously defined "mono"-center, the so-called central business district (CBD). The value of urban land emerges from a trade-off of access and transport cost to this center (e.g. Alonso, 1964; Mills, 1969; Muth, 1969). More recent models, in contrast, have acknowledged the polycentric structure of many cities in the world and attempted to explain the emergence of more complex patterns through the interplay of various forces of agglomeration and dispersion (e.g. Anas & Kim, 1996; Lucas & Rossi-Hansberg, 2002). Monocentric and polycentric views on the spatial structure of cities, therefore, feature very distinct but potentially complementary underlying mechanisms that generate economic densities.

The traditional view of a firm's bid-rent function is that bid-rents have to diminish as transport costs to the exogenous center increase. The city center is often referred to as a sort of market place where economic agents interact both with each other as well as with government institutions and local authorities. An alternative or complementary view is that of an export hub to which goods have to be shipped. It is, of course, questionable to which degree these characteristics apply to modern service-based (urban) economies. Alternative explications for the evident spatial clustering of firms have instead built on the idea of scale-economies and spatial interactions that drive productivity for firms in close proximity through various forms of spillovers and mutual access to (intermediate) inputs.

A common approach in the literature for empirically testing the predictions of the traditional (monocentric) models has been to look at the relationship between distance to city centers and observed land values. Although in the historical context it has been somewhat difficult to find appropriate data, the empirical literature has provided evidence for negative rent gradients, mostly for residential, but also for commercial land (McMillen, 1996). The magnitude of these gradients has been found to diminish considerably over time, a phenomenon that is widely interpreted as urban decentralization. Based on these findings, however, it is hardly possible to draw conclusions on the origin of the spatial pull that drives firms into the center in the first place. Do firms discount their willingness to pay for land on the transport costs associated with shipping goods to the center or do they take advantage of locating close to other businesses to enjoy a productivity externality, or both?

Similarly, it is not entirely clear *a priori* whether rent gradients that diminish over time reflect a reduction in transport costs to the city center or the increase in agglomeration economies as the fundamental determinant of productivity of commercial land, and, hence, its market price. Clearly, if strong agglomeration economies are present, they offer the potential for increasingly larger sub-centers and edge-cities to emerge, which would reduce the magnitude of (negative) CBD gradients. A much cited example is LA, where sub-centers dominate the CBD so that even a positive gradient was found (Heikkila et al., 1989). Another potential outcome, however, are clusters of extreme economic density, e.g. lower Manhattan or the London Square Mile. Once a critical level of economic concentration has been established (e.g. if firms were attracted due to natural advantages, a transport hub, or a government cluster), emerging spillovers between firms in such a cluster will reinforce densification through agglomeration benefits. In such a scenario, the historically grown center will maintain its dominant role (reflected in a steep negative CBD gradient), even though the original (natural) advantage vanishes over time – a hysteresis effect.

Against this background, we examine transport costs to the city center and the mutual attraction of economic activity as alternative and potentially complementary determinants for the value of commercial land. We chose Berlin, Germany, during the late period of industrial revolution (1890-1936) as a case in point for three important reasons. First, the city, in its development, resembles many European and Northern American cities during the Industrial Revolution. Berlin underwent a major transformation in its industry structure towards a predominantly service-based economy and developed a dense network of intra-urban rapid transit. Both incidents should have stimulated spatial interactions among economic agents and, thus, the relevance of agglomeration economies. Second, at the beginning of the study period, the city exhibited an unusually high density of economic activity within the relatively small urban core, which over centuries had established itself as the economic, political, and cultural center of Prussia. Third, even by the end of the study period, the city center exerted a particularly strong attraction on firms – at a time when the typical evidence for

U.S. cities suggests that the negative CBD gradients had almost disappeared (Ahlfeldt & Wendland, 2011). Together, these features make Berlin the perfect candidate for a study on the abovementioned hysteresis effect as well as on more complex spatial phenomena underlying an apparently monocentric structure.

To account for the fundamental change in accessibility due to the creation of a dense intra-city transport network, we model the effective travel time among each pair of commercial locations in the city for each observation year. In order to allow the spatial pull, which drives firms´ bid-rents, to originate from various locations and in order to model bidirectional spillovers, we make use of a gravity-type variable which had been previously employed to explain the impact of labor market accessibility on residential property prices (Adair, McGreal, Smyth, Cooper, & Ryley, 2000; Ahlfeldt, 2011; Osland & Thorsen, 2008), but has not yet been applied to commercial land. Unlike previous applications, we guide the empirical setup by means of a theoretical model that lays the foundation for an interpretation of distance-weighted aggregated land value as a measure of agglomeration benefits. With this approach we are able to distinguish between firm spillovers and CBD proximity effects in our empirical analysis.

Our results indicate a flattening of the CBD gradient over time, which is in line with previous evidence on historic land gradient evolution (Abelson, 1997; Atack & Margo, 1998; McMillen, 1996; Smith, 2003).[2] Even by the end of our observation period, we still observe a large and significantly negative CBD gradient, although there are notable signs for the emergence of local micro-agglomerations within the broadly monocentric structure. A closer look reveals a more fundamental change in city structure over the study period. While conditioning on agglomeration effects hardly affects the magnitude of the gradient estimate in 1890, it is able to explain almost the entire variation in land values related to the distance-based CBD gradient roughly 50 years later. Overall, our results indicate that by the end of our study period the large and significantly negative CBD gradient masked the presence of between-firm agglomeration economies. We conclude that a differentiated view is required when interpreting monocentric gradient estimates. While at the beginning of our study period the city center acted as an

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[2] For a brief discussion on corresponding findings and data sets see Ahlfeldt & Wendland (2011).

autonomous agglomeration force, in 1936 the negative gradient seems to reflect spatial interactions among firms whose location had been pinned down by historic accident.

2. Background

2.1 Theoretical Framework

The uneven distribution of clusters of economic activity across the planet is a striking regularity. The discussion of how and why economic densities emerge has for a long time been dominated by the idea of two different forms of agglomeration economies. So-called *first nature geography* may be responsible for individual firms' initial location decisions (Berliant & Konishi, 2000; Ellison & Glaeser, 1999; Kim, 1995, 1999).[3] Comparative advantages provided by certain locations create incentives for firms and industries to cluster around focal points of interest. In many cases, these might have offered perfect conditions for cities and CBDs to emerge in the first place, e.g. if those locational advantages were represented by well accessible points such as ports.

Intense interactions between producers and consumers at the same location generate additional benefits derived from *second nature geography* (Andersson, Burgess, & Lane, 2007; Berliant, Peng, & Wang, 2002; Fujita & Ogawa, 1982; Henderson, 1974, 1977, 1988; Jacobs, 1969). An important factor for productivity gains derived from spatial proximity to other firms consists in potential knowledge spillovers due to formal and informal communication (Ibrahim, Fallah, & Reilly, 2009; Mariotti, Piscitello, & Elia, 2010). Fujita and Ogawa (1982) construct a "locational potential function", where firms directly benefit from spatial proximity to other producers. They show how externalities can account for different urban configurations ranging from simple monocentric to polycentric outcomes. Notably, their model exclusively attributes location decisions to the existence of externalities. Similarly, Helsley (1990) relates his research directly to the fact that agglomeration economies might be strongest within the CBD and are most likely to decline with distance. Compared to the view that goods and services need to be transported to the city center, these models represent an opposite extreme case, emphasizing *second nature* at the expense of *first nature geography*.

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[3] For a comprehensive overview of the nature of agglomeration economies see Rosenthal & Strange (2004)

Our view of urban configurations is a hybrid of both perspectives, featuring elements of classic bid-rent theory where cities are aligned around an exogenous city core and an agglomerations literature that has emphasized externalities among firms as the driving force of spatial concentration. Our city consists of discrete city blocks indexed by *i* that can be used for commercial purposes. Urban land is scarce and provided inelastically. We assume a simplistic urban economy where identical firms produce a final good under perfect competition and constant returns to scale technology. The production technology is Cobb-Douglas with output χ at location *i* being a function of land area *L* and capital *K*, which is a composite of all non-land inputs

$$\chi_i = A_i K_i^{\alpha} L_i^{1-\alpha} \tag{1}$$

The productivity of the final goods production A_j depends on natural advantages, which are reflected in (a_i), and agglomeration forces. We distinguish between a predetermined (exogenous) center of spillovers named CBD in the spirit of classic rent theory (reflected in Λ) and a bidirectional, decentralized agglomeration force that depends on the effective distribution of the surrounding mass as is conventional in the literature (reflected in Γ).

$$A_i = a_i \Lambda_{\mathrm{i}} \Gamma_{\mathrm{i}} \tag{2}$$

Productivity at block *i* increases in proximity to the CBD, where D_i is a distance measure and θ determines the rate of decay in the proximity benefit. This will be the dominating agglomeration force in a world where all economic agents interact with each other at the city center (e.g. a central market place or transport hub), and derive large benefits from proximity to non-market actors who concentrate at that location (e.g. governments and authorities).

$$\Lambda_{\mathrm{i}} = e^{-\theta D_i} \tag{3}$$

Productivity also depends on a bidirectional agglomeration force that increases in the surrounding density of economic activity. There is a tradition in the urban literature to model these interactions as knowledge spillovers that depend on employment, which usually comes with the restrictive assumption of homogenous workers.[4] Instead, we assume a broader agglomeration economy encompassing urbanization, localization and coagglomeration effects. This black-box agglomeration force directly emerges from the surrounding economic mass, thus incorporating the productivity of all non-land inputs, and corresponds to total output at surrounding blocks *j* weighted by bilateral distances d_{ij}.

$$\Gamma_{\mathrm{i}} = e^{\beta Z_i} \text{ and } Z_i = \sum_{\mathrm{j}} \chi_j e^{-\tau d_{ij}} \quad (4)$$

While parameter $\beta \geq 0$ determines the relative importance of this agglomeration force for productivity, $\tau > 0$ parameterizes the rate of spatial decay of spillovers in distance. Natural advantages and complementary or undesirable land uses (*s*) further shift the productivity at a given block *i* depending on their distance (d_s) and the spatial decay in the spillover that is determined by parameters φ_s.

$$a_i = \prod_s e^{-\varphi_s d_{is}} \quad (5)$$

Firms maximize profits by choosing capital and land use while taking factor prices, productivity and the location choice of other firms as given. The price of land is bid-rent Ψ_i, while the price of capital is chosen as the numeraire. First order conditions define the marginal rate of substitution among input factors as a function of relative factor prices.

$$K_i = \frac{\alpha}{1-\alpha} L_i \Psi_i \quad (6)$$

With competitive markets, free entry and exit and, hence, zero profits, this condition can be used to determine the equilibrium condition for bid-rents at location *i*. In keeping with intuition, higher productivity makes a block more attractive, leading to higher equilibrium bid-rents.

$$\Psi_i = \alpha^\alpha A_i^{\frac{1}{1-\alpha}} \quad (7)$$

[4] Lucas & Rossi-Hansberg (2002) for a recent example. See also Alonso 1964, Fijuta and Ogawa 1982, Lucas 2000, Muth 1969, Mills 1969 and Sveikauskas 1975.

To determine the spatial equilibrium we can make further use of the zero-profit condition that must also hold at all other locations j in the city. Output at location j can be expressed as a function of the occupied land area and the local equilibrium rent.

$$\chi_j = \frac{1}{1-\alpha} \Psi_j L_j \tag{8}$$

Substituting (2), (3), (4), (5) and (8) into (7) and taking logs lays the foundations for a regression-based empirical test of the spatial equilibrium condition.

$$\log(\Psi_i) = \log(\alpha^\alpha) + \frac{\beta}{(1-\alpha)^2} \sum_j \Psi_j L_j e^{-\tau d_{ij}} - \frac{\theta}{1-\alpha} D_i - \sum_s \frac{\varphi_s}{1-\alpha} d_{is} \tag{9}$$

From the spatial equilibrium condition (9), some general implications regarding the city structure and its driving forces emerge. Land rents increase in access to economic activity and decrease in distance to the predefined historical center and locational amenities. The magnitudes of the marginal effects of all these location features increase in the share parameter of non-land inputs, which determines the rate of substitution between land and capital. This is particularly the case for the bidirectional decentralized agglomeration force, which is the intuitive result of surrounding firms substituting land for capital as the densities and agglomeration benefits increase.

Some simple comparative statics exercises also yield intuitive implications. Bidirectional agglomeration forces ($\sum_j \Psi_j L_j e^{-\tau d_{ij}}$) should exhibit an increasing impact on the spatial equilibrium structure of the city over time. For one thing, we expect the importance of agglomeration economies (β) in itself to increase over time due to the transformation into a service-based economy. For another thing, the share of non-land inputs (α) should certainly not decrease, as over time production and construction technologies, if changing at all, would improve. For the effect of proximity to the CBD (D_i) the implications are less clear. The effect of an increase in the share of non-land factors could work into the opposite direction of a decline in the importance of the historically predetermined center as an agglomeration force. If, however, a decline in the net-effect can be observed empirically, this will be indicative of the residual agglomeration force subsumed under distance to the CBD losing strength.

2.2 Berlin 1881-1936

Our study period covers the second phase of industrialization in Berlin. As is typical for this stage of development, the period was characterized by rapid population growth and technological innovations. This era is of particular interest for the purposes of this article for a number of reasons.

First, anecdotal evidence suggests that a traditional monocentric city structure began to break up and new, specialized sub-centers started to attract commercial activity by the beginning of the 20th century (Krause, 1958). However, these new business locations, namely plazas such as Potsdamer Platz and Alexanderplatz, were still located in close proximity to the very center of the CBD. This is directly related to one of the outstanding features of historical Berlin's inner city. The area of the CBD was characterized by an unusually dense concentration of quarter-like segregated business areas, where each function was represented by a highly specialized area.[5] These densities created opportunities for physical interactions and, therefore, potential agglomeration benefits. While these were located within relative proximity around the very center, new business agglomerations also emerged even at relatively remote locations.[6] The area around the Kurfürstendamm is probably one of the most prominent examples. After rising to become a major entertainment and luxury retail center in the 1920s, it grew to be the CBD of West-Berlin during the years of division and has maintained its status until today.

Second, this development was accompanied by the transformation from a craftsman-dominated economy into a service-based one (Bergmann, 1973). Holding the status of capital for both Prussia and the German Reich since the end of the French-Prussian War in 1871, this new prestige and various administrative and political entities drew firms and service-oriented industries such as banks and the media into the city. Table 1 shows how the industry structure of the city changed sustainably over our observation period.

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[5] Within the CBD, located at close proximity one could find the "Banking District" (Bankenviertel), the "Government District" (Regierungsviertel), the "News District" (Zeitungsviertel), the "Clothing District" (Konfektionsviertel), the "Export District" (Exportviertel), and the "Insurance District" (Versicherungsviertel).

[6] Alexanderplatz is located approximately 770 meters to the northeast of the historical City Palace (Stadtschloss) and PotsdamerPlatz lies about 2km to the southwest. We define the CBD as the metro station "Stadtmitte" (Downtown).

In 1890, the manufacturing sector with a share at total employment of 42.22 percent, clearly dominated trade and services (19.93 percent). Within the boundaries of the CBD, only 13.35 percent of the workforce was employed in sectors of trade and services, whereas the corresponding number for the manufacturing sector was about twice the size. This relationship was completely reversed by 1933. The total shares within the boundaries of Old-Berlin changed considerably to 35.8 percent for manufacturing and 43.01 percent for trade and services.[7] Especially after 1900, almost all large manufacturing firms had moved towards remote districts such that this change was even more fundamental for the CBD (the district of Berlin-Mitte). In this area, trade and services dominated manufacturing by a factor of two (65.67 vs. 34.4 percent). The CBD was mainly characterized by the unusually large work force within its finance and insurance industries as well as in retail and wholesale trade with more than 120.000 employees.

Tab. 1 Industry Employment in 1890 and 1933 (Old-Berlin Boundaries)

Area	Year	Manufacturing		Trade and Services	
		Employment	Employment Share	Employment	Employment Share
Total:	1890	313,799	42.22%	148,139	19.93%
	1933	329,352	35.80%	396,700	43.01%
CBD:	1890	117,556	27.11%	57,888	13.35%
	1933	91,931	34.30%	175,972	65.67%

Notes: Figures are taken from the industry census of Berlin for 1890 and 1936, respectively. The 1936 edition provides data based on the 1933 census. We use a 1936 spatial definition of the CBD in both years. Manufacturing numbers also include mining and construction, whereas trade and services include trade, transportation, communication and utilities, business services and FIRE industries. Domestic services (private Dienstleistungen) are excluded.

Third, a dense network of intra-urban transport emerged. In 1877, the circular line, which connected Berlin to its surroundings and to several regional lines, was inaugurated. Then, in 1882, an east-west connection joined several inner-city stations with the circular line (Borchert, Starck, Götz, & Müller, 1987). This, however, was only a first step in generating inner-city travel systems and it was not for several decades that

[7]We strictly refer to numbers within the outer city-boundaries of 1890 to ensure feasible comparison. In 1920, in the grand amalgamation, Old-Berlin had been joined with seven other cities, 59 rural municipalities (Landgemeinden), and 27 rural districts (Gutsbezirke).

gradually added stations created a highly developed and very dense network that fundamentally changed the pattern of urban accessibility.[8]

A number of additional events taking place during our study period are worth mentioning. First, an ambitious planning agenda, the so-called Hobrecht Plan, was pursued by local authorities, which in many respects followed the famous Parisien Haussman Plan. It is important to note, however, that the allocation of economic activity within that area was not explicitly influenced by zoning policies (Richter, 1987), except for a general ban on buildings that exceeded a height of 24m, the so-called "Traufhöhe". Second, some remarks must, of course, be directed towards WWI and the Great Depression. The depressing effects on the urban economy are clearly visible in our data for 1929, and to a smaller degree also for 1936. However, the epicenter of the fighting was far away and the city did not suffer major war damage that would have potentially caused major spatial reorganizations. While the entire German Reich was affected by reparations, historic sources provide little evidence for any notable impact on the spatial structure of Berlin. Movements of heavy industry towards remote districts had taken place mostly during the years before WWI. Throughout the study period, the CBD maintained its position as the main center for government activity, media and FIRE industries, which recovered quickly from WWI and the Great Depression. Some historians even argue that the effects of WWI strengthened Berlin's economic position and fostered its industrial growth (Erbe, 1987). Finally, our study period ends before Hitler imposed a general price stop by the end of 1936 to prevent a further inflation that would have been the natural consequence of an economic downturn and increased government spending.

[8] Car usage was, in general, only affordable to high-income families and very few firms resulting in a relative small number of about 77.000 privately used cars and about 28.000 commercially used trucks in 1936, which shows the small impact on general accessibility patterns across the city (Statistical Yearbook of Berlin, 1936).

3. Empirical Analysis

3.1 Data

In the selection of the sample area studied we faced a trade-off between a) keeping the sample to a balanced panel of the same plots throughout all years to prevent that estimated spatial decays are driven by changes in the overall size of the study area or changes in the composition of blocks within the study area and b) selecting plots primarily occupied by commercial activity that reflect the determinants of firm bid-rents (McMillen, 1996). We choose commercial plots based on a historical land value map drawn up by Bruno Aust (1986), which shows real land uses at the individual plot level for a large part of Berlin in 1940. Since, in principle, land use at a given location could change over time this selection implies that some locations temporarily used for commercial purposes could be missing in our sample while some of our plots could have been used for residential purposes temporarily. It is notable, however, that a large degree of persistency in spatial land use pattern has been a particular feature of Berlin. Commercial activity has mainly taken place along a grid of radial and circular boulevards created by the major urban redevelopments during the 19th century in the aftermath or the Hobrecht-Plan (resolved in 1862). Up until the late 20th century, differences in (persistent) building stock served as a natural determinant of land use segregation. For the balanced panel of 1470 plots where land values were continuously available from 1890 to 1936, we expect that these were the typical locations where commercial activity took place and that commercial use was mostly the dominant determinant of the local bid-rent throughout the observation period.

For these 1470 plots, we collect land values from historic maps (Müller, 1890-1910) and street indices (Kalweit, 1928, 1936) that refer to market prices of pure land, adjusted for building, soil, and garden characteristics. The resulting area covers an area of approx. 9 kilometer radius around the present-day subway station “Stadtmitte” (Downtown), which serves as a feasible proxy for the city center throughout the study period. A more detailed description of the land value data and the collection process is provided in the data appendix (A) and by Ahlfeldt and Wendland (2011).

A number of spatial variables were calculated using GIS. Among them, straight-line distances to the next major park or forest area and nearest body of water, which are time-invariant. Further, we calculate straight-line distances to the next industrial area based on available historical maps that fit the respective years as closely as possible.[9] Table 2 provides descriptive statistics for the discussed data. Bilateral travel times are discussed in the next subsection. Land values (NLV) in Table 2 (and the rest of the paper) are adjusted to 2005 values for ease of comparability. Note that the maximum values in each year are relatively close to the 2005 maximum (20,000 €/m²).[10]

Tab. 2 Descriptive statistics

	Obs.	*Min*	*Max*	*Mean*	*Median*	*Std*
NLV 1890	1470	32.26	19,892.47	1,908.68	1,075.27	2,467.04
NLV 1900	1470	111.11	22,555.55	3,293.97	2,216.67	3,454.75
NLV 1910	1470	175.93	20,833.33	4,045.66	2,916.67	3,699.32
NLV 1929	1470	16.85	22,471.91	1,420.95	674.16	1,910.02
NLV 1936	1470	20.83	17,361.11	1,581,05	775.46	2,187.48
Distance to the CBD	1470	0.06	8.16	3.20	3.21	0.91
Travel time to CBD 1890	1470	0.508	69.316	33.489	34.475	13.060
Travel time to CBD 1900	1470	0.508	61.017	32.735	33.067	12.549
Travel time to CBD 1905	1470	0.508	59.311	27.672	26.470	10.116
Travel time to CBD 1910	1470	0.508	44.221	18.434	18.236	5.926
Travel time to CBD 1936	1470	0.508	44.221	18.402	18.186	5.933
Agglomeration Pot. 1890	1470	0.207	738.461	80.402	26.443	119.901
Agglomeration Pot. 1900	1470	0.421	912.541	133.915	54.385	176.561
Agglomeration Pot. 1910	1470	0.667	1033.790	168.923	82.700	201.210
Agglomeration Pot. 1929	1470	0.064	491.354	73.260	34.238	93.706
Agglomeration Pot. 1936	1470	0.080	557.675	80.627	38.284	104.660
Distance to industry 1880	1470	0.001	2.02	0.33	0.22	0.33
Distance to industry 1910	1470	0.001	1.14	0.26	0.20	0.22
Distance to industry 1940	1470	0.001	1.35	0.33	0.24	0.29
Distance to water	1470	0.001	3.20	0.88	0.69	0.71
Distance to green spaces	1470	0.50	4.88	1.75	1.62	1.05

Notes: Distances are calculated in kilometers. Travel times are in minutes. NLV represents CPI adjusted land values in €/m². The agglomeration potentiality is defined in the empirical section. To improve comparability we show descriptive statistics assuming a decay parameter of 0.4.

Networks

In our empirical analyses we connect all city areas based on a bilateral travel time matrix that incorporates the rail transport infrastructure (subway and suburban rail) in a

[9] For the distances to the industrial areas, we match 1880 to 1890, 1900 and 1910 to 1910 and 1936 to 1940. Locations of industrial areas are all identified from Aust´s land use maps discussed in the main text.

[10] The adjustment is made via a consumer price index available at: http://www.privatschule-eberhard.de/interessant/Preisindex.htm. The land value peak in 2005 is at 'Pariser Platz' according to the Senatsverwaltung für Stadtentwicklung, 2006: Bodenrichtwertatlas.

given year. Therefore, the evolution of the city's complete public railway network, including up to 222 stations, has been traced back over the course of our study period in order to create digital maps.[11] Note that the total length of the network, which was calculated within a GIS environment, varied as much as from about 186 km in 1890 to more than 410 kilometers in 1936, which is close to the size of the contemporary network (475 km). Once the bilateral network distances between rail stations were calculated, the total trip length in terms of travel time was estimated based on a simple transport decision model as used in Ahlfeldt (2011). Accordingly, passengers choose the closest station in terms of distance *D* as the start of their train journey (station *s*) and the closest station to their final destination as the endpoint (station *e*). Between these stations they choose the shortest network path. Passengers walk to stations at walking speed (V^{walk} = 4 km/h), while trains run at a velocity of V^{train} = 33.8 km/h, which could be determined from historic train schedules. A buffer time of 2.5 minutes is added to account for the average waiting time at the station of departure, based on an average five minute train frequency. Passengers will choose to walk, instead of taking the train, strictly on the basis of travel time minimization. Travel time between areas *i* and *j* in year *t* therefore can be described as follows.

$$TT_{ijt} = \min\left(\frac{D_{ijt}}{V^{walk}}; \min\frac{D_{ist}}{V^{walk}} + \min\frac{D_{set}}{V^{train}} + \min\frac{D_{ejt}}{V^{walk}}\right) \tag{10}$$

Internal travel times are discounted at walking speed. Internal distances are calculated as in Redding &Venables (2004) as two thirds of the radius of a circle with the same surface area (*A*) as area *i*.[12]

$$TT_{ii} = \frac{2}{3}\frac{\left({A_i}/{P_i}\right)^{1/2}}{V^{walk}} \tag{11}$$

3.2 Empirical Strategy

Equation (9) serves as a natural starting point for a reduced form empirical specification, which can be taken to the data. The empirical model we estimate separately for years *t* = {1890, 1900, 1910, 1929, 1936} takes the following form.

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[11] For all following arguments, relevant information and network plans can be found at: http://www.bahnstrecken.de/indexf.htm; http://www.bahnstrecken.de/bse.htm; http://berlineruntergrundbahn.de/; www.stadtschnellbahn-berlin.de; www.berliner-verkehr.de.

[12] Internal travel times refer to the travel times encountered within the same spatial unit.

$$log(NLV_{it}) = \varsigma_t + \varrho_t\left[\sum_j \left(S_j \times NLV_{jt}\right) e^{-\phi_t \times TT_{ijt}}\right] + \rho_t DCBD_i + \sum_s \upsilon_{ts} X_{sit} + \varepsilon_{it} \quad (12)$$

where NLV_t denotes the land value (adjusted to 2005 prices) at a given location, S is the surface area of the plot of land in commercial use (measured in square km), which is fixed over time, TT_{ij} are bilateral travel times measured in minutes and defined in equations (10 and 11) and X_s is a vector of hedonic location control variables. While ε_{it} is a random error term, all other Greek letters denote parameters to be estimated that find their correspondence in the spatial equilibrium equation (9). Equation (12) can be estimated using a non-linear least squares estimator in a procedure similar to Ahlfeldt (2011), who uses a potentiality equation to explain the residential land gradient with labor market accessibility.[13] Throughout the empirical analysis we cluster standard errors on city municipalities to allow for variation across space. We therefore estimate a linearized version of equation (10), where we hold the spatial decay parameter ϕ constant. The same linearized regression equation is used in several robustness checks. We note that as it stands, equation (12) introduces a mechanical endogeneity problem as the dependent variable shows up on the right-hand side potentiality. To alleviate a correlation of the error terms with the exogenous regressor, we set the right hand side $NLV_{j=i}$ to the average normalized land value within a 1km buffer area around location i in our benchmark specifications. In robustness checks we exclude all $NLV_{j=i}$ from the spillover potentiality. In further robustness checks we instrument with lagged land values ($S \times NLV$ for $i \neq j$) to alleviate concerns regarding unobserved location components that affect nearby land values as well as the potential endogineity of lot size to land price.

An estimation of equation (12) at different points in time and a comparison of the relevant parameter estimates will address an important question we raise in this contribution. Has the strength of bidirectional spillovers among firms relative the attraction of the historically pre-determined center increased over time? Based on the implications of the equilibrium condition (9) and in light of the rapid process of industrial transformation and technological innovation, we would expect that both the intensity of spatial interactions amongst firms as well as the productivity of non-land

[13] Applications of similar gravity-type variables in the realm of the real estate economics literature include Adair et al. (2000) and Osland&Thorsen (2008).

inputs should have increased over time, giving rise to an increase in the relative importance of between-firm agglomeration forces.

In addition, we believe that much can be learned from comparing these estimates to standard bivariate distance-to-CBD gradient estimates, which have enjoyed some popularity in the empirical (historic) urban economics literature as a test of classic bid-rent theory. A common theme emerging from this literature is that during our observation period, cities were in fact monocentric, but that the magnitude of the marginal proximity effect diminished over time, which can be interpreted as a process of urban decentralization.[14] While informative for a description of the city structure, one limitation of that approach is that it is difficult to conclude on the determinants that pull firms into the CBD or why cities change their shape over time. To see the problem, consider our empirical specification (12) based on the spatial equilibrium condition (9). If the agglomeration potentiality variable is correlated with distance to the CBD – a condition that quite naturally seems true – and omitted from the model, the remaining estimated CBD parameter will reflect a composite of the attraction of the city center itself and spillovers among firms, which, more by historical accident than causally related to the contemporary attraction of the natural advantage, are located in close proximity to the historical center. The distinction made in our model becomes particularly relevant when looking at changes over time. A decline in the magnitude of the proximity effect to the city center can be interpreted as being in line with a decline in transport cost to the city center following the logic of classic bid-rent theory. The same effect, however, may be triggered by an increase in the relative importance of the spatial interactions among the firms that reduce the relative importance of co-locating close to a historically predefined center. A similar rationale can be applied to amenities whose spatial distribution is correlated with distance to the CBD and whose value changes over time.

A comparison of bivariate distance-to-CBD gradient estimates and the full estimation of equation (12), thus informs us on a) whether and to which degree the city resembled a monocentric economy, b) which forces pulled firms into the center, c) whether the city

[14] The available evidence refers to Berlin (Ahlfeldt & Wendland, 2011), Chicago (McMillen, 1996), Cleveland (Smith, 2003), New York (Atack & Margo, 1998) and Sydney (Abelson, 1997).

exhibits signs of decentralization and d) which forces were driving the change. Our main-stage empirical analyses are structured according to three basic steps. First, we run bivariate land gradient models to compare how the value of locating closer to the CBD changed over time. Second, we extend the bivariate gradient models by our hedonic controls to evaluate whether a potential decentralization was driven by an increase in the value (cost) of (dis-)amenities in the urban periphery (core). Third, and most importantly, we include our agglomeration variable in order to test for significant productivity spillover effects and to disentangle the direct effects of proximity to a predefined center from correlated agglomeration effects. Robustness checks follow to evaluate the sensitivity of our estimates with respect to functional forms and endogeneity problems as well as to account for changes in transport cost to the CBD over time. We identify the location of the historic center from the data in a way similar to Ahlfeldt (2011) and Plaut & Plaut (1998) by fitting a log-linear gradient into the 1890 data and letting the nucleus of the gradient vary across space.

$$\log(NLV_i) = \delta_0 + \delta_1[((\Theta_i^Y - Y_i)^2 + (\Theta_i^X - X)^2)^{0.5}] + \varepsilon_i \tag{13}$$

where X and Y are the respective coordinates of the geographic centroid of a city block i and $\hat{\Theta}_i^Y$ and $\hat{\Theta}_i^X$ denote the nucleus of the CBD gradient. It turns out to appear at the intersections of the prestigious boulevards “Unter den Linden” and “Friedrichstrasse”, right at the heart of the government and business center.

3.3 Empirical Results

Table 3 shows the results of a series of bivariate gradient models corresponding to equation (12) where land values are exclusively regressed on distance to the endogenously defined CBD (see equation 13). Throughout our study period, we find negative and statistically highly significant land gradients, which are in line with the predictions for a monocentric urban economy. As expected, the marginal value of locating 1 km closer to the city center diminishes constantly over the study period, a phenomenon widely described as urban decentralization. While in 1890 land values decrease by as much as about 79% per 1 km increase in distance to the CBD, this figure more than halves to 38% in 1936. Still, the magnitude of the point estimate is large in comparison with previous evidence. Note that the most comparable results available in the literature are provided by McMillen (1996) for commercial land values in Chicago, a city of roughly the same size as Berlin. McMillen´s gradient estimates for the same period, however, are much lower, ranging from 0.31 in 1892 to 0.12 in 1928.[15] The explanatory power of our bivariate gradient models diminishes over time. However, even by the end of our study period a considerable proportion of variation in land values is still explained by the simple distance model and the explanatory power exceeds McMillen´s findings for Chicago in all years. From 1890 to 1936 we find a reduction in the R^2 from 0.74 to 0.39 compared to 0.58 and 0.24 for the case of Chicago in 1892 and 1928.

Tab. 3 Bivariate gradient estimates (OLS)

	(1)	(2)	(3)	(4)	(5)
	1890	1900	1910	1929	1936
Distance to the CBD	-0.788**	-0.539**	-0.437**	-0.396**	-0.378**
(km)	(0.07)	(0.037)	(0.033)	(0.068)	(0.069)
Constant	9.361**	9.419**	9.392**	8.006**	8.076**
	(0.157)	(0.113)	(0.115)	(0.241)	(0.243)
Observations	1470	1470	1470	1470	1470
R-squared	0.75	0.76	0.67	0.39	0.39

Notes: Dependent variable is CPI adjusted land value in all models. Standard errors (in parentheses) are clustered on city municipalities. Standardized coefficients are in brackets. + significant at 10%; * significant at 5%; ** significant at 1%

Taking these results as a basis we are able to conclude on our first question by noting that despite a pronounced process of decentralization, Berlin remained a roughly monocentric city throughout the study period. This is in line with the cited historical evidence regarding the unusually high density of economic activity across the business districts within Old-Berlin (section 2). However, the results, while replicating previous evidence for other cities, do not allow for an evaluation of the origins of the spatial pull that drives businesses to the city center nor do they allow for an assessment of why the decentralization actually happened and why the explanatory power of standard gradient models diminishes so markedly over time. In the remainder of this section we turn our attention to these open questions.

First, we focus on our second question, i.e. which spatial forces drove firms into the CBD in the first place. Therefore, in the next step we estimate a series of land gradient

[15] Note that for the purposes of comparability, McMillen´s estimates have been rescaled from miles to km.

models extended by selected (dis-)amenities, but excluding the agglomeration variable. If decentralization was driven by an increasing response of firms' bid-rents to the presence of (dis-)amenities rather than the value associated with being close to the city center, we would expect the reduction in the point estimates of the land gradient to be less pronounced than in the bivariate models of Table (3). The corresponding empirical results are presented in Table (4). The environmental control variables add to the explanatory power of the baseline models, most notably in 1929 and 1936. They show the expected signs, with water spaces and green spaces acting as amenities and with industrial areas emanating negative (net)externalities in all years, except 1890. A possible explanation for this exception would be complementarities among commerce and heavy industry, which at the beginning of industrial transformation could have dominated negative environmental effects.

As the estimated gradient coefficients are all reduced following the inclusion of the hedonic controls, Table (4) results indicate that the steep decline in land values when moving out of the city center was partially attributable to the presence of amenities within the center. Central areas benefitted from the ease of access to the Spree river and proximity to prestigious parks, e.g. the "Tiergarten", while more peripheral areas seem to have suffered from (increasingly costly) negative externalities emanating from heavy industries in the industrial belt outside the "Wilhelminian" ring. Despite their reduction compared to Table (3), the magnitudes of the gradient coefficients are still large and a clear tendency towards decentralization is visible. However, it remains questionable whether the idea of transport costs to a central market place in the city center could explain a reduction in land value of close to 30% for every 1 km increase in distance, at least within the service-based economy into which Berlin, and especially its CBD, had transformed itself into by the end of the observation period.

Tab. 4 Gradient estimates with (dis)amenities (OLS)

	(1)	(2)	(3)	(4)	(5)
	1890	1900	1910	1929	1936
Distance to the CBD	-0.675**	-0.496**	-0.407**	-0.304**	-0.285**
(km)	(0.051)	(0.036)	(0.034)	(0.065)	(0.058)
Distance to the nearest	-0.450**	-0.117+	-0.038	-0.095	-0.074
water body (km)	(0.098)	(0.067)	(0.05)	(0.068)	(0.062)
Distance to the nearest	-0.033	0.014	-0.005	-0.058	-0.077
green space (km)	(0.06)	(0.042)	(0.043)	(0.068)	(0.056)
Distance to the nearest	-0.042	0.524*	0.595**	0.979**	1.030**
industrial area (km)	(0.156)	(0.226)	(0.214)	(0.264)	(0.223)
Constant	9.466**	9.223**	9.182**	7.573**	7.636**
	(0.153)	(0.181)	(0.173)	(0.294)	(0.226)
Observations	1470	1470	1470	1470	1470
R-squared	0.8	0.79	0.72	0.48	0.52

Notes: Dependent variable is CPI adjusted land value in all models. Standard errors (in parentheses) are clustered on city municipalities. Standardized coefficients are in brackets. + significant at 10%; * significant at 5%; ** significant at 1%

To address these doubts and to follow our agenda, in the third step of our analysis, we extend the model to allow equilibrium land values to depend on access to the whole economic mass of the city. Again, we aim at isolating the forces that lead to the spatial concentration of firms in the center. Specifically, our specification aims at empirically disentangling the effects of agglomeration spillovers, including those that are correlated with the distance to the CBD, from the direct benefits of locating near the CBD as well as the effects of natural and environmental (dis-)amenities. We run the extended specifications both with and without (dis-)amenity controls and present the qualitatively similar key findings in Figure 1. We limit the presentation of the estimation results to the full specification since we believe that the inclusion of hedonic controls adds to the validity of the model.

In sum, our results support the relevance of bi-directional firm agglomeration externalities and indicate a clear tendency of a transformation into a more decentralized urban economy. These conclusions are based on a number of individually interesting insights. First, the coefficients of both the agglomeration variable and the spatial decay parameters are positive and estimated at high levels of statistical significance in all models, which supports the presence of significant agglomeration economies. Second, the explanatory power of the models is increased considerably following the introduction of the agglomeration variable. The increases are particularly large for the later years. Third, the point estimate on the marginal price effect of the distance to the

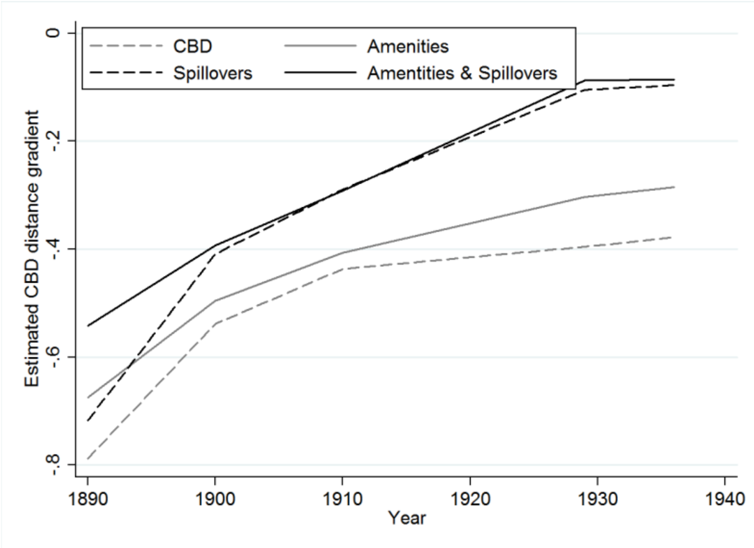
CBD is reduced considerably. In 1936, the gradient coefficient is reduced to less than one third compared to the bivariate gradient model and is no longer statistically significant. The point estimates for the CBD gradient, conditional on spillover effects, are not very sensitive to the inclusion of hedonic controls, except for 1890, when the gradient estimate is reduced remarkably. Figure 1 summarizes our point estimates of the CBD gradients highlighting that the inclusion of the agglomeration variable not only reduces the estimated CBD gradient, but also that the magnitude of the reduction increases over time.

Tab. 5 Gradient estimates with (dis-)amenities and spillover effects (NLS) (exponential decay)

	(1)	(2)	(3)	(4)	(4)
	1890	1900	1910	1929	1936
Distance to the CBD	-0.542**	-0.393**	-0.292**	-0.087	-0.086
(km)	(0.076)	(0.052)	(0.038)	(0.058)	(0.056)
BETA	**[-0.597]**	**[-0.637]**	**[-0.549]**	**[-0.138]**	**[-0.141]**
Spillover Potentiality	0.002**	0.001**	0.001**	0.007**	0.005**
(ϱ)	(0.001)	(0)	(0)	(0.001)	(0.001)
BETA	**[0.184]**	**[0.253]**	**[0.332]**	**[0.596]**	**[0.586]**
Spillover decay	0.435**	0.351**	0.256**	0.430**	0.404**
(ϕ)	(0.080)	(0.055)	(0.020)	(0.022)	(0.209)
Distance to the nearest	-0.428**	-0.109+	-0.03	-0.099*	-0.079+
water body (km)	(0.101)	(0.057)	(0.037)	(0.045)	(0.039)
Distance to the nearest	-0.028	0.008	0.006	-0.026	-0.044
green space (km)	(0.061)	(0.039)	(0.034)	(0.051)	(0.04)
Distance to the nearest	-0.362*	0.141	0.234	0.345+	0.324+
industrial area (km)	(0.157)	(0.236)	(0.175)	(0.198)	(0.179)
Constant	8.950**	8.816**	8.625**	6.605**	6.766**
	(0.239)	(0.185)	(0.164)	(0.253)	(0.204)
NLV at *i=j*	Mean of 1km buffer				
NLV at *i≠j*	Current values				
Observations	1470	1470	1470	1470	1470
R-squared	0.81	0.8	0.74	0.63	0.64

Notes: Dependent variable is CPI adjusted land value in all models. Standard errors (in parentheses) are clustered on city municipalities for all variables with the exception of the decay parameter and taken from a linearized version estimated by OLS. Standardized coefficients are in brackets. + significant at 10%; * significant at 5%; ** significant at 1%

Fig. 1 Estimated gradient effects

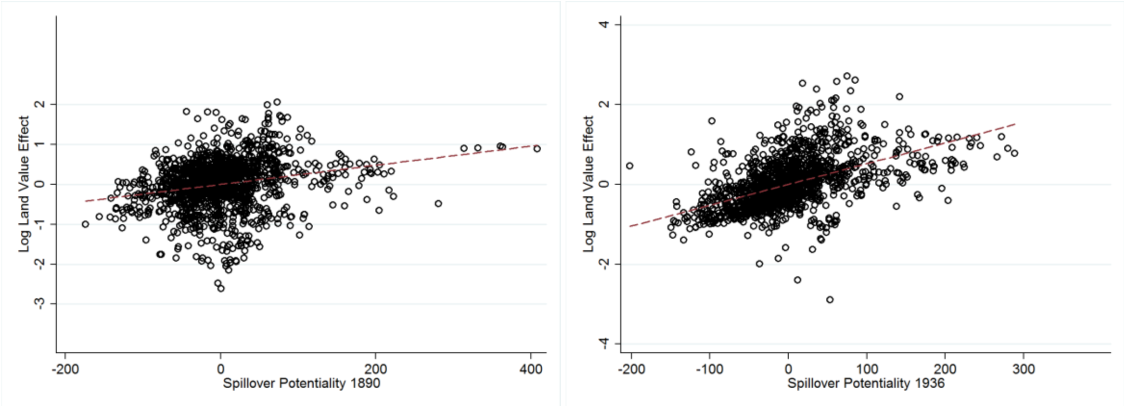


Notes: Figure illustrates point estimates on the effects of distance to the CBD from Tables 3-5 and a not separately reported set of estimates including the spillover variable but excluding the amenity controls.

Besides the change in the magnitude of the distance to CBD effect, we are interested in the relative contribution to the explanatory power of *spillover potentiality* and *distance to CBD*. For the coefficients of interest, Table 5 shows standardized coefficients [in brackets], which express the impact of the explanatory variables on the dependent variable in units of standard deviations (SD). From the results, it is evident that at the beginning of our study period, physical distance to the CBD was a strong determinant of land value, even conditional on our agglomeration variable and the hedonic controls. While an increase in distance to the center by 1 SD yields a reduction in the log of normalized land value by 0.597 SD, the respective increase is no more than 0.18 SD if we increase the spillover potentiality by 1 SD, holding all other factors constant. Very interestingly, over the study period this relationship nearly perfectly reverses. By the end of the observation period, we find the magnitude of the standardized coefficient to clearly exceed the one on the distance gradient (0.586 vs. 0.141) as well as any other variable in the model. Assuming a share parameter for non-land inputs of 0.85, which is roughly in line with typical assumptions (Lucas & Rossi-Hansberg, 2002) and recent evidence (Cheshire, Hilber, & Kaplanis, 2011), we can derive the agglomeration productivity parameter $\beta = \hat{\varrho} \times (1-\alpha)^2$. To make the results comparable to the elasticity estimates found in the agglomeration literature, we compute the agglomeration elasticity at the mean $(\partial A/A)/(\partial Z/\bar{Z})$. In line with our expectations, our estimates indicate an increase in elasticity from 3.5% in 1890 to 8.3% in 1936. These magnitudes are roughly in line with Ciccone & Hall (1996) and Ciccone (2002), who found that a doubling in employment density increases worker productivity by 4.5-6% based on a comparison across US and European regions.

Summing up our results from Tables 3-5, we conclude that throughout the study period the city center was very attractive for businesses and that this attractiveness was amplified by a high concentration of amenities and agglomeration economies within the same area. This becomes evident from the negative gradients in Table 3, which are reduced once we control for (dis-)amenities (4) and agglomeration effects (5). At the beginning of the study period, bi-directional agglomeration economies played a relatively limited role in shaping firms' bid-rents for land, as suggested by standardized coefficients in Table 5. At the same time, the center itself, as an autonomous agglomeration force, exhibited a strong attraction, be it because of its role as a government center, connections to the outside world via mainline stations, or the prestige attached to the established economic, political and cultural center. In line with our expectations regarding the effects of a transformation into a service and knowledge-based economy, the relevance of decentralized agglomeration forces increases at the expense of the direct CBD effect over our study period. Figure 2 visualizes the conditional correlation between (log) land values and the spillover agglomeration variable in 1890 and 1936, demonstrating how the relationship has gained in strength over time.

Fig. 2 Land value effects of spillovers



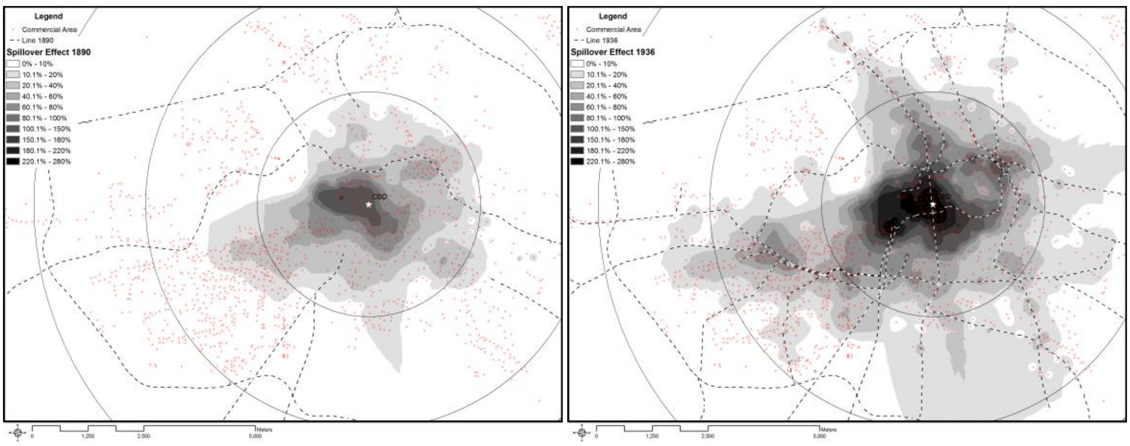
Notes: Figure illustrates the partial correlation between the spillover potentiality ($\hat{\varrho}_t[\sum_j(S_j \times NLV_{jt})\exp(-\hat{\phi} \times TT_{ijt})]$ and (log) land value as estimated in Table 5. Scatter plots are based on the residuals from regressions of log land value on all covariates except the spillover potentiality (y-axes) as well as of spillover potentiality on other covariates (x-axes).

Our results further indicate that the increase in decentralized agglomeration effects gave rise to the emergence of a number of micro-agglomerations corresponding to the anecdotal evidence on specialized business areas, among them Potsdamer Platz and a part of Leipziger Strasse, the government district around the Brandenburg Gate, the banking district around the central bank and, with a smaller magnitude, Alexanderplatz at the eastern end of the downtown section (see Figures 3 and 4). We note that plotting the localized agglomeration forces identified with the method proposed can be seen as complementary approach to the established methods for the identification of sub-centers (McMillen, 2001).

The change in the pattern of agglomeration economies becomes evident from Figure 3 where we plot the spillover-component in land values $\hat{\varrho}_t[\sum_j(S_j \times NLV_{jt})\exp(-\hat{\phi} \times TT_{ijt})]$ in 1890 and 1936. The process of spatial transformation is illustrated in Figure 4 where we plot the price component (in log of normalized land values) that is jointly attributable to the distance to the CBD and the spillover potentiality into three-dimensional space ($\hat{\rho}_t DCBD_{it} + \hat{\varrho}_t[\sum_j(S_j \times NLV_{jt})\exp(-\hat{\phi} \times TT_{ijt})]$).

One striking feature of the 1936 pattern is that the new micro-agglomerations emerged exclusively within a close range of the historic center. This is a notable finding, since in a world with strong spillovers theory predicts the existence of multiple equilibria and the well-known Mills map with one dominating urban core to be just one of various potential outcomes (Lucas & Rossi-Hansberg, 2002). Effectively, we observe the existence of edge-cities and sub-centers in most US metropolitan areas (Garreau, 1991; Glaeser, Kolko, & Saiz, 2001), which goes hand in hand with a weakening of the traditional CBD. Here, to the contrary, emerging agglomeration economies seem to have reinforced or, at least, not weakened the historic downtown area, so that the city continued to resemble a roughly monocentric economy, albeit with a notably more polycentric structure at the micro-level. Apparently, the presence of a historically grown center of business, policy, culture, transport and trade exhibited a strong attraction on businesses when technological changes reconfigured the spatial pattern of the city. This made the concentration in potentially more specialized micro-agglomerations in close proximity to the established center attractive, despite the associated higher land cost. We interpret the result as an effect of path dependency or hysteresis, where the historical center, if the initial location advantage was strong enough, survives even though the importance of the associated direct benefits become less important over time. We further suggest that this phenomenon might be representative for historically evolved dense cities and at least partially explains why many European cities differ substantially from their North American counterparts. An admittedly casual comparison of the two US mega cities New York and LA does at least not contradict this notion.

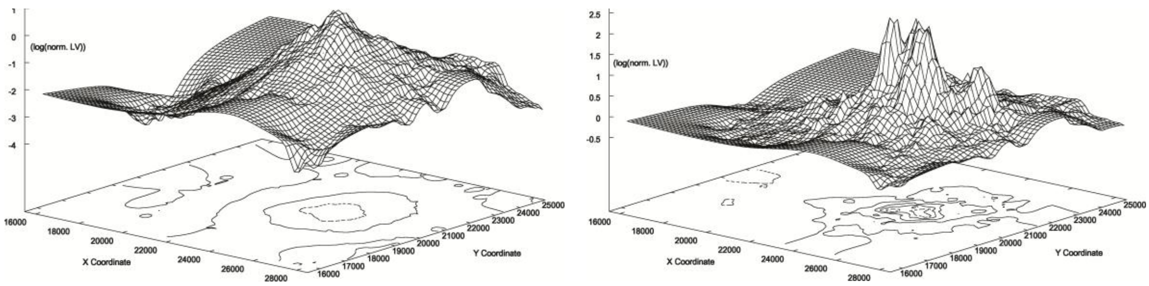
Fig. 3 Land value effects of spillovers



Notes: Figure illustrates the effect of the spillover potentiality based on Table 5 estimates $(\hat{\varrho}_t[\sum_j (S_j \times NLV_{jt}) \exp(-\hat{\phi} \times TT_{ijt})]$.

Fig. 4 Joint effect of distance to the CBD and spillover potentiality

1890 1936



Notes: Figures illustrate the joint effect of distance to the CBD and spillover potentiality based on Table 5 estimates ($\hat{\rho}_t DCBD_{it} + \hat{\varrho}_t\left[\sum_j \left(S_j \times NLV_{jt}\right)\exp(-\hat{\phi} \times TT_{ijt})\right]$).

3.4 Robustness and Extensions

Functional Form

The full estimation equation, despite being a reduced form, follows more or less directly from the theoretical framework developed in section 2 and the underlying assumptions made. We acknowledge that there is at least one somewhat arbitrary assumption that seems at the heart of the paper and deserves further attention: the exponential decay in between firm spillovers. While the assumed exponential form is standard in the related theoretical literature (Lucas & Rossi-Hansberg, 2002; Rossi-Hansberg, Sarte, & Owens, 2010), other functional forms are clearly imaginable. In order to evaluate the sensitivity of the presented results with respect to the assumed functional form of the spatial spillover, we repeat Table 5 estimations employing a power function in the spillover component $\left[\sum_j S_j \times NLV_{jt} \times TT_{ijt}^{-\Phi}\right]$. We note that in some few cases where $TT_{ij} < 1$ min we set the bilateral travel time to one in order to avoid spatial weights exceeding 100%, which would seem implausible.

Table 6 confirms the previous results and provides an even more pronounced picture where the CBD gradient is brought even closer to zero. We note that we still prefer the exponential function on the grounds that it avoids the abovementioned problem with TT_{ij} <1. We therefore keep the more conservative Table 5 results as our benchmark.

Tab. 6 Gradient estimates with (dis-)amenities and spillover effects (NLS) (power function decay)

	(1)	(2)	(3)	(4)	(4)
	1890	1900	1910	1929	1936
Distance to the CBD	-0.493**	-0.292**	-0.270**	-0.027	-0.038
(km)	[0.088]	[0.053]	[0.034]	[0.063]	[0.059]
BETA	**[-0.543]**	**[-0.472]**	**[-0.507]**	**[-0.042]**	**[-0.063]**
Spillover Potentiality	0.002**	0.001**	0.001**	0.008**	0.007**
(ϱ)	(0.001)	(0)	(0)	(0.001)	(0.001)
BETA	**[0.233]**	**[0.428]**	**[0.416]**	**[0.717]**	**[0.695]**
Spillover decay	1.144**	1.175**	1.466**	1.600**	1.162**
(Φ)	(0.152)	(0.081)	(0.067)	(0.048)	(0.022)
Distance to the nearest	-0.398**	-0.05	0.009	-0.0514	-0.038
water body (km)	(0.101)	(0.069)	(0.046)	(0.054)	(0.049)
Distance to the nearest	-0.028	-0.011	-0.007	-0.086+	-0.094*
green space (km)	(0.058)	(0.029)	(0.028)	(0.043)	(0.037)
Distance to the nearest	-0.384*	-0.299	-0.150	-0.106	-0.05
industrial area (km)	(0.154)	(0.216)	(0.180)	(0.244)	(0.238)
Constant	8.344**	8.974**	8.285**	5.851**	6.084**
	(0.382)	(0.295)	(0.210)	(0.325)	(0.280)
NLV at $i=j$	Mean of 1km buffer				
NLV at $i\neq j$	Current values				
Observations	1470	1470	1470	1470	1470
R-squared	0.81	0.81	0.75	0.63	0.63

Notes: Dependent variable is CPI adjusted land value in all models. Standard errors (in parentheses) are clustered on city municipalities for all variables with the exception of the decay parameter and taken from a linearized version estimated by OLS. Standardized coefficients are in brackets. + significant at 10%; * significant at 5%; ** significant at 1%

Endogeneity

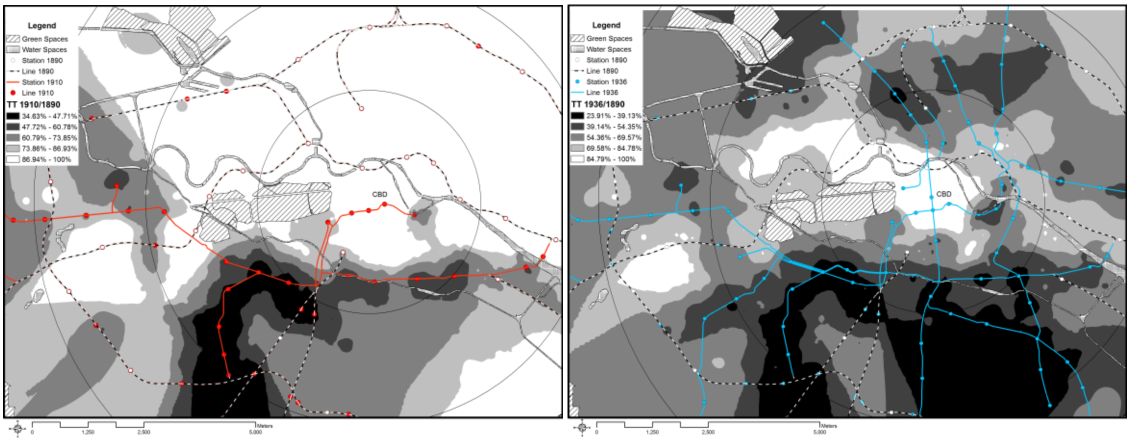
Our benchmark specification gives cause for concerns regarding endogeneity problems for at least two reasons. First, it introduces a mechanical endogeneity problem as the dependent variable shows up in the right-hand side potentiality. Second, the price at any location j not only reflects a firm's productivity at that location pinned down by observable agglomeration and location effects but also includes a potentially correlated unobserved location component which indirectly enters as a determinant of the land value at location *i*.

As discussed, we address the first problem in our benchmark specification by setting the unit land value for block $i=j$ to the mean of a surrounding 1km buffer area. Another way to circumvent the problem is to assign zero weights to the aggregate land value ($S_j \times NLV_j$) at location $i=j$ in an alternative spillover variable that can be used as an instrument for the actual spillover potentiality. The results presented in columns (1) and (2) of Table 7 show that this alteration hardly affects the results. The second problem is more difficult to tackle. To alleviate the concerns, we re-estimate Table 5 models in a two-stage procedure where we first predict land values at locations *j* based on two (where possible) past observations with the longest lags and then use the predicted values on the right hand side of the potentiality equation. At the same time we go one step further in addressing the "self-potential" problem by excluding $i=j$ observations in the spillover variable. First and second stage results can be found in Tables A1 and A2 in appendix B. Reassuringly, the pattern of results remains very much unchanged. To investigate the spatial dependence problem we conduct the classic spatial LM- tests on our Table 5 benchmark models (Anselin, 1995). The test results indicate significant spatial dependency in the data and favor the spatial error-correction (SEM) over the spatial-lag model. SEM results are in columns (3) and (4) and again replicate the basic pattern, even though the decrease in the CBD gradient in 1936 is somewhat reduced.

Reduction in Travel Times

One last question we want to address is whether the willingness to pay for locating closer to the CBD, conditional on amenities and agglomeration effects, diminished over time because of the associated benefits becoming relatively less important or because of decreasing travel cost as a result of transport improvements. Figure 5 illustrates which areas improved in connectivity by plotting travel times to the CBD for 1910 and 1936 expressed in terms of percentages of the respective 1890 times. Cleary, based on our definition of travel time in equation (10), relatively remote areas experienced considerable reductions in travel times as a result of the development of the urban rapid transit system. If the reduction in the magnitude of the CBD gradient parameter was driven by an improvement in connectivity of these areas rather than agglomeration benefits replacing direct benefits of co-location with natural advantages and institutions in the city center, we would expect the reduction in the magnitude parameter to be less pronounced if changes in transport cost to the CBD were accounted for.

Fig. 5 Travel Time to CBD in % of 1890



Notes: Dark shaded areas show the area with a relatively large reduction in travel time to CBD from 1890 to 1910 and to 1936. The surface is spatially interpolated using inverse distance weights (IDW).

To correct for the effect of improved accessibility to the CBD we thus replace the plain distance to CBD measure used so far with a travel time as defined in equation (10) in models (5-6) of Table 7. While the coefficient on distance to the CBD is reduced and switches from being significant to insignificant, the reduction in magnitude is significantly smaller than in terms of distance. This seems, however, not to be the result of a relative loss in predictive power of the spillover variable. Instead, travel times seem to perform inferior to the standard distance measure in terms of capturing the benefits associated with proximity to the in CBD in 1890. The R^2 drops substantially (by about 5 percentage points) once the distance measure is changed. The quantitative impact of spillovers relative to CBD accessibility actually rises to the same level in 1936 as in the previous findings.

One plausible explanation for this pattern relates to the process of industrial transformation referred to in the history section. At the beginning of the study period, actual transport of goods to and from the center played more a substantial role and these transport cost where hardly reduced by the availability of rapid transit. By the end of the study period, when the center had transformed into a modern service-based economy, travel times had become a feasible proxy for CBD accessibility and replacing the plain distance measure with travel times even slightly improves the model fit. Still, the effect of travel times to the CBD, when estimated conditional on spillovers, no longer can be statistically distinguished from zero. We conclude that the evident reduction in firms' willingness to pay for locating close to the CBD, conditional on agglomeration and amenity benefits, was not primarily driven by a reduction transport costs, which benefited especially more remote areas.

Tab. 7 Robustness Tests

	(1) 1890 IV	(2) 1936 IV	(3) 1890 SEM	(4) 1936 SEM	(5) 1890 OLS	(6) 1936 OLS
Distance to the CBD	-0.533***	-0.084	-0.617**	-0.164**	-0.030***	-0.025
	(0.076)	(0.056)	(0.047)	(0.039)	(0.008)	(0.016)
BETA	**[-0.587]**	**[-0.138]**	**[-0.677]**	**[-0.262]**	**[-0.287]**	**[-0.160]**
Spillover	0.003***	0.005***	0.002**	0.005**	0.006***	0.005***
Pot. (ϱ)	(0.001)	(0.001)	(0)	(0)	(0.001)	(0.001)
BETA	**[0.197]**	**[0.593]**	**[0.162]**	**[0.537]**	**[0.478]**	**[0.572]**
Distance to water body	-0.427***	-0.079	-0.233**	-0.044	-0.397***	-0.097**
	(0.101)	(0.039)	(0.038)	(0.033)	(0.103)	(0.035)
Distance to green space	-0.027	-0.044	-0.050	-0.11**	-0.023	-0.064
	(0.061)	(0.040)	(0.043)	(0.037)	(0.076)	(0.042)
Distance to Ind. area	-0.383*	0.317	-0.136+	-0.125*	-1.217***	0.278
	(0.156)	(0.178)	(0.072)	(0.061)	(0.171)	(0.190)
Constant	8.916***	6.758***	9.462**	7.17**	8.194***	7.020***
	(0.238)	(0.203)	(0.595)	(0.377)	(0.296)	(0.382)
CBD distance measure	Plain distance	Plain distance	Plain distance	Plain distance	Travel time	Travel time
NLV at $i=j$	IV with pot. excluding $NLV_{i=j}$	IV with pot. excluding $NLV_{i=j}$	Mean of 1km buffer	Mean of 1km buffer	Mean of 1km buffer	Mean of 1km buffer
NLV at $i \neq j$	Current values					
Observations	1470	1470	1470	1470	1470	1470
R2	0.810	0.639			0.743	0.643

Notes: Dependent variable is CPI adjusted land value in all models. Standard errors (in parentheses) are corrected for a corrected for spatial dependence in (3-4) and are clustered on city municipalities in all other models. Spatial error-models use a row-standardized weights matrix with a minimum distance threshold for neighbors that ensures that no islands are created (1794m). Spatial LM statistics for 1890 are: LM (lag) 234.67, Robust LM (lag) 15.08 LM (error) 1227.74, Robust LM (error) 1008.15. Spatial LM statistics for 1936 are: LM (lag) 837.58, Robust LM (lag) 83.26 LM (error) 3585.61, Robust LM (error) 2831.29. All estimated linearized models take the decay parameters from Table 5 as given. Distance are in km, travel times in minutes. Standardized coefficients (BETA) are in brackets. + significant at 10%; * significant at 5%; ** significant at 1%

4. Conclusion

This study evaluates the change in the spatial city structure of Berlin during the second era of industrialization vis-à-vis the traditional monocentric city model and an alternative approach that allows firms to benefit from access to other firms reflected in the surrounding economic mass. As expected, the city´s transformation into a modern, service-based economy together with the creation of a dense rapid transport network gave rise to increasing spatial interactions across space. Our results suggest that the average productivity effect of a doubling of between-firm spillovers over the study period increased from 3.5% to 8.3%.

Rather than discounting the value of location on transport costs to a dimensionless central market place or export hub, approaching the 1930s, firms valued access to the whole economic mass of the city, which had clustered into numerous local micro agglomerations. A theoretically motivated gravity-type variable, which to our knowledge is used for the first time to explain the spillover component in commercial land values, captures about three quarters of the variation in land values with respect to distance to the CBD in 1936. Notably, these micro agglomerations emerged in relatively close proximity to the historic city center, probably because of a strong attraction to the historically grown central business, government and cultural district. As a result, even by the end of the study period the city exhibited a roughly monocentric pattern mirrored in bivariate gradient estimates that perform satisfactorily in statistical terms but mask the presence of a more complex and polycentric micro geography.

These findings highlight the fact that a differentiated view is required when interpreting rent gradients for commercial properties. Although a significantly negative CBD gradient may be in line with the early rent theory prediction for a monocentric urban economy rather than simply reflecting transport costs to the CBD, it may be masking a) a limited degree of polycentricity and b) the fact that the true determinant of concentration in the urban core is a productivity gain from locating close to other businesses. The idea of firms being drawn into an exogenous center seems to apply, if at all, only to cities in an early state of industrial evolution, but to a much lesser extent to the service-based economies which have dominated the central areas of cities since at least the mid-20th century. Still, if initial location advantages of the historic center are strong enough, the interplay of first-nature geography and second-nature geography may lead to a hysteresis effect where between firm spillovers amplify and ultimately replace the initial location advantages, so that the city center maintains its dominating role even though proximity to the first nature advantage is no longer valued directly. We suggest that such a path dependency could partially explain why, up to the present day, many old and historically evolved cities in Europe exhibit a much more evident orientation towards a historic town center than most US cities, although we acknowledge that more research is required to affirm this notion.

Finally, it is important to note that, despite the differentiations made, our findings do not dismiss the basic assumptions of rent theory entirely. Our results still support the view that firms discount the value of a location on transport costs. Rather than distance to a virtual, dimensionless CBD with natural advantages or important institutions, however, access to other economic activities in a city seems to have become the most important determinant of commercial rent in a service-based economy.

Appendix A - *Data*

Due to the huge loss of raw data caused by the two wars, the identification of reliable information on land values covering a sufficiently long time period proved to be challenging. However, two valuable sources could be retrieved from Berlin’s historical archives. The first was created by the renowned technician Gustav Müller (1881-1910). In cooperation with official planning authorities he published a collection of very detailed colored maps. These maps were presented in a similar way to Olcott’s land values, which contributed to Chicago becoming a unique laboratory for urban economics in an historical context. Müller’s maps provide data at an astonishingly disaggregated level of individual plots. The stated objective was to provide official and representative guides for both private and public investors participating in Berlin’s real estate market. While Müller himself did not explicitly reveal the exact procedure of land valuation, the imperial valuation law (Reichsbewertungsgesetz) of the German Reich stipulated the use of capital values for the assessment of commercial plots based on fair market prices. In line with the valuation laws for commercial land, Müller claims that his assessment refers to the pure value of land, which is adjusted for all building and even for garden characteristics. He also corrects for specific location characteristics such as single and double corner lots, subsoil and courtyard properties, leaving a land value per square meter for a given location that refers to a plot shape and soil quality that is representative for the city. The maps cover an area similar in scope to Bruno Aust’s (1986) map of land uses.

The second source was created by Ferdinand Kalweit (1928, 1936). He was the first to provide detailed information on land prices in Berlin after Müller. In his function as a chartered building surveyor (“gerichtlich beeideter Bausachverständiger”), he offered great expertise regarding land valuation procedures, and was commissioned by the government to overcome the lack of documentation created by the troubled environment of WWI and hyperinflation. Kalweit´s work resulted in two books containing land values for all streets in the city in 1928 and 1936. Like Müller, he followed the explicit rules of the imperial valuation law. He additionally considered information on real sales as a basis for local adjustments. After controlling for subsoil property and location characteristics in a manner similar to Müller, he assigned representative minimum and maximum values of the pure land value to each street. These street stretches were frequently larger than single commercial areas and often contained non-commercial uses. To the maximum extent possible, we applied consistent rules in order to identify the provided land value information as precisely as possible. First, we assume that within residentially and commercially used streets, Kalweit's upper bound estimate refers to commercial use. Second, if the values provided referred to very long road stretches, they were divided into smaller stretches and the average value of each stretch and it's crossing street was assigned. In addition, a colored map for 1938, prepared by Runge (1950), which shows many similarities to the Müller maps, served as a guidance and helped to validate the applied rules. After WWII, Runge was officially commissioned to provide an overview of land values based on the pre-WWII situation. Due to a lack of comprehensive documentation, this map was not considered a primary source in the analyses but nevertheless provided valuable information and crosschecks on the spatial structure during the inter-war period.

Appendix B – *2SNLS Estimates*

Tab A1 2SNLS – First Stage

	(1)	(2)	(3)	(4)	(5)
	1890	1900	1910	1929	1936
Land Value 1880	1.223**	0.405**	0.423**	0.311**	0.085
	(0.059)	(0.062)	(0.063)	(0.080)	(0.087)
Land Value 1890		0.949**	1.003**	0.249**	0.395**
		(0.024)	(0.023)	(0.028)	(0.033)
Observations	1470	1470	1470	1470	1470
R^2	0.852	0.931	0.930	0.646	0.655

Notes: Dependent variable is CPI adjusted land value in all models. Included instruments are distance to CBD, distance to nearest water body, distance to nearest green space, distance to nearest industrial area, spillover potentiality. Standard errors (in parentheses) are clustered on city municipalities. + significant at 10%; * significant at 5%; ** significant at 1%.

Tab A2 2SNLS – Second Stage

	(1)	(2)	(3)	(4)	(5)
	1890	1900	1910	1929	1936
	2SNLS	2SNLS	2SNLS	2SNLS	2SNLS
Distance to the CBD	-0.545**	-0.400**	-0.350**	-0.108+	-0.099+
(km)	(0.077)	(0.052)	(0.029)	(0.063)	(0.055)
BETA	**[-0.601]**	**[-0.647]**	**[-0.657]**	**[-0.170]**	**[-0.163]**
Spillover Potentiality	0.002**	0.001**	0.000**	0.004**	0.003**
(ϱ)	(0.001)	(0)	(0)	(0.001)	(0)
BETA	**[0.180]**	**[0.237]**	**[0.242]**	**[0.508]**	**[0.503]**
Spillover decay	0.424**	0.399**	0.350**	0.349**	0.309**
(Φ)	(0.022)	(0.013)	(0.011)	(0.021)	(0.019)
Distance to the nearest water body (km)	-0.424**	-0.109+	-0.008	-0.090+	-0.067
	(0.102)	(0.058)	(0.046)	(0.049)	(0.042)
Distance to the nearest green space (km)	-0.03	0.011	0.025	-0.042	-0.062
	(0.059)	(0.039)	(0.042)	(0.055)	(0.045)
Distance to the nearest industrial area (km)	-0.362*	0.163	0.436*	0.460*	0.484*
	(0.155)	(0.236)	(0.174)	(0.211)	(0.193)
Constant	8.964**	8.839**	8.261**	6.685**	6.783**
	(0.236)	(0.188)	(0.303)	(0.294)	(0.216)
NLV at *i=j*	Excluded				
NLV at *i≠j*	Instrumented with lagged values				
Cragg-Donald Wald F	4029	3748	579	2496	3802
Hansan J	Exactly	0.040	0.282	3.193	3.331
(P-Value)	identified	(0.842)	(0.596)	(0.074)	(0.068)
Observations	1470	1470	1470	1470	1470
R-squared	0.809	0.797	0.733	0.584	0.598

Notes: Dependent variable is CPI adjusted land value in all models. Standard errors (in parentheses) are clustered on city municipalities for all variables with the exception of the decay parameter and taken from a linearized version estimated with OLS. Weak instrument and overidentification statistics are taken from an auxiliary IV regression where the spillover potentiality is instrumented using potentiality variables that use the contemporary decay parameter and network, but the land values from 1880 and 1890. Standardized coefficients are in brackets. + significant at 10%; * significant at 5%; ** significant at 1%.

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