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The Vertical City: The Price of Land and the Height of Buildings in Chicago 1870-2010

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July 2015

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Abstract
We analyze the determinants of building heights in Chicago by combining a micro-geographic data set on tall buildings with a unique panel of land prices covering 140 years. Consistent with the predictions of classic urban economics models, we find that developers respond to increasing land prices by increasing density, i.e. building taller. In 2000, the elasticity of height with respect of land price was about 45% for tall commercial buildings and 30% for tall residential buildings. As expected given significant improvement in construction technology over time, we find that the height elasticity approximately doubled over the last 100 years. We find evidence for dissipative height competition within cities, as excessively tall buildings are significantly less likely to be constructed near to each other than other buildings. Proximity to scenic amenities creates an extra incentive to outrival competitors, particularly in the residential market.

Keywords: Chicago, density, height, land value, skyscraper
JEL Classifications: R20; R30

1 Introduction

The relationship between productivity and spatial density has been central to urban economics and economic geography research since at least Marshall (1920). Density makes locations more productive, especially so within cities (Ahlfeldt et al., 2015). More productive locations attract firms and workers, in particular those who are particularly productive (Combes et al., 2012). Nowhere do the mutually reinforcing effects of productivity and density become as apparent as in iconic metropolitan skylines.

In spatial equilibrium, the productivity advantages of dense central business districts (CBDs) must be offset by correspondingly high land prices (Alonso, 1964; Roback, 1982; Rosen, 1978). Higher land prices in turn create an incentive to use land more intensely, allowing developers to further bid up the price of land (Ahlfeldt and McMillen, 2014; Brueckner, 1987; McDonald, 1981). One of the main congestive forces that prevents the city from collapsing into a singular tall building is a concave production function of floor space (Epple et al., 2010), which implies increasing marginal cost of building taller. Over time, however, improvements in construction technology such as the elevator and the steel frame have pushed the margin of economically efficient building heights, leading to ever-higher skyscrapers.

While the standard urban economics framework offers a powerful explanation for the existence of skylines, the economics of skyscrapers seem more complex in practice. The tallest buildings are often not economically viable, at least in a narrow sense (Tauranac, 1995). The famous skyscraper race for the tallest structure during the first half of the 20th century in New York culminated in the 381 meter tall Empire State Building, which then topped the list of tallest-buildings in the world for nearly forty years. The Burj Khalifa in Dubai, at about 830 meters, exceeds the height of the second largest building in world, the Shanghai Tower, by about 200 meters, despite its location in an area where land seems abundant. Such excessively tall buildings are difficult to rationalize economically, even with high land prices in New York or low construction costs in Dubai.

Motivated by this apparent anomaly, Helsley and Strange (2008) develop a model of skyscraper competition in which there is an intrinsic value of being the tallest – a feature that is absent from standard urban models. Their game-theoretical model predicts dissipative competition in skyscraper development to pre-empt rivals. The implication is that excessively tall buildings, once established, should remain unrivaled for some time within a given unit of geography, be it world, country, region, city or neighborhood level. Being the tallest in the world, or even within a city, comes with an obvious reputational effect, which may boost rents or enhance the reputation of the developer or architect. Moreover, being the tallest in a neighborhood provides the tangible benefit of a panoramic view, which will be particularly valuable if scenic amenities such as rivers, lakes, mountains or the sea are within sight (Baranzini and Schaerer, 2011; Jim and Chen, 2009).

To test these theoretical predictions, we collect a novel micro-geographic data set with quasi-temporal variation. Our data set includes about 1,750 tall buildings in Chicago for which we know the exact location, the height, and the construction year. Using a variety of data sources, we combine these data with a unique panel of spatially disaggregated land prices, covering the whole of Chicago from 1873 onward. Matching land prices to tall buildings based on location and construction year allows us to capture the economic conditions at the time when the decisions to construct these buildings were made. In addition to its reputation as a city that closely matches the features of the stylized Alonso-Muth-Mills model (Alonso, 1964; Mills, 1967; Muth, 1969), Chicago is a particularly interesting case for our study because it has a long history of innovative architecture and an unusually high concentration of tall buildings. Its relatively lax zoning code present few restrictions on the construction of tall buildings in prime areas.

We use this combination of data sets to estimate the elasticity of height with respect to land price for different land uses and for different construction date cohorts covering 140 years. We use locally weighted regressions (LWR) to predict the fundamental height for each building as a function of its location and the land price at the time of construction of a building. We argue that deviations from the fundamental height represent excess heights, which are potentially attributable to height competition. To analyze the locations of excessively tall buildings we employ a test for localization in the spirit of Duranton and Overman (2005). We argue that significant spatial dispersion at short distances would be in keeping with competition for being the tallest in a local market.

Our results yield a number of novel insights into the determinants of building heights and the nature of skylines. Though our results are consistent with standard supply side urban equilibrium models, there is also evidence of spatial competition for being the tallest within a city neighborhood. As predicted by standard urban models, the price of land is a strong predictor of building height, and there is a positive and statistically significant elasticity of height with respect to land price throughout our study period. In 2000, the elasticity was 45% for commercial buildings and 30% for residential buildings. Over 100 years, the elasticity approx. doubled, which is in line with significant improvements in construction technology. However, we also find evidence of spatial competition for tall building locations. When analyzing the locational pattern of excessively tall buildings relative to other tall structures we find significant dispersion at short distances, in particular for residential buildings. Excessively tall buildings are less likely to be constructed at the same location and in the same or subsequent decade than other buildings. Our results further suggest that scenic views create an extra incentive to build tall and that the prize for being the tallest in a neighborhood comes at least partially in the form of a good view.

While skyscrapers represent a striking and widely visible form of extreme urbanization, they have attracted relatively limited attention in economics research. The theoretical literature has analyzed the relationship between building height and agglomeration (Grimaud, 1989; Helsley and Strange, 2007), as well as building height and between- and within building transport cost (Sullivan, 1991). Helsley and Strange (2008), as discussed above, introduce an intrinsic value of being the tallest in a game-theoretical analysis to rationalize why skyscrapers are developed beyond what appears to be a fundamentally efficient height.[1] Empirically, a number of studies have found that rents tend to be relatively high in tall office buildings (Colwell et al., 1998; Koster et al., 2014; Shilton and Zaccaria, 1994), with the notable exception of Eichholtz et al. (2008), who find mixed results.

Solid empirical evidence on the determinants of building heights is particularly scarce and essentially confined to Jason Barr's work on tall building structures in Manhattan.[2] Barr (2010) provides a time-series analysis of building height, which suggests that skyscraper height is mainly determined by economic fundamentals. Barr (2012) finds a spatial auto-regressive structure in building heights, which he interprets as evidence for builders engaging in height competition. Barr (2013) analyses the skyscraper competition between New York and Chicago. Barr et al. (2010) show that solid bedrock influences where skyscrapers are developed within business districts, but not the locations of business districts themselves. Compared to these studies, the main advantage of our data set is that we observe the price of land at the location and time when decisions on building heights were made for virtually all tall buildings in Chicago. Since the price of land is the primary determinant of the intensity of development, we are able to provide a relatively clean separation of actual building heights into fundamental heights and excess heights.

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[1] A broadly related literature has analysed the cost of building height restrictions theoretically (Arnott and MacKinnon, 1977; Bertaud and Brueckner, 2005).

[2] Cheshire and Derricks (2014) show that employing an award-winning architect allows developers negotiate the right to build taller in London, UK.

Our research is related to a number of strands in the urban economics literature. In particular, we contribute to the literature on the substitution of land for capital in the production process for housing (Ahlfeldt and McMillen, 2014; Albouy and Ehrlich, 2012; Epple et al., 2010; McDonald, 1981).[3] Our research is also closely related to studies that have analyzed building density (Barr and Cohen, 2014; McMillen, 2006) and land price (Ahlfeldt and Wendland, 2011; McMillen, 1996) gradients. The study is also related to empirical analyses of spatial competition (Brueckner, 2003; Brueckner and Saavedra, 2001) and the literature on the effects of very high densities and localized agglomeration (Ahlfeldt et al., 2015; Arzaghi and Henderson, 2008).[4]

The remainder of the paper is organized as follows. Section 2 introduces our data. In section 3 we analyze the relationship between the price of land and the height of buildings. In Section 4 we use these results to separate building heights into fundamental and excess heights, and analyze the latter for signs of localization and dispersion. Section 5 concludes the paper.

2 Data and context

2.1 Building heights

The major component of our data was acquired from Emporis.com, a commercial data provider that collects technical information on various types of buildings, including skyscrapers, high-rises, and various structures such as halls or stadiums. The data base is considered the most complete data base on tall structures to date, and has been used in various analyses of the Manhattan skyline (Barr, 2010, 2012, 2013; Barr and Cohen, 2014; Barr et al., 2010).

From this world-wide data base we extract information on the construction of buildings in Chicago with at least five floors and with complete information on the exact location (geographic coordinates), the year of construction, and a measure of building height.[5] In our analysis, we normally use the architectural height of a building, which excludes antenna masts. For a handful of buildings with missing data, we use regressions of height on the number of floors to impute heights.

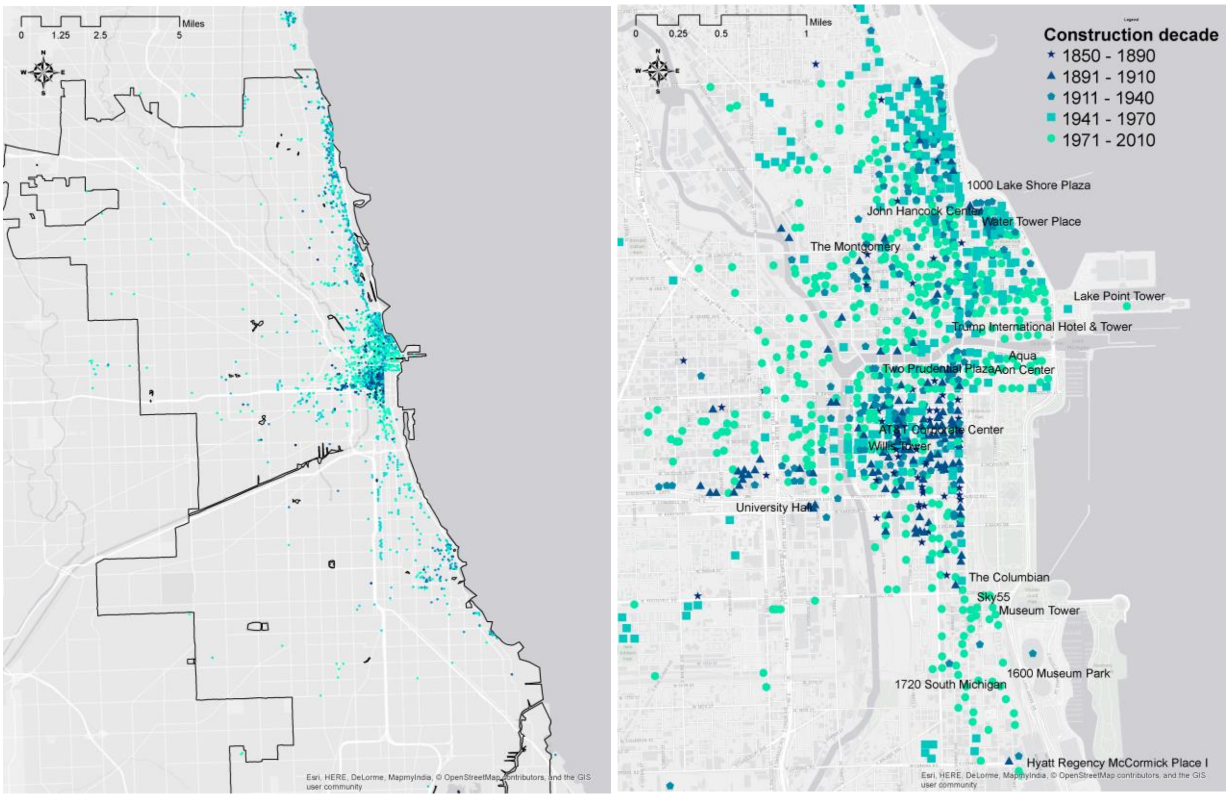
3 Research into the supply side of the urban economy goes back to Mills (1967) and Muth (1969).

4 Examples of more aggregated analyses include Ciccone (2002), Ciccone and Hall (1996), Dekle & Eaton (1999), Glaeser and Mare (2001), Henderson, Kuncoro and Turner (1995), Moretti (2004), Rauch (1993), and Sveikauskas (1975).

5 As we restrict the sample to observations for which construction years are available, some planned but neverbuilt projects drop out. The most impressive is Frank Lloyd Wright's plan for a one-mile tall mega-skyscraper called the Illinois Building.

Within the area covered by our land price data (discussed in the next subsection), we have 1,737 tall buildings, whose location we plot in Figure 1. Despite the long time frame, only 4.4% (77) of these tall buildings had been demolished by 2014. As expected, the vast majority of tall buildings are located near Lake Michigan and, in particular, the central downtown sections of the city. The earliest construction of tall buildings occurred within the Loop, west of Grant Park.

Fig. 1. Location of tall buildings by construction date cohort



Notes: Own illustration based on © Emporis.com and base maps from © OpenStreetMap, accessed via the ESRI ArcGIS Online service.

Table 1 presents descriptive statistics by construction date cohorts. We generally define cohorts as buildings constructed within a given decade. The exceptions are cohorts defined for the 1870s and 1880s as well as the 1890s and 1900s because data on constructions is sparse and there is only one cross-section of land prices available in each case. Construction activity of tall buildings has tended to increase over time, although the 1920s show almost as much new construction as the 2000s. The mean heights of the constructed buildings in our data have approximately doubled over the nearly one and a half century covered by our data set. From the 1920s onward, residential use has replaced commercial as the primary use of tall buildings, which is consistent with the increasingly less centralized location of new buildings. From the 1950s onward, there is a trend for the construction of tall buildings to be more centrally located in the city.

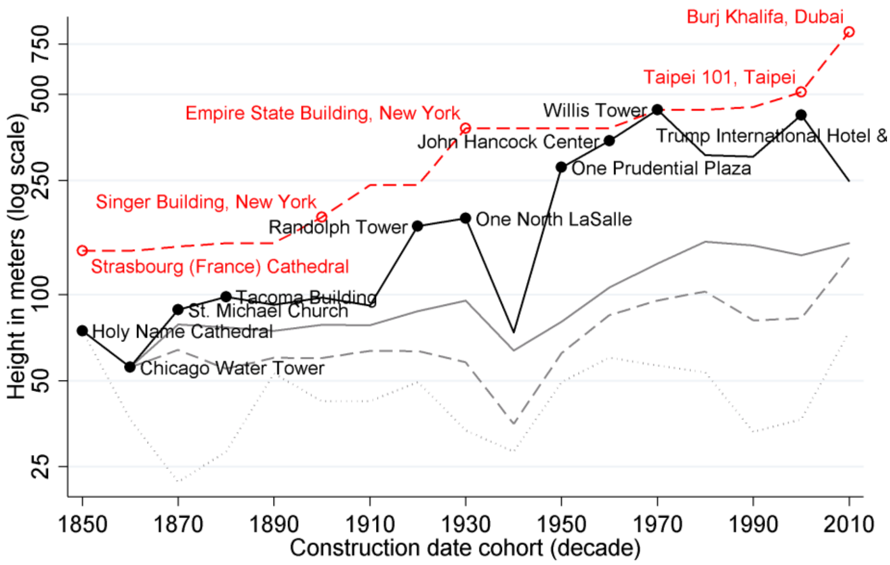
Tab. 1. Descriptive statistics of building constructions

Construction date cohort (decades)	Building height				Land use		Distance to CBD (miles)
	N	Min	Mean	Max	Residential (0,1)	Commercial (0,1)	
1870s & 1880s	17	17.64	42.13	98.15	0.18	0.53	0.81
1890s & 1900s	90	17.64	48.82	97.54	0.30	0.46	1.12
1910s	90	17.64	49.10	91.44	0.32	0.49	1.45
1920s	309	17.57	56.09	173.13	0.62	0.22	3.53
1930s	66	17.64	52.87	184.41	0.68	0.20	4.19
1940s	18	17.64	34.14	73.76	0.61	0.11	5.43
1950s	110	21.17	55.69	278.00	0.66	0.04	4.02
1960s	271	17.57	73.17	344.00	0.69	0.10	3.94
1970s	167	17.64	89.78	442.00	0.70	0.19	2.97
1980s	131	17.64	98.82	306.94	0.59	0.35	1.88
1990s	99	17.64	74.36	303.28	0.56	0.17	2.67
2000s	314	17.64	68.73	423.20	0.83	0.07	2.61
2010s	55	17.64	92.34	249.56	0.76	0.02	1.87
Mean	133.62	17.90	64.31	235.80	0.64	0.19	2.96

Notes: Data from Emporis.com. 1870 construction date cohort includes all buildings constructed from 1870 to 1889. 1890 construction date cohort includes all buildings constructed from 1890 to 1909. All other construction date cohorts are defined for the respective decades. Land use and distances are given as means.

To put this construction activity into perspective, Figure 2 provides a comparison to the tallest buildings in the world at a given time. Up to the 1890s, churches were the tallest structures in the world. The Strasbourg Cathedral with 142 m was the tallest in the world from 1647 to 1874 after a number of taller churches had collapsed or burned down. In the subsequent years it was replaced by the Church of St. Nicholas (Hamburg, Germany), the Rouen Cathedral (France), the Cologne Cathedral (German) and finally the Ulm Minster (Germany). These tall structures are hard to explain with the canonical urban model, and they suggest that height competition and an intrinsic value of being the tallest is not entirely a recent phenomenon. Similarly, up to the 1870s the tallest buildings in Chicago where churches or structures like water towers that required a certain height to function. This pattern changed in the late 1890s with the seminal Tacoma Building in Chicago, the first structure in the world using a modern framework of iron and steel. Together with the elevator, which became increasingly common toward the end of the 19th century, the steel frame dramatically reduced the costs of building tall structures. In 1908, the Singer building in New York became first commercial building to earn the title as the tallest building in the world. Its construction served to jump-start the famous skyscraper race in New York, which culminated in the Empire State Building in the 1930s. Though Chicago was an early entrant in the skyscraper race, it was not until the 1960-1970s that its building heights rivaled New York's. The Willis Tower (formerly the Sears Tower) became the tallest building in the world upon its completion in 1973. Since the 1960s, there has been at least one building exceeding 300 meters constructed in each decade in Chicago, making it one of the most vertical cities of the U.S.

Fig. 2. Tallest constructions by decade



Notes: Dashed red line shows the height of the tallest building in the world in a given decade. Black solid line shows the height of the tallest building constructed in Chicago in a decade. Solid (dashed) [dotted] line shows the 90th (75th) [50th] percentile in the height distribution of buildings constructed Chicago in a decade.

We note that over the course of our study period, eight different buildings held the title of being the tallest in Chicago. On average, these tallest buildings remained in the leading position for slightly more than 20 years, which is perhaps suggestive of overbuilding and dissipative height competition (see appendix section 2 for more information).

2 . 2 Land prices

Our second main data source is a digitized version of various editions of *Olcott's Blue Books of Chicago*. Olcott's Blue Books provide front-foot land value estimates for Chicago and many of its suburbs in the form of detailed printed maps. Olcott's land values offer astonishing spatial detail. They typically vary for street segments along the same block, across different sides of the same street, and even take distinct values for corner lots. Olcott's Blue Books are a reputable source from an established assessment company that stayed in business for more than 80 years. Smaller samples of Olcott's land values have previously been used in such studies as Berry (1976), Kau and Sirmans (1979), McDonald and Bowman (1979), McMillen (1996), McMillen and McDonald (2002), Mills (1969), and Yeates (1965). This project is the first to take advantage of a newly digitized version of nine editions ranging from the first edition in 1913 to one of the last editions in

1990, at approximately in 10-year intervals.[6] The Olcott's data were coded for 330 x 330 feet tracts that closely follow the Chicago grid street structure.

For earlier years we rely on Hoyt (1933) who provides similar printed land value maps for Chicago in 1873 and 1892. The maps are as detailed as Olcott's maps for the CBD. Outside the downtown area, Hoyt's land values are more aggregated and typically refer to rectangular segments of about a square mile. To enrich the data in the remote areas, we first merge the 1873 and 1892 Hoyt land values to the same 330 x 330 feet grid we created for the Olcott land values. We next run a set of locally weighed regression (Cleveland and Devlin, 1988; McMillen, 1996) using the log of Hoyt's land values estimates for either 1873 or 1892 as the dependent variable and the log Olcott's 1913 land values as the explanatory variable. Specifically, we run a LWR for each developed grid cell *j* using kernel weights: $w_{ij} = \exp\left(-\tau^2 D_{ij}^2\right)$, where D_{ij} is the straight-line distance between grid cells *i* and *j*, and τ=0.2 is a decay parameter that ensures that nearby grid cells receive a higher weight. All grid cells *j* outside the downtown area that were developed in the given year are then assigned the predicted value from the respective LWR. This procedure ensures that the general spatial price trends follow the 1873 or 1892 Hoyt land values, but incorporate the additional spatial detail provided by Olcott at the local level. For blocks that were undeveloped in a given year, we assign the predicted value of similar LWR of (log) Hoyt land values on distance from Lake Michigan, the CBD, and geographic coordinates. These LWR serve to smooth the land value surface across the boundaries of the one square mile Hoyt land value areas. The collection and processing of the Olcott and Hoyt raw data is described in more detail in the appendix (section 2).

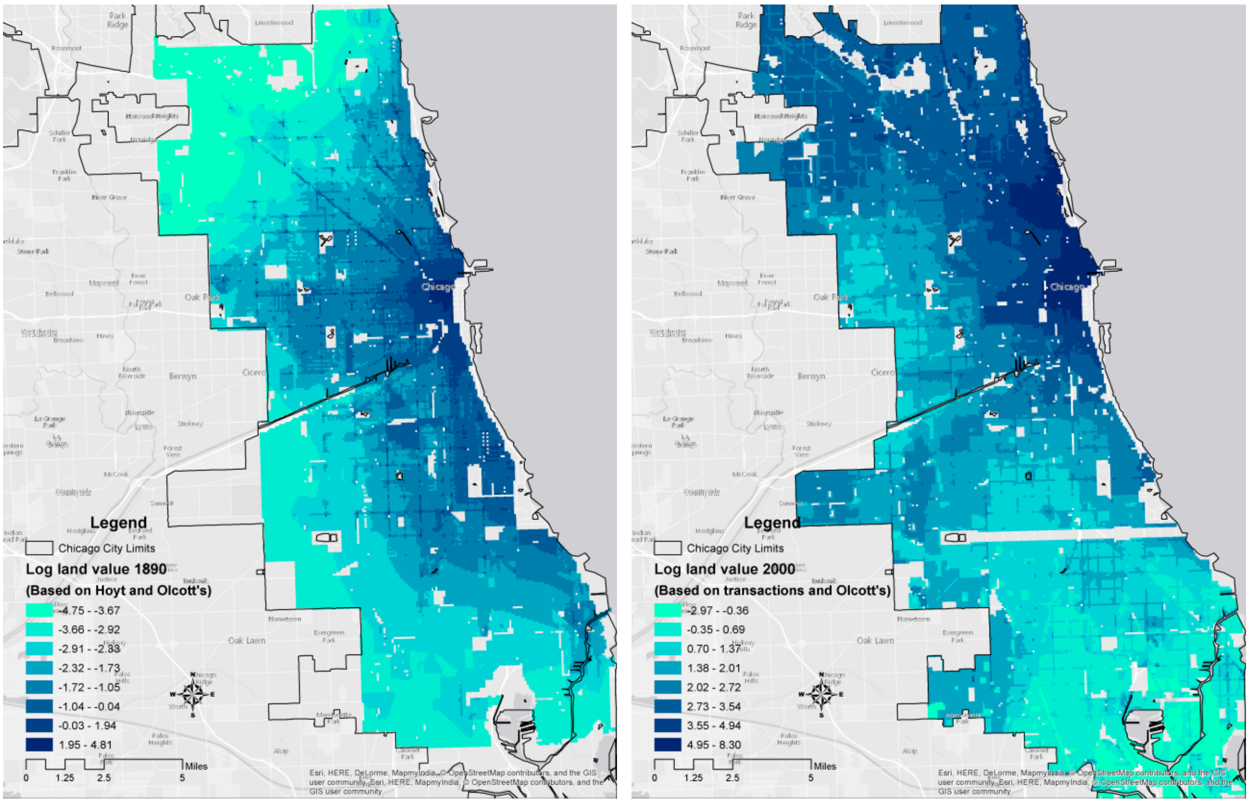
The final step in the construction of our data set is the addition of data from the Illinois Department of Revenue on sales prices of vacant parcels of land. We employ a similar approach to generate comparable and similarly detailed land values for 2000 and 2010. We run LWR of vacant land transaction prices on 1990 (log) Olcott land values and year effects. For 2000 and 2010, we use a temporal window of ±4 years. Again, we run a LWR for each grid cell, in each case weighting all observations (transactions) by the distance from the grid cell, and use the predicted values as our measure of local land value.

6 We collected this data set with the generous financial support by the Lincoln Institute of Land Policy.

This combination of recent vacant land sales, 1913 – 1990 Olcott's data, and our estimates for 1873 and 1892 combining Olcott's and Hoyt data creates a unique micro-geographic panel data set for 330 x 300 feet grid cells covering virtually the whole of Chicago and 13 cross-sections spanning almost one and a half centuries. Figure 3 compares the estimated land values for 2000 and 1890, when the area within the boundaries of Chicago was already largely developed. Both maps show the typical pattern of land values in Chicago, revealing a clearly monocentric pattern and a large degree of persistency over time. Land prices tend to decline in all directions from the CBD and tend to be higher close to Lake Michigan, which is a natural amenity. The most evident change in the spatial pattern of land prices is a relative increase in land prices in the north compared to the south.

Fig. 3. Estimated land values

1890[a] 2000[b]



Notes: Base maps from © OpenStreetMap, accessed via the ESRI ArcGIS Online service. [a] Locally weighted regression interpolation of Hoyt 1 square mile parcels in areas undeveloped in 1890. Predicted values from LWR of Olcott's 1913 on Hoyt 1892 in areas developed in 1890. [b] predicted values from LWR of vacant land prices on 1990 Olcott's.

We then merge this land price panel data set to the data set on tall building constructions described in the previous section. Each building is assigned a land value based on its construction date cohort and the land value grid in which it is located. Table 2 compares the land prices merged to our construction data with the distribution of land prices within the city. As is evident from the table, we have merged land values from roughly the beginning of each decade to the construction date cohorts. The exception is the 1920s, for which data covering the entire area of the city were not accessible to us for years prior to 1926. A comparison of Figures 1 and 3 suggests that tall buildings tend to concentrate in areas with high land prices close to the CBD and Lake Michigan, as predicted by the standard urban model. Indeed the mean land price merged across new constructions is, on average, more than ten times the mean across grid cells in the city, which reflects the exposed locations of tall buildings.

Tab. 2. Land prices in the city and in the tall building constructions sample

Construction date cohort (decades)	Land value year	All grid cells				Grid cells matched to new constructions			
		N	Min	Mean	Max	N	Min	Mean	Max
1870s & 1880s	1873	37458	0.00	0.11	21.00	17	0.13	3.93	13.50
1890s & 1990s	1892	37458	0.01	0.35	123.00	90	0.15	29.45	123.00
1910s	1913	43324	0.01	0.52	148.33	90	0.52	32.06	141.67
1920s	1926	43324	0.02	1.22	206.00	309	0.11	17.66	109.00
1930s	1932	43324	0.02	1.16	163.33	66	0.93	12.69	100.00
1940s	1939	43324	0.00	0.58	116.35	18	0.36	3.17	20.20
1950s	1949	43324	0.01	0.67	145.00	110	0.11	3.14	65.00
1960s	1961	43324	0.07	1.28	180.00	271	0.28	5.68	86.90
1970s	1971	43324	0.30	2.20	200.00	167	0.72	22.68	90.00
1980s	1981	43324	0.33	2.90	250.00	131	0.80	61.88	230.00
1990s	1990	43324	0.12	7.41	800.00	99	1.30	128.57	600.00
2000s	2000	43201	0.20	26.76	3961.96	314	1.81	348.32	3410.68
2010s	2010	42367	0.68	25.27	454.21	55	3.25	146.05	406.85
Mean			0.14	5.42	520.71		0.81	62.71	415.14

Notes: Land values are given in $/square foot. Land values for all grid cells refer to a balanced panel of Olcott land values (1913-1990) to which own estimates for 1873 and 1892 (based on Hoyt) and 2000 and 2010 (based on vacant land sales) have been merged.

3 The spatial structure of building height

3.1 Fundamental determinants of building height

In the absence of strategic interactions developers choosing the optimal building height face a relatively simple problem. Given a price of floor space *p*, the revenues a building generates is *pS*, where *S* is a measure of building height. Construction costs depend on the height because taller buildings require more sophisticated structural engineering, expensive building materials, and additional facilities such as elevators. An empirically convenient parametrization is bS^{θ}, where b is a scale factor and θ>1 monitors the degree of convexity of the cost function. Developers buy each unit of land at a price *r*. Assuming that the floor space price does not depend on the height of a building, the profit function is defined as:

$$\pi = pS - bS^{\theta} - r \quad (1)$$

The first order condition determines the efficient height given the floor space price p at a given location, which depends on locational features such as the degree of agglomeration and the level of amenities. Assuming a competitive construction sector with free entry and exit, land prices r must adjust to equate economic profit to zero at all locations. In spatial equilibrium, the fundamental height of a building can therefore be expressed as the following log-linearized function of the land price:

$$\log(S) = -\frac{1}{\theta}(\log(\theta - 1) + \log(b)) + \frac{1}{\theta}\log(r) \quad (2)$$

In its simplest form, the empirical specification that follows from this relationship is

$$\log(S_{it}) = \alpha + \beta \log(r_{it}) + \varepsilon_{it} , \quad (3)$$

where i and t indicate location and a building's construction date, ε_{it} is a random error term, and $0 < \beta = \theta^{-1} < 1$ is the elasticity of height with respect to land price, which simply mirrors the degree of convexity of the cost function. The straightforward implication is that locations that are more expensive will have taller buildings, whether amenities or the benefits of agglomeration are the source of the high land price. It is notable that the cost of constructing tall buildings and, in particular, the degree to which the cost increases in building height may depend on location. As an example, solid bedrock is sometimes argued to reduce the cost of building taller (Barr et al., 2010).[7] For obvious logistical reasons it is more expensive to build a very tall structure within a dense CBD than at a more peripheral location with plenty of space for materials and equipment and little surrounding traffic. The empirical implication is that the parameters α and β may vary across locations. The elasticity parameter β may also change over time due to innovations in construction technology that reduce the relative cost of building taller.

3 . 2 Height and land price gradients

As is evident from Figure 1, the geography of tall buildings in Chicago allows for a stylized representation of urban form as a function of the vertical (latitude) geographic coordinate. Figure 4 compares building heights in 2014 to 1990 land prices of the respective plots of land. The heights in the figure give a stylized representation of the Chicago skyline as seen from Lake Michigan. Two

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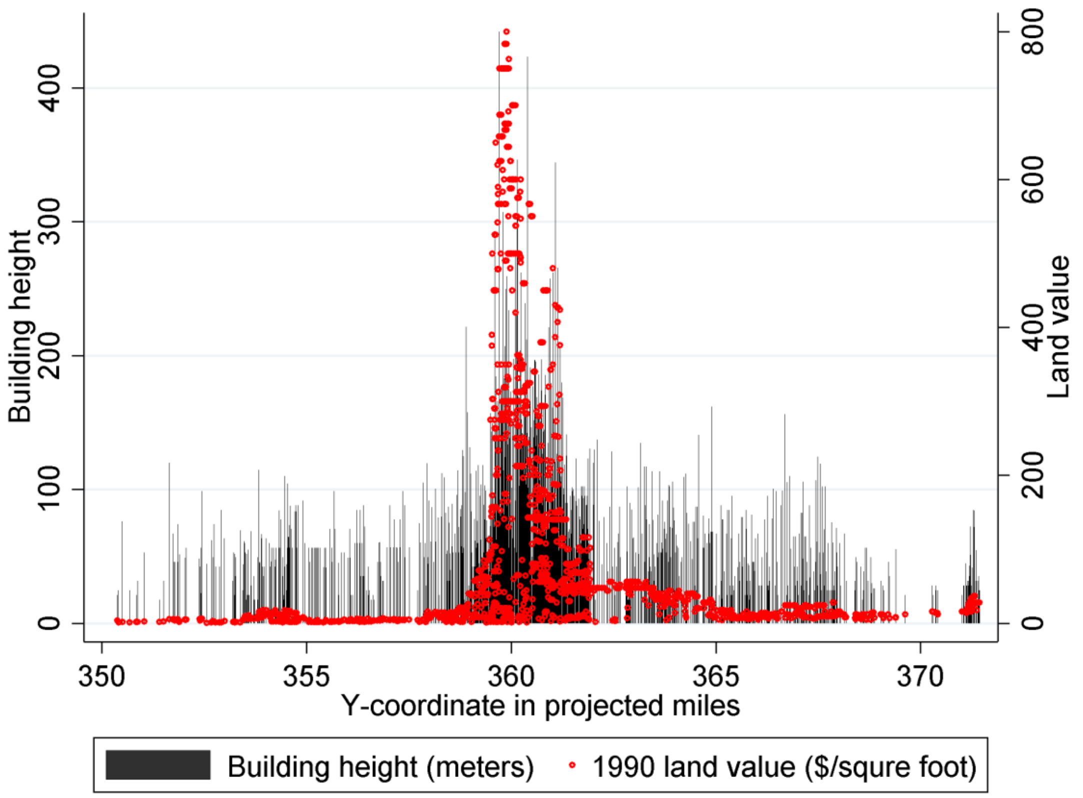
[7] Rosenthal and Strange (2008) and Combes et al. (2010) use geology to instrument for density. It is notable that Chicago is built nearly entirely on sandy soil with virtually no bedrock near the surface.

stylized facts emerge from Figure 4. First, the degree of correlation between building heights and land prices is striking within the CBD where the highest land prices and building heights are observed. Second, outside the densest central area we frequently observe relatively tall buildings of about 100 meter's height, despite relatively low land prices, which suggests that the cost of building taller rapidly increases beyond this threshold.

Fig. 4. Building height and land prices

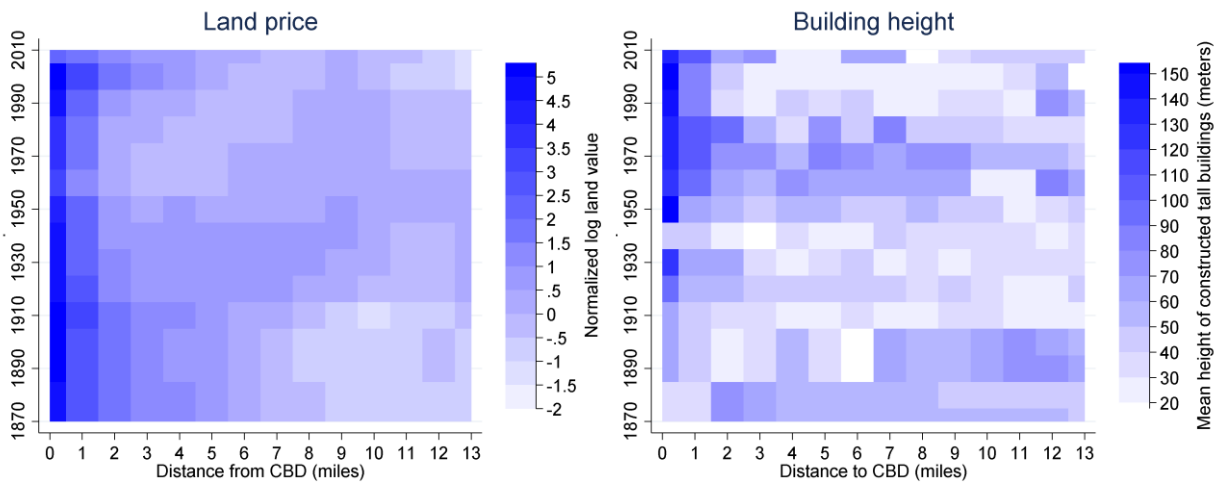


Notes: Building heights in 2014 from Emporis.com. 1990 land values from Olcott's blue books. Y-coordinate is vertical Cartesian coordinate in the State Plane Coordinate System (Illinois East).

In Figure 5 we summarize the spatiotemporal pattern of land prices and heights of newly constructed tall buildings. The left heat map shows the mean log land value normalized to a zero mean within a cohort. The grid cells are defined for each combination of decade and one-mile distance from the CBD. The right heat map similarly shows the mean height of newly constructed buildings within the same grid cells. We identify the CBD as the nucleus of log-linear height and land price gradient in auxiliary NLS estimations, which are discussed in more detail in the appendix. In general, our estimates suggest that the center of gravity of the city has changed very little over time and is located close to the intersection of Washington Street and State Street, which we choose as CBD in all years.[8]

The two heat maps are reflective of some of the major urban phenomena of the 20th century, suburbanization and gentrification. Land prices were highest within the CBD at any time. Starting in the 1920s a tendency of decentralization of high land prices is evident, which is in line with reductions in transport cost due to the completion of the elevated train lines and the rise of the automobile. The trend is reversed from the 1990s onwards. A similar height gradient starts emerging in the 1920s when construction technology allowed for increasingly tall residential and commercial buildings. From then on, with the exception of the 1940s, the CBD is the location of the tallest construction. At the peak of suburbanization during the 1960s and 1970s, we observe construction of relatively tall buildings at relatively remote locations. Another notable feature is the inverse height gradient in the 19th century, which is largely explained by the majority of tall buildings being technical structures or churches (see also Figure 2).

Fig. 5. Land price and height gradients: Spatiotemporal heat maps



Notes: Heat maps show mean values (using all data) within one-mile distance from CBD x construction date cohorts (decades). Log land values are normalized to have a zero mean within a cohort. Tall buildings are defined as buildings with at least five floors. Building heights from Emporis.com. Land values based on Hoyt and Olcott (1870s-1900s), Olcott (1910s-1990s) and vacant land transactions and Olcott (2000s-2010s).

[8] For each decade t we run an auxiliary NLS estimations of the following form: $\log(C_{it}) = \gamma_{0t} + \gamma_{1t}((X_{it} - \gamma_t^X)^2 + (Y_{it} - \gamma_t^Y)^2)^{0.5} + \epsilon_{it}$, where C_{it} is either the height of a building i constructed in a decade t or the price of the underlying plot of land, X_{it} and Y_{it} are cartesian coordinates of buildings, and γ_t^X and γ_t^Y are the coordinates of the CBD to be estimated along with the other parameters γ_{0t} and γ_{1t}. The traditional center of Chicago, at the intersection of State and Madison Street, is only one block south of the site identified using this procedure.

In Table 3 we provide parametric estimates of land price and height gradients obtained from separate regressions of log land prices and log heights against log distance from the CBD for every construction cohort. We distinguish between the full set of land prices covering the entire city area and the land prices matched to the construction data set. The results are consistent with Figure 5, reflecting suburbanization during the mid-20th century and subsequent gentrification. Notably, the price gradient is generally steeper within the sample of new construction than for the city as a whole, reflecting that land prices decline particularly quickly within the downtown section, as evident from Figure 4. Importantly, we find that that the land price elasticity is significantly larger than the height elasticity. This points to an elasticity of height with respect to land price of less than one (β<1), which is required for a cost function that is convex in height (θ>1).

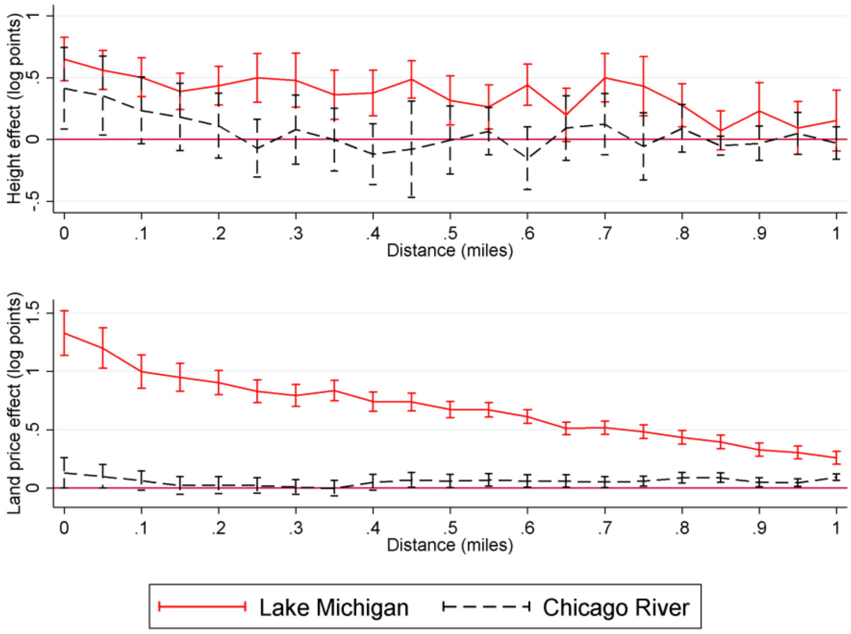
Tab. 3. Land price and height gradients: Parametric estimates

Construction cohort	Land price: All grid cells		Land price: New constructions		Height of new constructions	
	Elasticity	R2	Elasticity	R2	Elasticity	R2
1870s & 1880s	-1.63***	0.72	-4.89***	0.78	0.46	0.05
1890s & 1900s	-1.39***	0.49	-3.33***	0.70	-0.33***	0.13
1910s	-1.63***	0.43	-2.18***	0.63	-0.46***	0.36
1920s	-0.97***	0.23	-1.00***	0.52	-0.36***	0.33
1930s	-0.85***	0.21	-0.91***	0.45	-0.56***	0.50
1940s	-0.75***	0.20	0.20	0.02	-0.06	0.01
1950s	-0.56***	0.15	-0.84***	0.10	-0.37***	0.25
1960s	-0.19***	0.03	-0.94***	0.20	-0.29***	0.18
1970s	-0.32***	0.08	-1.48***	0.48	-0.37***	0.18
1980s	-0.42***	0.08	-1.80***	0.61	-0.56***	0.29
1990s	-0.69***	0.17	-2.05***	0.73	-0.70***	0.36
2000s	-1.42***	0.43	-1.99***	0.68	-0.75***	0.40
2010s	-1.03***	0.38	-0.83***	0.18	-0.78***	0.30
Mean	-0.91	0.28	-1.70	0.47	-0.40	0.26

Notes: Tables shows gradient estimates obtained from regressions of log of land price or log of height on log of distance from the CBD. Height data from Emporis.com. Olcott land values (1913-1990) to which own estimates for 1873 and 1892 (based on Hoyt) and 2000 and 2010 (based on vacant land sales) have been merged. *** $p < 0.01$.

In Figure 6 we turn our attention to two important amenities in Chicago, Lake Michigan and the Chicago River. Lake Michigan offers attractive recreational spaces such as parks and beaches along its shore. Both offer attractive views, which tend to add to the value of properties and may create incentives to build taller, although the river was once heavily polluted and only recently has become a highly desirable amenity. As expected, we find that, controlling for time-varying proximity to CBD effects, new buildings are significantly taller and land is significantly more expensive nearer to Lake Michigan and Chicago River. Whereas heights and land prices decline relatively gradually with distance from Lake Michigan, the effects of the Chicago River are more localized. Building heights, on average, increase by about 50% within a fifth of a mile as one gets closer to the river. A similar but somewhat smaller localized effect is evident for land prices. Such a localized effect can be rationalized with a view amenity that gets easily obstructed by other buildings within the CBD. The wider effects found for Lake Michigan suggest that the view can be enjoyed over larger distances since the density of tall buildings is lower along the lake, or that Lake Michigan is an amenity that is not enjoyed exclusively through a view.

Fig. 6. Distance from Lake Michigan and Chicago River effects



Notes: The figure illustrates results from two regressions of log of height (upper panel) and log of land price (lower panel) on 0.05 mile distance from Lake Michigan bins and 0.05 mile distance from Chicago River bins. We include 21 distance bins defined as follows: 0-0.025 miles, 0.025-0.075 miles, … 0.975-1.025 miles. In each regression we include two dummy variables indicating a 0-2 miles buffer, so that the point estimates displayed give the difference within a distance bin and the respective 1.025-2 miles area in the buffer. In each regression we control for a full set of quarter mile distance from the CBD bin x decade effects. Standard errors are clustered on quarter mile distance from the CBD bin x decade effects. Solid lines connect the distance bin point estimates. Vertical error bars indicate the 95% confidence intervals.

In Table 4 we present estimates of the height gradient obtained by regressing the log of building height against a set of covariates using the entire sample of new constructions. Besides the CBD, which is the primary concentration of economic activity and urban amenities, we also consider Lake Michigan and the Chicago River as additional important amenities. Informed by Figure 6 we choose to approximate the amenity value of Lake Michigan in terms of a gradual distance measure while the more localized effects of the Chicago River are captured by a variable indicating that the building is within a tenth of a mile of the river. We control for the construction year using a trend variable that is zero in 2000.

According to our baseline model (column 1) the elasticity of height with respect to distance from the CBD is -39.6%, which is close to the mean across construction cohorts of -40% reported in

Table 3. The effect of Lake Michigan is smaller, but with an elasticity of -14% still large. Being within a tenth of a mile of the Chicago River on average increases heights by 28.4%. On average, building height increased by 4% every decade. In column (2) we allow for an interaction between the trend variable and the other covariates. In 2000, the predicted CBD distance elasticity of 49.4% is more than twice as large as in 1900 (49.4%-3%×100=19.4%). Similarly, the effects of proximity to Lake Michigan and Chicago River have increased over time, pointing to an increase in amenity value. In columns (3) and (4) we replicate model (2) separately for commercial and residential buildings. The parameter estimates are within the same range, but generally larger for commercial buildings.

In columns (5) and (6) we replicate the models from columns (1) and (2) using the log of land price as the dependent variable. The CBD effects are generally in line with the estimates provided in Table 3. The time interaction suggests that the general tendency of the past 140 years has been decentralization, but the linear time interaction does not allow capturing the resurgence of the CBD since the late 20th century. Unlike in heights, we find that the effect of Lake Michigan on the land price gradient has decreased over time. In line with our estimated height gradients, the amenity value of the Chicago River has increased. In fact the river has turned from a disamenty, which depreciated land price by about $0.11 - 100 \times 0.02 \approx -9\%$, into an amenity, which increases land prices by about 11% from 1900 to 2000. These capitalization effects presumably reflect a number of improvements made over the course of the 20th century to transform the "stinking river" as it was called at the end of the 19th century into the amenity it currently represents.[9]

[9] The reversion of the Chicago River in 1900, which was named a 'Civil Engineering Monument of the Millennium' by the American Society of Civil Engineers (ASCE News, 2001), represented a milestone that relieved the river from sewage and pollution. During the 1990s the river underwent extensive cleaning from garbage as a part of the beautification program by Chicago Mayor Richard M. Daley.

Tab. 4. Pooled gradient estimates

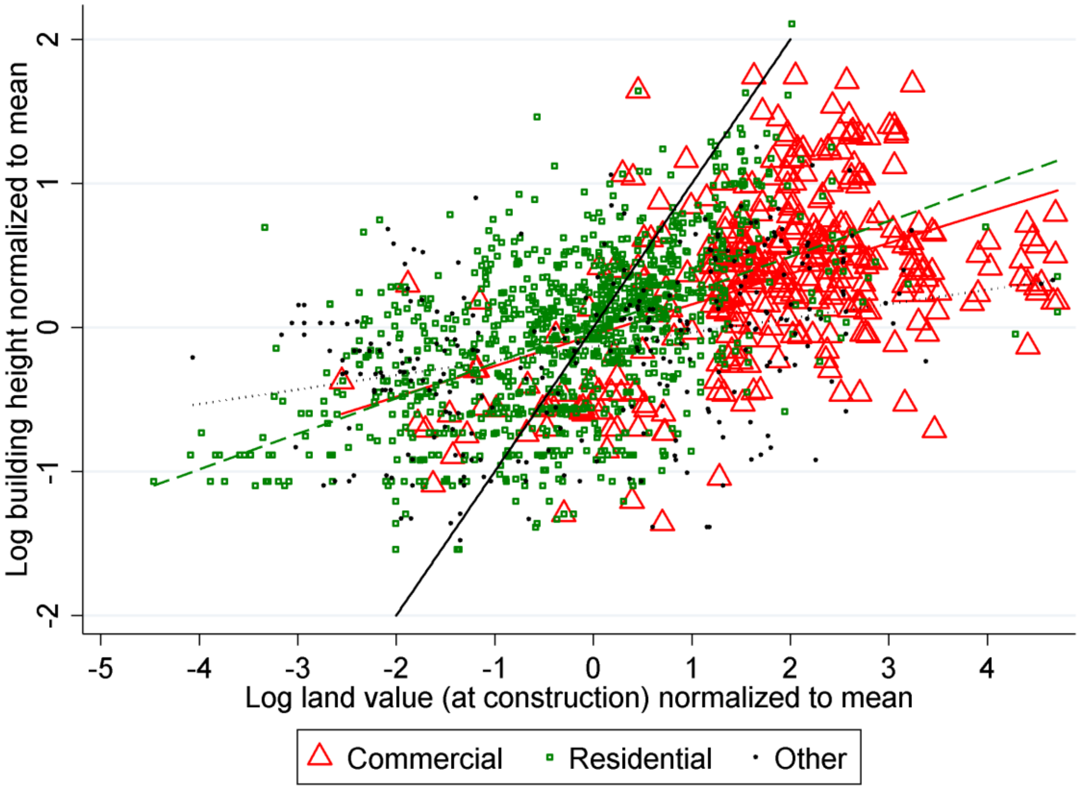
	(1) Log building height	(2) Log building height	(3) Log building height	(4) Log building height	(5) Log land price	(6) Log land price
Log distance to CBD	-0.396***	-0.494***	-0.541***	-0.451***	-1.030***	-0.624***
	(0.018)	(0.033)	(0.119)	(0.037)	(0.003)	(0.007)
Log distance to Lake Michigan	-0.140***	-0.189***	-0.261***	-0.228***	-0.477***	-0.195***
	(0.011)	(0.024)	(0.080)	(0.026)	(0.002)	(0.004)
Chicago River within 0.1 mile (dummy)	0.250***	0.290***	0.305***	0.241***	-0.011	0.110***
	(0.046)	(0.063)	(0.112)	(0.074)	(0.008)	(0.017)
Year - 2000	0.004***	0.019***	0.010	0.026***	0.040***	0.019***
	(0.000)	(0.004)	(0.012)	(0.004)	(0.000)	(0.000)
Log distance to CBD x (year - 2000)		-0.003***	-0.001	-0.003***		0.007***
		(0.001)	(0.002)	(0.001)		(0.000)
Log distance to Lake Michigan x (year - 2000)		-0.002***	-0.000	-0.002***		0.005***
		(0.000)	(0.001)	(0.001)		(0.000)
Chicago River x (year - 2000)		0.002*	0.004**	0.002		0.002***
		(0.001)	(0.002)	(0.003)		(0.000)
Constant	5.681***	6.167***	7.181***	6.422***	4.626***	3.357***
	(0.095)	(0.192)	(0.646)	(0.211)	(0.008)	(0.015)
Unit of observation	Buildings	Buildings	Buildings	Buildings	Grid cells	Grid cells
Land use	All	All	Commercial	Residential	All	All
Observations	1,737	1,737	327	1,109	625,316	625,316
R^2	0.325	0.346	0.505	0.363	0.788	0.798

Notes: Data used in columns (1-4) is a cross-section of building constructions. Data used in columns (5) and (6) is a panel where grid cells define the spatial dimension and cohorts (see Table 2) are the time dimension. Grid cells are defined as 330 x 330 feet tracts that closely follow the Chicago grid street structure. Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

3 . 3 The elasticity of height with respect to land price

A central prediction of supply side urban models is that as land prices increase, developers should increase the density of land use, i.e. build taller. Figure 7 plots building heights against the land prices at the beginning of the decade when a building was completed. To account for land price inflation and changes in construction technology, log land prices and log heights are normalized to have means of zero within construction cohorts (decades). Figure 7 suggests a positive elasticity of height with respect to land price across all construction cohorts. As suggested by Table 3, the elasticity's value is less than one, which is consistent with the expected increasing marginal cost of building taller. Figure 7 is also reflective of the typical urban land use pattern, with tall commercial building occupying the most central and expensive spots in the city.

Fig. 7. Elasticity of height with respect to land price I – pooled correlations



Notes: Log heights and log land values are normalized to zero means within decades. The red solid (green dashed) [black dotted] line is the linear fit for commercial (residential) [other] buildings. The black solid line is the 45 degree line.

Table 5 presents parametric estimates of the elasticity of height with respect to land price according to specification (3). All models feature cohort specific intercepts so that the elasticity is identified by variation within cohorts. We note that solid bedrock could affect the elasticity of height with respect to land price since it reduces the cost of building taller (Barr et al., 2010). However, in the case of Chicago, it is plausible to abstract from bedrock since the whole city is built on sandy soil. Indeed, it is the lack of bedrock near to the surface in Chicago that is often reported to have spurred architectural innovations such as the steel frame (Bentley and Masengarb, 2015; United States Department of Agriculture, 2012).

Our estimates suggest an average elasticity of height with respect to land price of 24.6% (column 1). One concern with this estimate is that the assessors may have been influenced by the announcement of tall buildings and assigned high land values not because of a fundamental locational advantage but because they knew a tall building was under construction. To minimize this risk our land prices refer to the beginning of each cohort period (usually decades). To further address the concern, we use the land price from the previous decade as an instrument for land price in column (2). The point estimate is slightly larger than in the OLS estimation, which is not consistent with a reverse-causality problem.

Given ongoing innovations in construction technology, we expect the construction cost function to become less convex over time, which would be reflected in an increasing elasticity of height with respect to land price. Thus, in column (3) we allow for an interaction with a linear year trend, set to zero for 2000. The estimates imply an elasticity of 30.5% in 2000 and a doubling over the course of the century (the implied elasticity in 1900 is 30.5% - 100 x 1.6% = 14.4%).

In column (4), we allow the elasticity and its time trend to differ across commercial, residential, and other buildings. The elasticity is largest and increases fastest over time for commercial buildings, and is particularly small for non-commercial non-residential buildings. In 2000, the estimated elasticity for commercial buildings was 47.9%, as opposed to 17.9% in 1900. Likewise, the estimated elasticity for residential buildings was 32% in 2000, compared with 12% in 1900. For the remaining buildings the elasticity is around 20% in 2000 and, again, about half that size in 1900. In column (5), we add a number of controls for non-commercial and non-residential land uses. The most impressive finding is that churches tend to be almost 2.6 (exp(0.951)=2.58) times as tall as would be predicted by the underlying land price for the category of non-commercial and non-residential buildings. In column (6), we use the lagged land price and the interactions with land use and time trend as instruments for the current land price and the respective interactions. The coefficients of interest increase moderately as in column (2). Since this pattern is not in line with a potential reverse-causality problem, we prefer the OLS estimates in column (5).

Tab. 5. Elasticity of density with respect to land price: Parametric estimates

	(1) Log building height	(2) Log building height	(3) Log building height	(4) Log building height	(5) Log building height	(6) Log building height
Log land price	0.246***	0.270***	0.305***			
	(0.032)	(0.033)	(0.026)			
Log land price x (Year - 2000)			0.002***			
			(0.000)			
Log land price x commercial				0.479***	0.478***	0.498***
				(0.038)	(0.039)	(0.046)
Log land price x residential				0.320***	0.311***	0.400***
				(0.024)	(0.029)	(0.048)
Log land price x (1 - commercial - residential)				0.206***	0.205***	0.185***
				(0.037)	(0.037)	(0.060)
Log land price x commercial x (year - 2000)				0.003***	0.003***	0.003***
				(0.000)	(0.000)	(0.000)
Log land price x residential x (year - 2000)				0.002***	0.002*	0.002**
				(0.001)	(0.001)	(0.001)
Log land price x (1 - commercial - residential) x (year - 2000)				0.001	0.001*	0.001
				(0.001)	(0.001)	(0.001)
Retail (dummy)					-0.133	-0.148
					(0.116)	(0.095)
Hotel (dummy)					0.416***	0.401***
					(0.072)	(0.073)
Industrial or storage (dummy)					0.172	0.171
					(0.180)	(0.184)
Public, administrative or education (dummy)					0.239**	0.224**
					(0.081)	(0.078)
Museum, movie theatre or other cultural use (dummy)					-0.238	-0.235
					(0.303)	(0.305)
Sports facility (dummy)					0.323*	0.330**
					(0.167)	(0.145)
Church (dummy)					0.951***	1.003***
					(0.269)	(0.274)
Constant	3.390***	3.440***	3.346***	3.428***	3.160***	3.263***
	(0.083)	(0.017)	(0.055)	(0.051)	(0.079)	(0.146)
Cohort effects	YES	YES	YES	YES	YES	YES
Cohort x commercial effects	-	-	-	YES	YES	YES
Cohort x residential effects		-	-	YES	YES	YES
IV	-	YES	-	-	-	YES
r2	0.419	0.416	0.437	0.487	0.514	0.501
N	1,737	1,737	1,737	1,737	1,737	1,737

Notes: Standard errors (in parentheses) clustered on construction date cohorts (decades). Land use controls (none are significant) include dummies for the following categories: Retail, hotel, warehouse, public use, cultural facility, sports facility. IV is the land price of the previous cohort (the same cohort for the 1870 cohort) in model (2) and the same interacted with land use indicators and time trends in (6). * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

The models reported in Table 5 are relatively restrictive in that they assume a construction technology that changes at a constant rate over time and an elasticity of height with respect to land price that is otherwise constant within the three land use categories. It is possible however that the time trend follows a non-linear pattern and that the elasticity varies across locations, e.g. because it is more expensive to build a tall structure within a dense CBD. To allow for more flexible variation in the elasticity we estimate LWR versions of models (5) and (6) in Table 5. For each construction $\tilde{\iota}$ we run one LWR in which we weight observations using a Gaussian kernel:

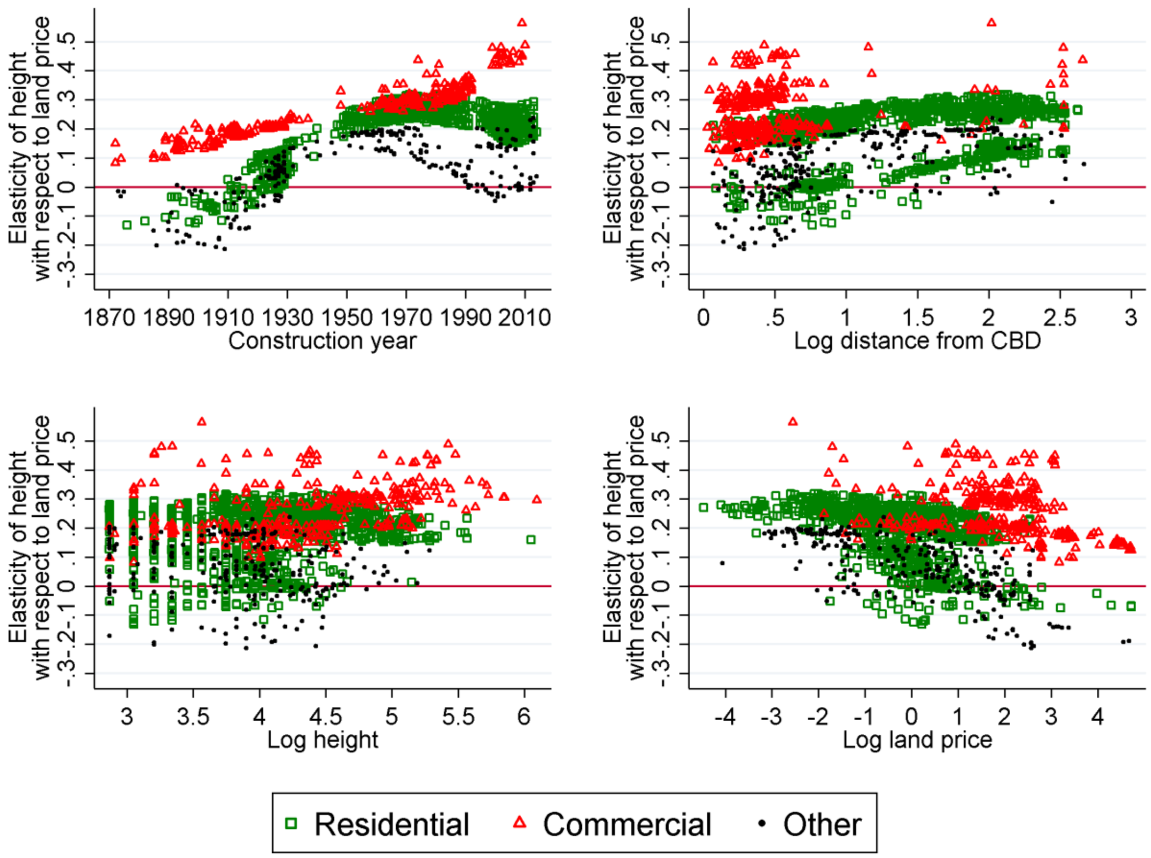
$$w_{i\tilde{\imath}} = \prod_n \frac{1}{\lambda_n \sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{d_{i\tilde{\imath}n}}{\lambda_n}\right)^2\right) \quad (4)$$

, where n indexes a vector of variables describing the proximity between two variables i and $\tilde{\imath}$, including the geographic distance as well as difference between the years of construction, and λ_n is the bandwidth.[10]

In Figure 8 we plot the resulting local elasticity estimates against a number of characteristics. The results are generally consistent with the parametric estimates. The elasticity increases over time and is higher for commercial buildings than other buildings. It turns out that the linear time trend in the elasticity is a reasonable approximation for commercial buildings, but the trend for other buildings is non-linear. The elasticity of height with respect to land price is around or even below zero for residential constructions before 1920, then rapidly increases until the 1950s and then stays roughly at the same level. For other buildings, the trend follows an inverse u-shape, which is in line with the intuition that the price of land is not the primary determinant of height for structures such as churches, stadia, or water towers. We find no similarly clear correlation between the local estimates of the elasticity and the height of a building, the distance from the CBD, or the land price. The LWR-IV estimates look very similar and are reported in the appendix (Section 4).

[10] We use the Silverman (1986) rule for the selection of the bandwidth $\lambda_n = 1.06 \times \sigma_n N^{-\frac{1}{5}}$.

Fig. 8. Elasticity of density with respect to land price: LWR estimates



Notes: Each icon represents a LWR estimate of the elasticity of height with respect to land price for a given building $\tilde{\imath}$ built in year $\tilde{t}$. The regression model in the same as in Table 5, column (5). Observations are weighted using Gaussian Kernel weights based on the geographic distance from $\tilde{\imath}$ and the time distance from $\tilde{t}$. The bandwidth is selected according to the Silverman (1986) rule. A LWR-IV version based on the model reported in Table 5, column (6) is in the appendix.

4 Spatial interactions in excess height

4.1 Testing for height competition

Helsley and Strange (2008) argue that in addition to the fundamental determinants of building height discussed above, an intrinsic value of being the tallest creates an additional incentive to build tall. They argue that height competition takes place at various geographic levels, from world-wide to national to within-city scale, on which we focus. The empirical implications are similar. A central prediction of their game-theoretic analysis of skyscraper development is dissipative competition. Developers deliberately overbuild beyond what appears to be the fundamentally justified height to accumulate the returns for being the tallest and to pre-empt rivals. Obtaining the best possible view seems like a natural motivation for being the tallest within a neighborhood, in addition to the reputational effect, which is perhaps more important at higher geographic levels. In any case, if an existing excessively tall building implies that the cost of winning the prize of being the tallest at a given location is disproportionate, an ambitious developer will go elsewhere. The implication is that excessively tall buildings will be spatially dispersed. A competing hypothesis is that developers imitate each other's behavior and overbuild where other developers have previously overbuilt (Barr, 2012). The implication would be that excessively tall buildings should be spatially concentrated. Similarly, such buildings would be spatially concentrated if some unobserved locational fundamentals made certain locations particularly suitable for tall buildings.

To analyze the spatial pattern of overbuilding we first identify the buildings with the largest positive deviation in the log of actual height from the log of fundamental height predicted by the LWR underlying Figure 8. We refer to these buildings, which are excessively tall given the underlying land price, as over-buildings. We then test for patterns of localization of over-buildings using a spatial point pattern approach that draws from Duranton and Overman (2005).

First, we compute the bilateral straight-line distances between each pair of buildings in our data set. Second, we compute the Gaussian kernel smoothed distribution across bilateral distances between over-buildings. Third, we use a Monte Carlo approach to generate counterfactual distributions of bilateral distances. We randomly draw 1000 samples of bilateral distances of the same size as the sample of bilateral distances between over-buildings and generate the kernel smoothed distribution for each sample. Fourth, we pick the 5th and the 95th percentile in the distribution of kernel densities at any bilateral distance to represent a confidence interval of a counterfactual distance distribution. If at a given distance the kernel density for over-buildings exceeds the upper confidence band, this result will be interpreted as localization. Symmetrically, if the kernel density for over-buildings is below the lower confidence band, this will be interpreted as dispersion.

Unlike in Duranton and Overman (2005) there is a time dimension to our analysis. We therefore conduct the analysis in several alterations focusing on distances between buildings constructed within a certain time distance. To test for localization in over-buildings developed at the same time we keep bilateral distances between buildings within the same construction cohort (usually defined as decades). To test for dissipative competition we keep for each building in a construction cohort the distances to buildings that belong to the previous cohort. Similarly, we allow for two lags. Dissipative competition would imply that the density of the distance distribution between over-buildings and previously developed over-buildings should be dispersed at short distances.

In taking this strategy to the data we need to make a number of choices. First, we need to decide on a bandwidth in the kernel density estimation. We follow Duranton and Overman (2005) and set the bandwidth according to the Silverman (1986) rule. Second, we need to decide on the range of distances over which we want to test for localization. In the present setting, we are concerned with dissipative height competition for being the tallest in local markets within a city. In account of the neighborhood scale of this competition, we focus on pairs of buildings separated by no more than two miles as we presume there is no interaction beyond this threshold. Third, and specific to our case, we need to decide on a threshold for excess height that defines what constitutes an over-building. Our baseline approach is to select the top decile in the distribution of the log-differences in actual and fundamental height as over-buildings. We present robustness checks defining over-buildings based on the top quartile in the appendix (section 4). We replicate all steps of the analysis for all land uses as well as commercial, residential and other-use buildings separately. We also distinguish between constructions near and further away from scenic amenities.

4.2 Characteristics of over-buildings

Table 6 presents the top decile in terms of relative excess height within the sample of commercial buildings. As expected, the table features some of the tallest structures such as the Willis Tower, which was the tallest structure in the world for 14 years, or the iconic John Hancock Center.[11]

In Figure 9, we compare the distribution of construction years and building heights within the sample of commercial over-buildings and residential over-buildings to counterfactual distributions. The counterfactual distributions are based on random draws from all commercial buildings or residential buildings using the Monte Carlo approach described above. The distribution of construction years of commercial over-buildings is representative for all commercial buildings as the distribution is well within the confidence band. In contrast, residential over-buildings are over-represented in more recent construction cohorts. As expected, the height distributions of over-buildings are skewed significantly to the right compared to the counterfactual.

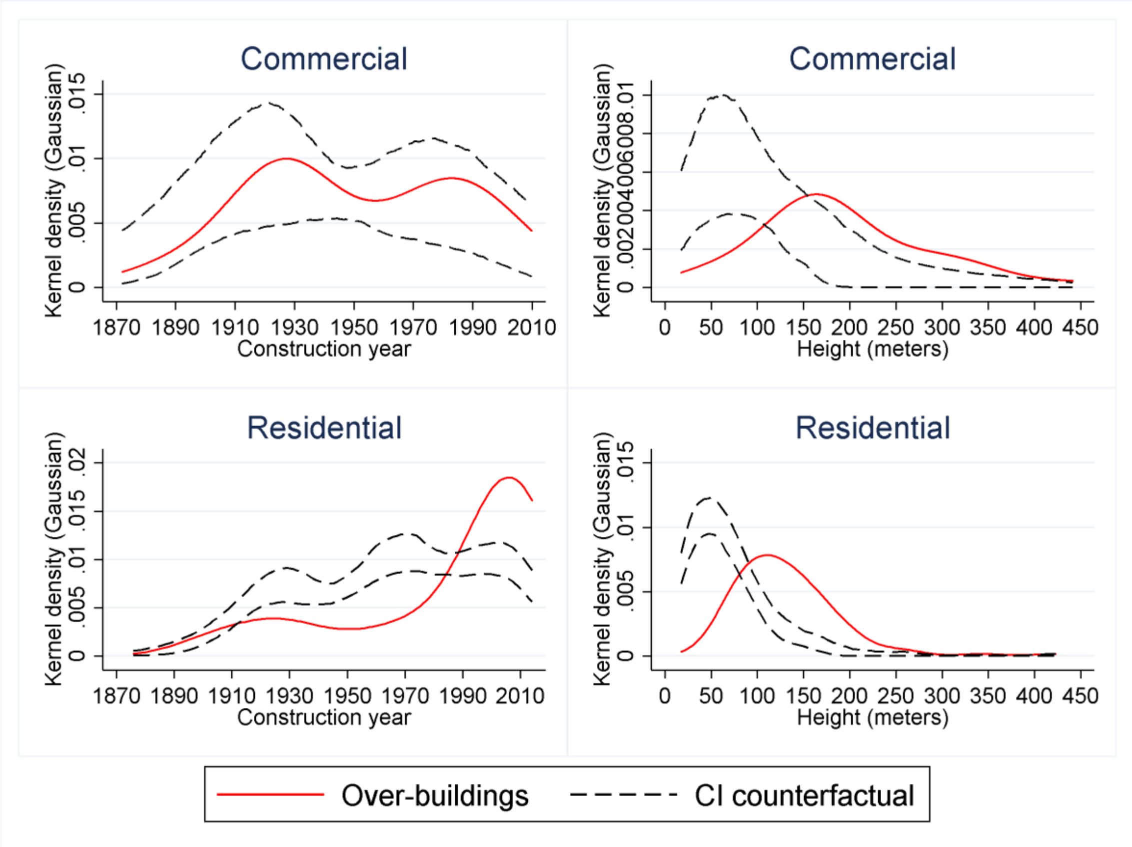
[11] The 423 meter Trump Tower, which is currently the second-tallest building in Chicago, is not included as it hosts a hotel and apartments rather than offices alone.

Tab. 6. Commercial over-buildings

Rank	Name	Excess height	Actual Height	Fund. height	Relative excess height (log)	Year of construction	Distance from CBD
1	Willis Tower	344	442	98	1.50	1974	0.51
2	John Hancock Center	278	344	66	1.65	1969	1.01
3	Aon Center	242	346	104	1.20	1973	0.40
4	AT&T Corporate Center	229	307	78	1.37	1989	0.43
5	Two Prudential Plaza	207	303	96	1.15	1990	0.35
6	One Prudential Plaza	176	278	102	1.00	1955	0.34
7	311 South Wacker	175	293	117	0.91	1990	0.58
8	Chase Tower	156	259	103	0.92	1969	0.25
9	Chicago Board of Trade	128	184	56	1.19	1930	0.53
10	Chicago Temple Building	123	173	50	1.24	1924	0.13
11	AMA Plaza	120	212	92	0.84	1973	0.27
12	NBC Tower	120	191	71	0.99	1989	0.56
13	Blue Cross-Blue Shield Tower	120	226	107	0.75	2010	0.53
15	Pittsfield Building	115	168	53	1.15	1927	0.25
16	Civic Opera Building	115	169	54	1.14	1929	0.46
17	35 East Wacker Drive	112	159	47	1.22	1927	0.20
18	Citigroup Center	108	179	71	0.92	1987	0.57
19	181 West Madison	107	207	100	0.73	1990	0.34
20	Tribune Tower	106	141	35	1.39	1925	0.51
21	Leo Burnett Building	105	194	89	0.78	1989	0.13
23	American Furniture Mart	103	144	41	1.25	1926	0.95
24	One Financial Place	100	157	57	1.02	1985	0.65
25	Metropolitan Tower	94	145	51	1.04	1924	0.54
26	LaSalle-Wacker Building	89	166	76	0.77	1930	0.16
27	Wrigley Building	89	134	45	1.09	1922	0.42
31	One North LaSalle	86	162	76	0.76	1930	0.21
33	Roanoke Building	85	138	53	0.95	1925	0.21

Notes: We rank the buildings by the excess height defined as the absolute deviation of the actual height from the fundamental height. However, the buildings were selected based on the relative excess height defined as the log-difference between actual height and fundamental height. Log fundamental height is determined using LWR of the log of actual height and the log of land price, allowing for various interactions with land use and a time trend. LWR are weighted by geographic and time distance. The local estimates of the elasticity of height with respect to land price of the underlying LWR are presented in Figure 7. Over-buildings reported in this table are the top decile in the distribution of commercial buildings.

Fig. 9. Over-buildings by height and construction year



Notes: Over-buildings are the top decile in the distribution of relative excess heights across commercial or residential buildings. Kernel density estimator uses a Gaussian kernel and a bandwidth set according to the Silverman (1986) rule. Confidence bands are generated based on 1000 random draws of samples of commercial or residential buildings of the same size as the respective sample of over-buildings. Upper and lower bounds represent the 95% and the 5% percentile in the distribution of counterfactual densities at a given year or height.

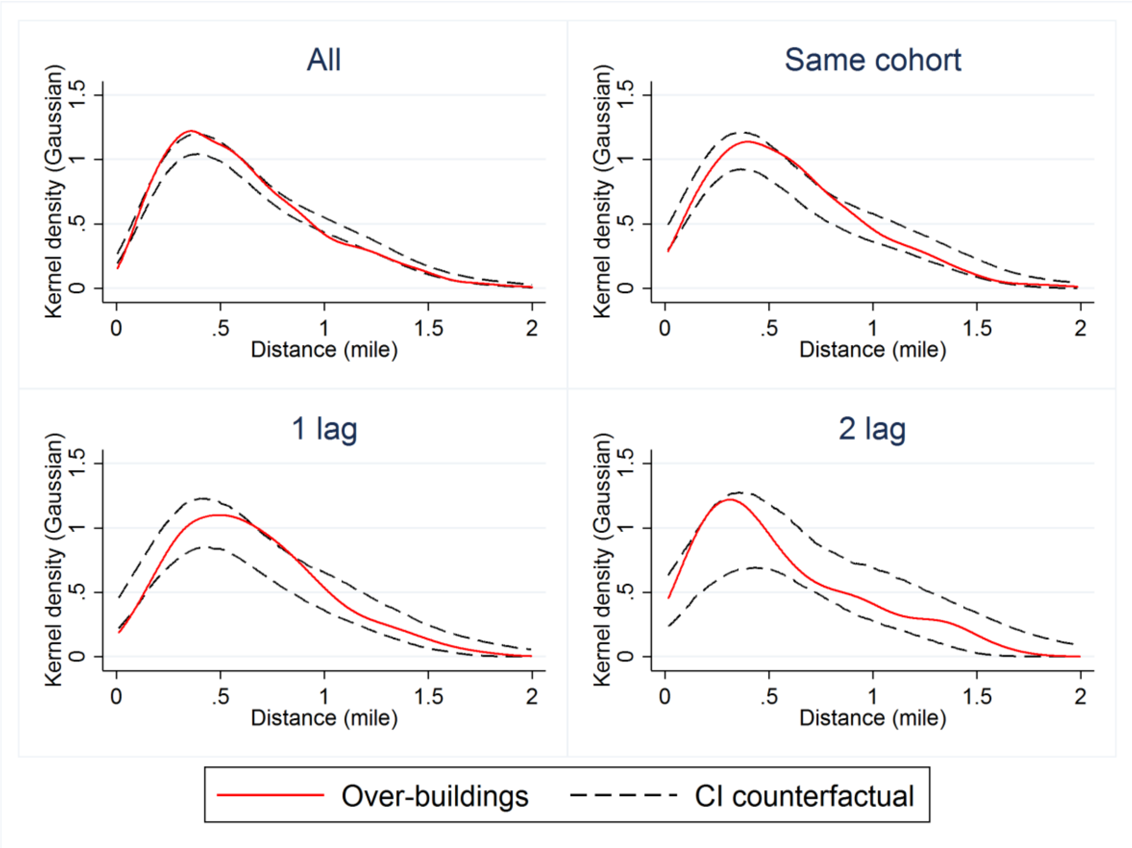
4 . 3 Localization of over-buildings

In Figure 10 we present the distribution of bilateral distances between commercial over-buildings. The density distributions are generally close to or within the confidence band, regardless of whether we consider the distribution across all commercial properties, those belonging to the same cohort, or those with a lag between construction dates. There is weak evidence of dissipative competition as the over-buildings tend to be dispersed at very short distances. The effect is strongest when comparing over-buildings constructed in a given decade to other over-buildings developed in the preceding decade, which is perhaps expected. Still, the significance level is borderline at best.

In Figure 11, we present identical tests using residential instead of commercial buildings. The tendency of dispersion at short distances is somewhat clearer than is the case for the commercial buildings. Again, the effect tends to be strongest when considering the location of over-buildings relative to those constructed during the previous decade. In this sample, over-buildings are significantly more dispersed than other tall buildings up to about a half mile.

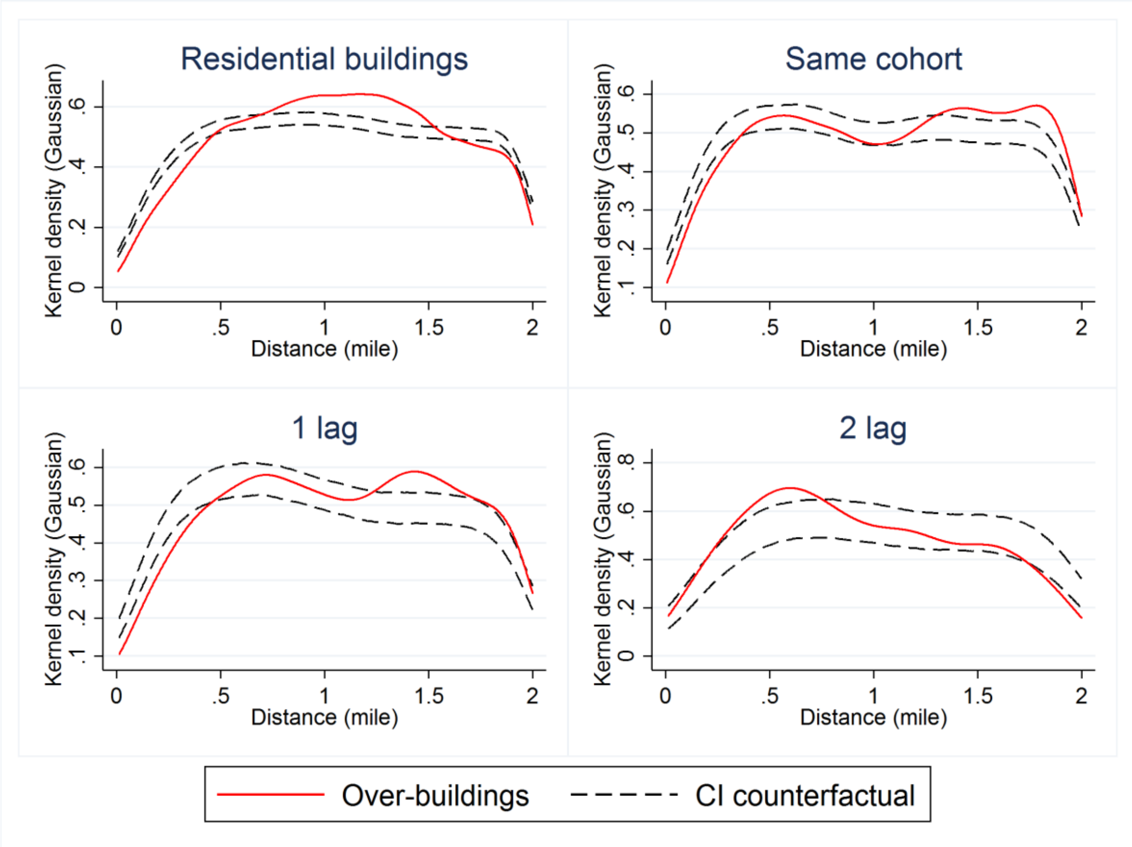
We find no significant dispersion at short distances for over-buildings from the "other" class (both non-commercial and non-residential), which is perhaps the expected result as for many of these buildings (e.g. stadia, water towers, etc.) the height is determined by technical requirements, making height competition less likely. The relative distance distributions for all buildings, as expected, resemble a mix of the three land use categories, with weak signs of dispersion of over-building at short distances. The respective figures are in the web appendix.

Fig. 10. Bilateral distances between commercial over-buildings



Notes: Over-buildings are the top decile in the distribution of the relative excess height across commercial buildings. Kernel density estimator uses a Gaussian kernel and a bandwidth set according to the Silverman (1986) rule. Confidence bands are generated based on 1000 random draws of samples of commercial or residential buildings of the same size as the respective sample of over-buildings. Upper and lower bounds represent the 95% and the 5% percentile in the distribution of counterfactual densities at a given year or height.

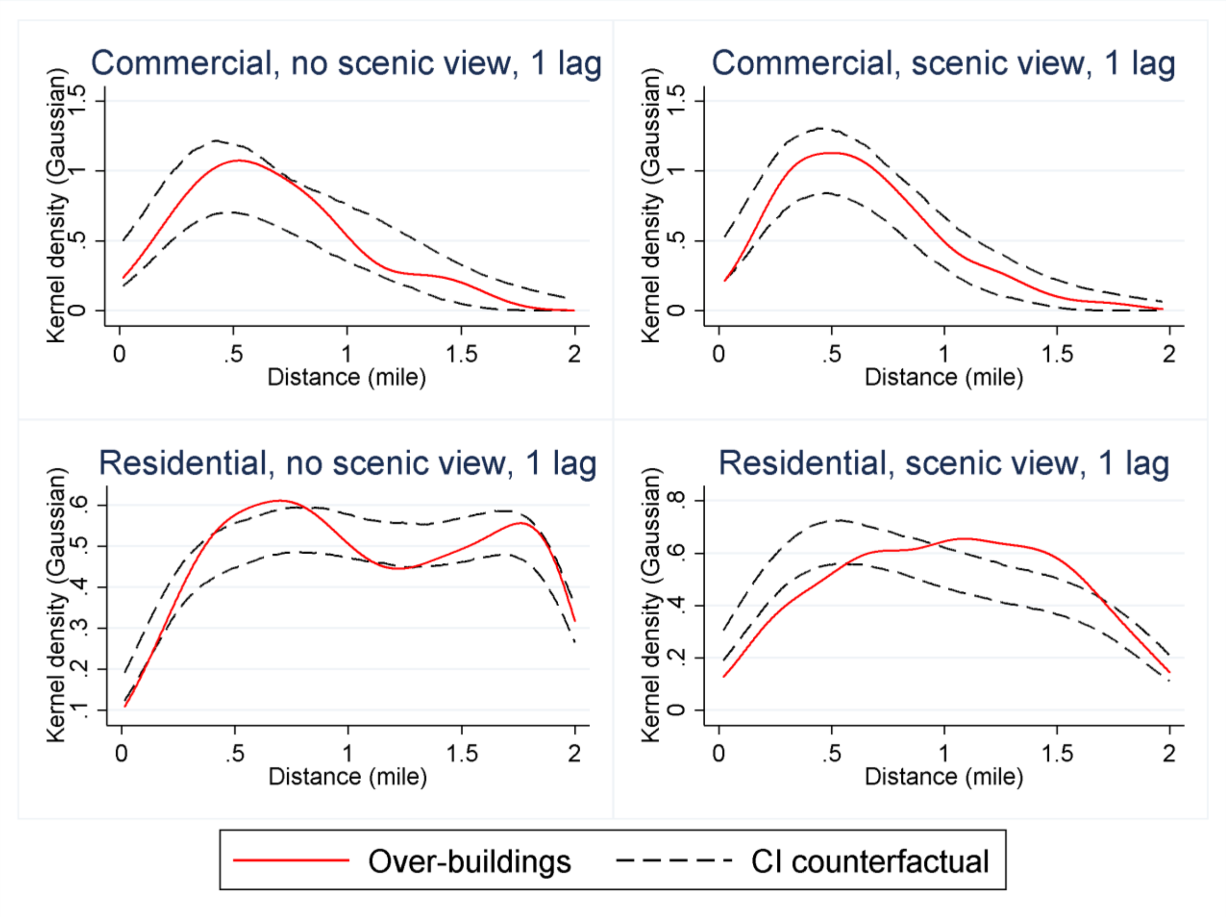
Fig. 11. Bilateral distances between residential over-buildings



Notes: Over-buildings are the top decile in the distribution of the relative excess height across residential buildings. Kernel density estimator uses a Gaussian kernel and a bandwidth set according to the Silverman (1986) rule. Confidence bands are generated based on 1000 random draws of samples of commercial or residential buildings of the same size as the respective sample of over-buildings. Upper and lower bounds represent the 95% and the 5% percentile in the distribution of counterfactual densities at a given year or height.

In our last series of tests, we seek to uncover what the exact nature of the prize for being the tallest in a neighborhood might be. As discussed above, obtaining the best view appears to be a natural candidate. Hypothesising that spatial competition should be more intense if the prize that can be won is bigger, we replicate our analysis for subsamples of constructions that occurred within 0.1 miles (presumably with a scenic view) or beyond 0.2 miles (presumably with no scenic view) of Lake Michigan or Chicago River. We focus on distances between constructions separated by one temporal lag where we found the strongest evidence for dissipative competition so far. In line with our hypothesis, Figure 12 provides stronger evidence for dispersion in the location of over-buildings if they are located near to Chicago's main scenic amenities. As with the full samples, dispersion at short distances is relatively stronger for residential over-buildings, suggesting that the premium for a good view is larger in the residential housing market than in the commercial office market.

Fig. 12. Bilateral distances between commercial or residential over-buildings with or without a scenic view



Notes: Over-buildings are the top decile in the distribution of the relative excess height across residential buildings or commercial buildings. With (without) scenic view includes constructions within 0.1 (beyond 0.2) miles from Chicago River or Lake Michigan. Kernel density estimator uses a Gaussian kernel and a bandwidth set according to the Silverman (1986) rule. Confidence bands are generated based on 1000 random draws of samples of commercial or residential buildings of the same size as the respective sample of over-buildings. Upper and lower bounds represent the 95% and the 5% percentile in the distribution of counterfactual densities at a given year or height.

Finally, we note that all interpretations presented here are consistent with the results from the analysis of over-buildings defined as the top quartile in the distribution of excess height (see appendix section 4).

5 Conclusion

The standard urban economics framework predicts that productivity advantages of dense central business districts must be offset by correspondingly high land prices, which creates incentives for using land more intensely and building taller. Yet, it is often argued that the economics of skyscrapers are more complex and that there is an intrinsic value of being the tallest, which leads to developments in excess of what appears to be a fundamentally justified height.

Our results yield a number of novel insights into the determinants of building heights and the nature of skylines. Our results are consistent with the standard supply side urban equilibrium models, but there is also some evidence for spatial competition for being the tallest within a city neighborhood. We find that the price of land is a strong predictor of building height. There is a positive and statistically significant elasticity of density with respect to building height throughout our study period. In 2000, the elasticity of density with respect to land price was 45% for commercial buildings and 30% for residential buildings. Over 100 years, the elasticity approx. doubled, which is in line with significant improvements in construction technology.

When analyzing the locational pattern of excessively tall buildings relative to other tall structures we find significant dispersion at short distances, in particular for residential buildings. Excessively tall buildings are less likely to be constructed at the same location and in the same or subsequent decade than other buildings. This in line with dissipative competition to pre-empt rivals as predicted by Helsley and Strange (2008). Our results further suggest that the prize for being the tallest within a neighborhood at least partially comes in the form of a good view, in particular in the residential market.

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Appendix to
The vertical city: The price of land and the height of buildings in Chicago 1870-2010

Version: May 2015

1 Introduction

This technical appendix complements the main paper by providing complementary evidence and additional details on the data used. The appendix is not designed to stand alone or replace the main paper. Section 2 provides additional detail on the data. Section 3 presents estimates of CBD coordinates as well as LWR-IV estimates of the elasticity of height with respect to land price not reported in the main paper for brevity. Section 4 adds to the analysis of spatial interactions among developers.

2 Data

2.1 Tallest buildings

Table A1 and Figure A1 present the tallest buildings of their times in Chicago since the 1850s. Typical for the period, the tallest buildings were churches up until the late 19th century. The first commercial building to carry the title of the tallest building in Chicago was the board of trade building constructed in 1885 and demolished in 1929. Most of the buildings, which were the tallest at their time held their leading position for at least ten years. The exceptions are the John Hancock Center and its successor the Aon Center (formerly Amoco Building), which both were replaced as tallest buildings within a small number of years. The latter was replaced by the Willis Tower (formerly Sears Tower) in 1974, which is still the tallest building in the city. On average the

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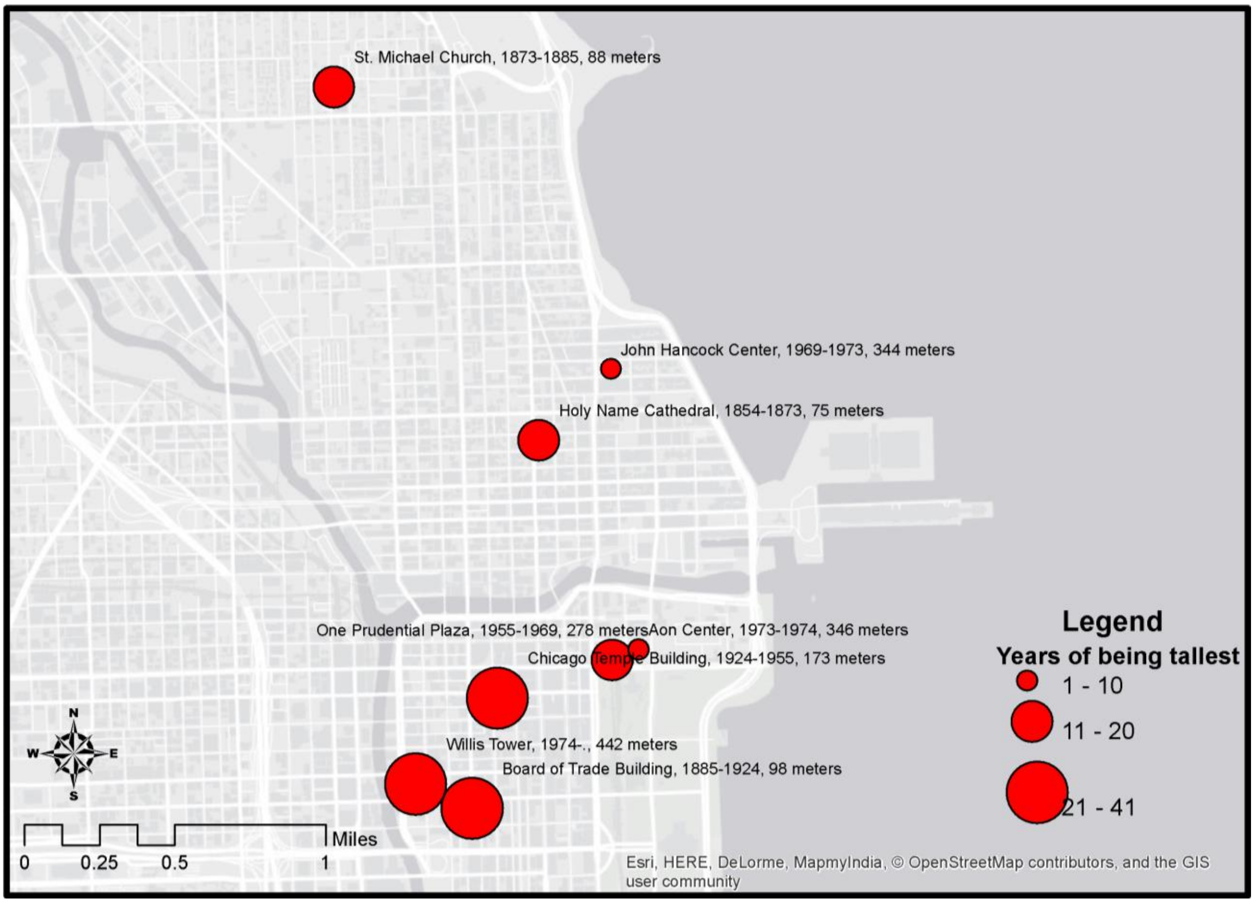
tallest buildings remained in the leading position for slightly more than 20 years, which is perhaps suggestive of overbuilding and dissipative height competition.

Tab A1. Ever tallest buildings in Chicago since the 1850s

No.	Name	Construction year	Years being the tallest	Height (m)
1	Holy Name Cathedral	1854	19	75
2	St. Michael Church	1873	12	88
3	Board of Trade Building	1885	39	98
4	Chicago Temple Building	1924	31	173
5	One Prudential Plaza	1955	14	278
6	John Hancock Center	1969	4	344
7	Aon Center	1973	1	346
8	Willis Tower	1974	41	442

Notes: Source: © Emporis

Fig. A1. Ever tallest buildings in Chicago since the 1850s



Notes: Own illustration based on © Emporis.com and base maps from © OpenStreetMap, accessed via the ESRI ArcGIS Online service.

2 . 2 Olcott's Land Values – Blue Book of Chicago

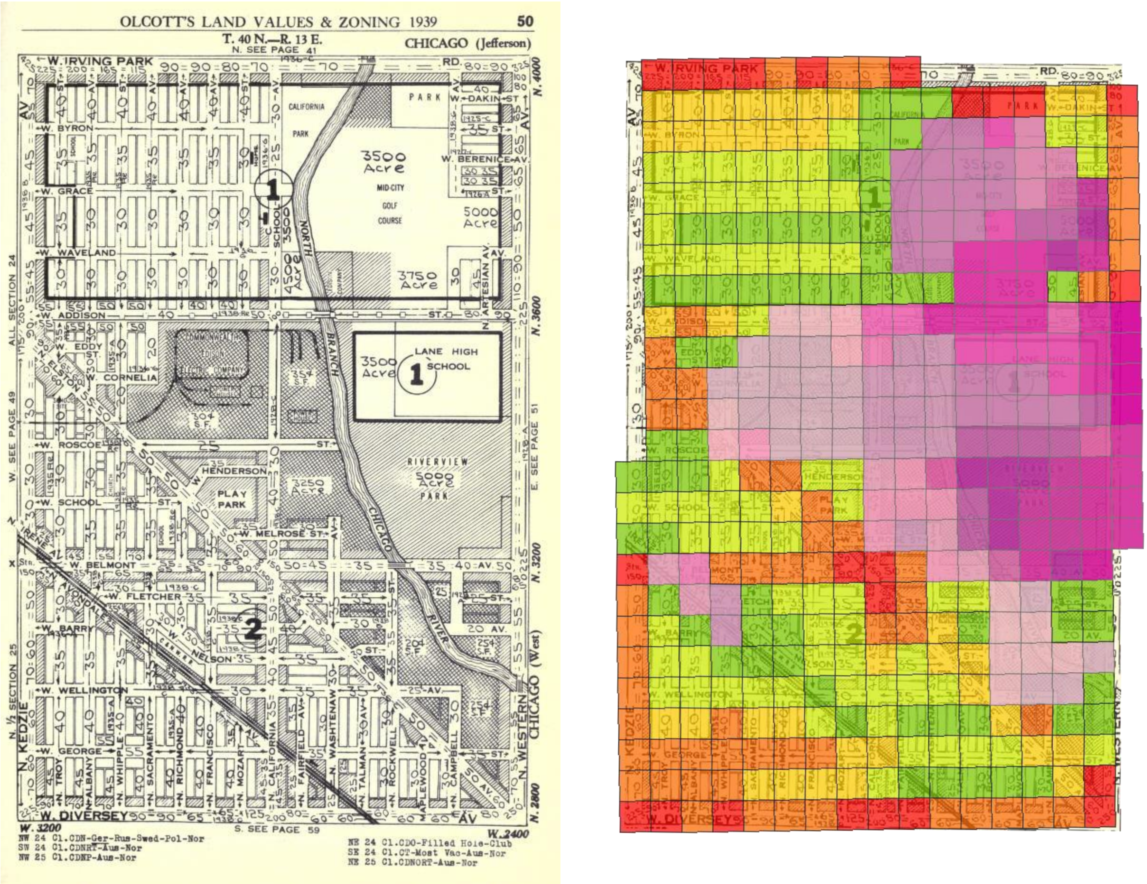
With nine cross-sections spreading from 1913 to 1990, Olcott's Blue Books provide the core of the land price data used in this paper. The section provides a brief summary of the nature and the collection of Olcott's land value data. A detailed discussion is in Ahlfeldt et al. (2012).

The series *Olcott's Land Values – Blue Book of Chicago* reports land values for Chicago, Illinois, and was originally established in 1900. In the beginning George C. Olcott only published individual subsections of Chicago on a monthly base. He later switched to the annual issuing of books covering the entire city area plus the surrounding suburbs of Cook County. Land values were collected and published until the first half of the 1990s. Olcott's Blue Books were "designed by means of valuation maps to enable one to determine the approximate values of lots in each block of the city" (Olcott 1913). The reported land values are conservative, "impartial estimates" (Olcott 1913) based on sales, bids, and asking prices as well as on opinions of people working in real estates. The value collection involved a careful exploration of the territory, interviews with local dealers, and consolations of data on sales, leases, etc. They are supposed to reflect the current market value of pure land and to follow actual market transactions.

The data collection begins with scanning and georeferencing the various map pieces provided in each Olcott's edition. The actual data extraction process involves two steps. In the first step we create a shapefile which describes the spatial geometry of the land value data, typically polylines drawn along street stretches with identical land values. The next step involves the data entry. For each polyline the respective land value reported on the Olcott map is entered into an attribute table that underlies the electronic polyline map. In some cases, Olcott aggregates standard front foot values for presumably homogenous areas. For those areas only the minimum and the maximum values are reported. In these cases we draw polygons around these areas and assign the mean value that is representative for the area.

In the last step of the data extraction procedure, we aggregate land values to a spatial grid. The grid squares approach has various advantages: It is not density biased, it embodies the underlying grid structure of the city, and yet the areal units remain consistent over time and space. Each individual grid measures a size of 330 x 330 feet which is 1/256 of a square mile. As each map piece measures 1 x 1.5 miles it covers exactly 384 grid squares. Figure A2 illustrates Olcott's land values as presented in the Blue Book (left) along with the outcome of our digitization procedure.

Fig. A2. Olcott's: Raw data versus output

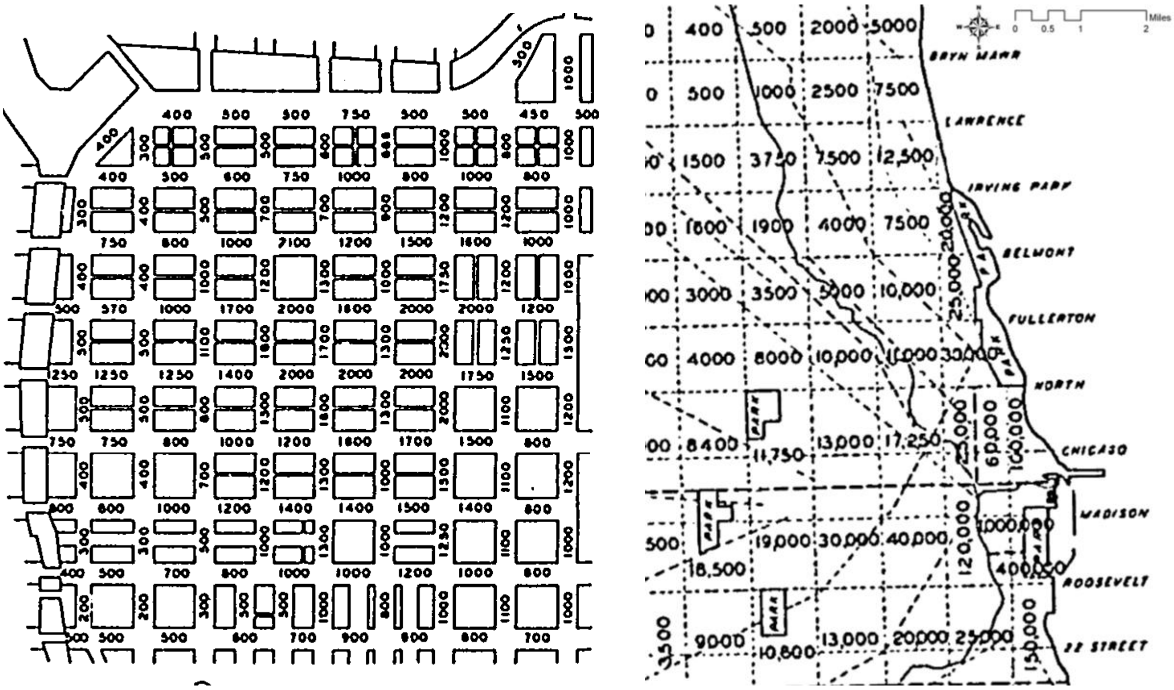


Notes: Standard street front foot values shaded from green to red. Industrial land values shaded from light to dark purple.

2 . 3 Hoyt's land values

As describe in the main paper we rely on Hoyt (1933) to approximate land values for 1873 and 1893. In general, Hoyt's maps look similar to Olcott's maps described above. The maps are as detailed as Olcott's maps for the CBD. Outside the downtown area, Hoyt's land values are more aggregated and typically refer to rectangular segments of about a square mile. Figure A3 exemplarily illustrates the 1873 raw data as reported in Hoyt (1933).

Fig. A3. Hoyt's land values: 1873

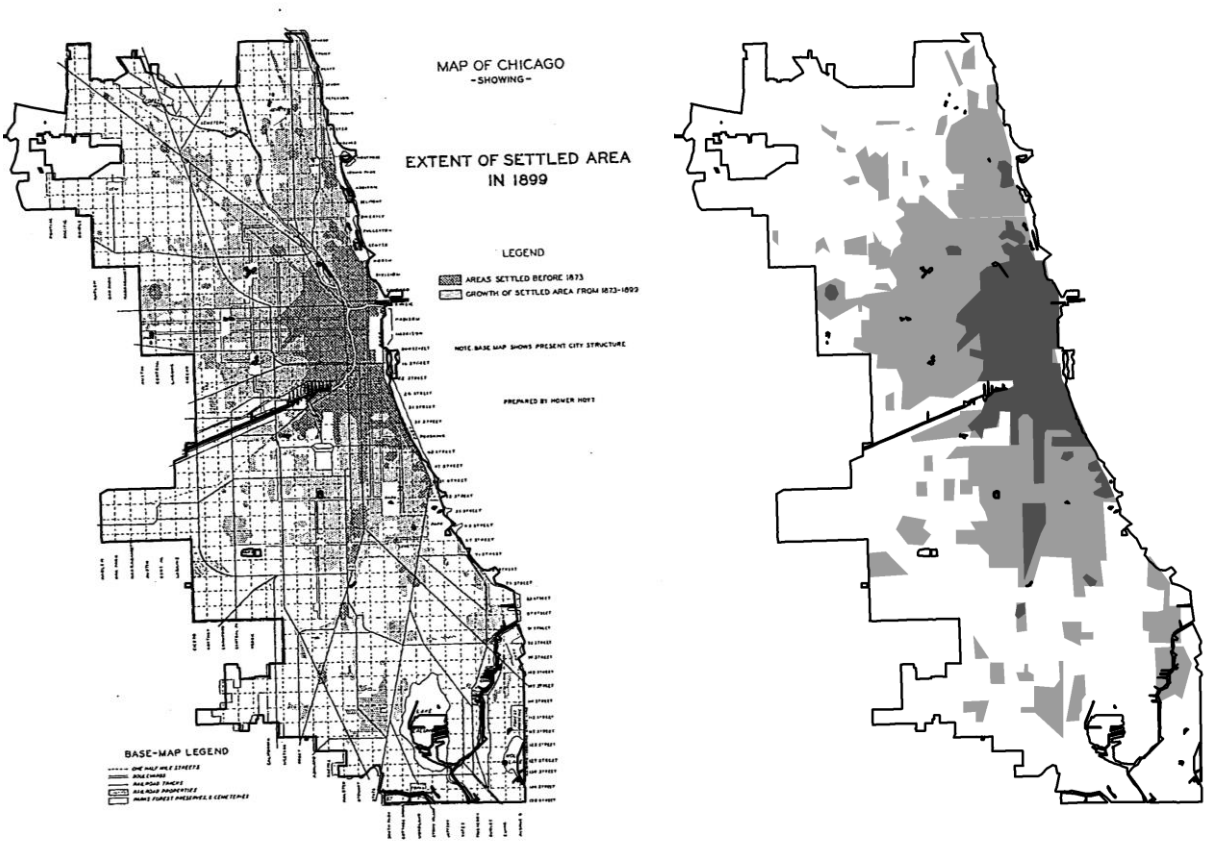


Notes: Left panel shows Hoyt's land values for the CBD section, roughly corresponding to the "Loop". Right panel shows a representative section of the remaining area.

To digitize these data we use exactly the same techniques as for the extraction of the Olcott data, which we describe in the previous sub-section. However, because of the more aggregated nature of the Hoyt data outside the CBD we require an additional step to approximate land values at a sufficiently fine geographic scale. As discussed in the main paper we use locally weighted regression techniques to process the raw data reported in Hoyt. In particular, we seek to incorporate the spatial detail provided by Olcott for the developed areas outside the CBD and to smooth out the discrete changes in land values across the boundaries of the rectangular land value zones outside the developed area.

To apply these techniques we require a definition of the areas that were developed in 1873 and 1893. Hoyt provides a map illustrating the boundaries of the settled area in 1973 and the growth in of settled area from 1873 to 1893. Our approach to digitizing this information is similar to our processing of the land value data. We begin by georeferencing a scan of the map. We then manually draw polygons around the shaded areas in GIS because the low resolution of the original print complicates the application of automated extraction processes based on colour recognition. Lastly, we merge the resulting polygons with the 330x330 ft. grid described in the previous subsection. If a geographic centroid of a grid cell falls within the boundaries of the extracted settled area in a given year, we code that grid cell as developed. Else, it is coded as undeveloped. Figure A4 illustrates the settled area as presented in Hoyt as well as the resulting output after processing the raw data in GIS.

Fig. A4. Settled area in 1873 and 1893



Notes: Left panel shows the settled area before 1873 and the grown between 1873 and 1893 as illustrated by Hoyt. Right panel shows the outcome after processing in GIS. Dark shaded polygons approximate the settled area in 1873. The light and dark shaded areas combined approximate the settled area in 1893. Chicago city boundaries are illustrated by the thick black lines.

3 The spatial structure of building height

3.1 CBD location

At various stages of the empirical analysis in the main paper we make use of a measure that captures proximity to the CBD. We identify this CBD as the nucleus of log-linear height and land price gradient in auxiliary NLS estimations, which we run separately for each construction cohort.

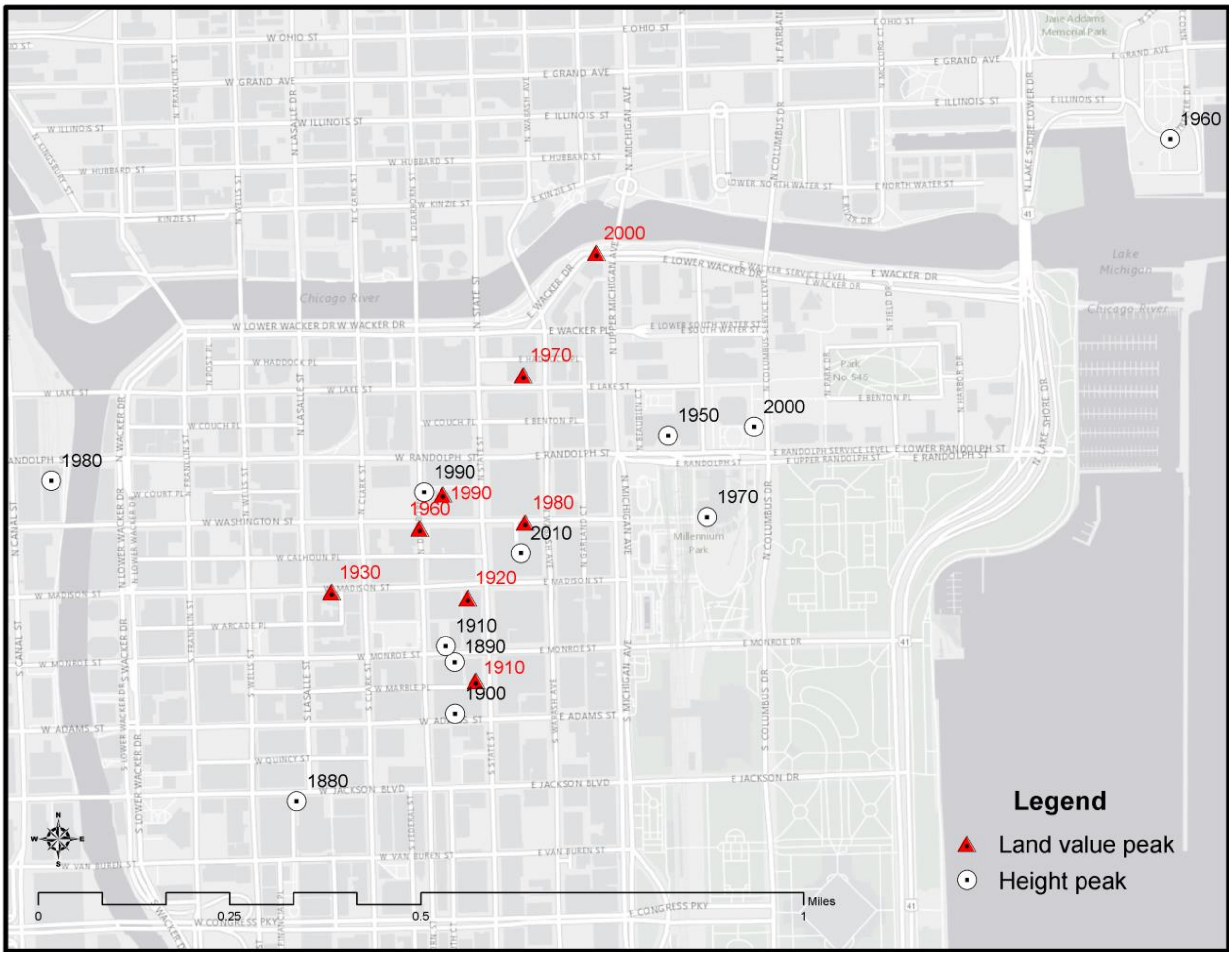
$$\log(C_{it}) = \gamma_{0t} + \gamma_{1t}((X_{it} - \gamma_t^X)^2 + (Y_{it} - \gamma_t^Y)^2)^{0.5} + \epsilon_{it},$$

where C_{it} is either the height of a building i constructed in a decade t or the price of the underlying plot of land, X_{it} and Y_{it} are cartesian coordinates of buildings (in projected miles), and γ_t^X and γ_t^Y are the coordinates of the CBD to be estimated along with the other parameters γ_{0t} and γ_{1t}.

Parametric estimates are presented in Tables A2 and A3. As expected there is a negative relationship between height and land price on the one hand and the distance from the nucleus of the gradients on the other in virtually all years ($\gamma_{1t} < 0$). The exception is the 1940s cohort, which is a period of sparse data and limited construction activity in the CBD (see also Figure 5 in the main paper).

We plot the locations identified by the estimated coordinates in Figure A5. In general, our estimates suggest that the center of gravity of the city has changed very little over time. Virtually all estimated CBD locations, based on height and land price data, are located within less than a square mile. The majority of estimated CBD locations are around the intersection of Washington Street and State Street, which we therefore choose as CBD in all years. Notably, the traditional center of Chicago, at the intersection of State and Madison Street, is only one block south of the site identified using this procedure.

Fig. A5. Show the parametric estimates



Notes: Base maps from © OpenStreetMap, accessed via the ESRI ArcGIS Online service.

Tab A2. NLS estimates of CBD coordinates – building height

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
	Log building height												
Cohort	1870s & 1880s	1890s & 1900s	1910s	1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000s	2010s
γ_0 (intercept)	-0.378*	0.859***	1.985***	2.793***	2.393***	-16.545	66.24***	1.526***	3.063***	3.443***	4.271***	5.453***	4.623***
	(0.209)	(0.095)	(0.069)	(0.044)	(0.112)	(101.51)	(20.533)	(0.097)	(0.092)	(0.086)	(0.096)	(0.052)	(0.143)
γ_1 (CBD distance elasticity)	-1.784***	-1.502***	-1.189***	-0.664***	-0.574***	5.292	-20.45***	-0.687***	-0.964***	-1.100***	-1.267***	-1.315***	-0.481***
	(0.389)	(0.067)	(0.052)	(0.03)	(0.072)	(25.321)	(5.042)	(0.068)	(0.074)	(0.074)	(0.081)	(0.045)	(0.13)
γ^X (x-coordinate)	222.4***	222.8***	222.8***	222.8***	222.6***	199.7**	246.0***	222.7***	222.8***	222.9***	222.6***	222.9***	222.9***
	(0.083)	(0.015)	(0.021)	(0.042)	(0.132)	(90.364)	(5.4)	(0.064)	(0.1)	(0.057)	(0.052)	(0.033)	(0.228)
γ^Y (y-coordinate)	359.8***	359.8***	359.8***	359.9***	359.9***	350.0***	368.8***	360.0***	360.2***	360.0***	360.2***	360.3***	360.9***
	(0.059)	(0.015)	(0.014)	(0.042)	(0.08)	(34.979)	(1.9)	(0.046)	(0.092)	(0.053)	(0.048)	(0.033)	(0.168)
Observations	17	90	90	309	66	18	110	271	167	131	99	314	55
R^2	0.819	0.858	0.863	0.623	0.587	0.257	0.531	0.29	0.522	0.672	0.751	0.756	0.228
AIC	40.1	208.3	169.1	605.5	139.6	53.3	297.3	830.7	459.8	328.3	255.4	739.2	159.2

Notes: Unit of observation is new constructions. Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Tab A3. NLS estimates of CBD coordinates – land price

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
	Log land price												
Cohort	1870s & 1880s	1890s & 1900s	1910s	1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000s	2010s
γ_0 (intercept)	3.656***	3.631***	3.678***	4.101***	4.728***	-478.93*	4.211***	4.389***	4.510***	4.424***	4.171***	4.242***	4.364***
	(0.21)	(0.05)	(0.036)	(0.041)	(0.345)	(269.53)	(0.059)	(0.036)	(0.062)	(0.049)	(0.1)	(0.042)	(0.095)
γ_1 (CBD distance elasticity)	0.843**	-0.200***	-0.258***	-0.255***	-0.653***	73.872*	-0.236***	-0.193***	-0.242***	-0.307***	-0.473***	-0.566***	-0.502***
	(0.382)	(0.035)	(0.028)	(0.027)	(0.168)	(41.239)	(0.042)	(0.025)	(0.047)	(0.043)	(0.075)	(0.035)	(0.1)
γ^X (x-coordinate)	222.0***	222.8***	222.7***	223.0***	224.2***	-463.0	223.0***	222.8***	223.1***	222.3***	223.0***	223. 2***	222.8***
	(0.284)	(0.062)	(0.035)	(0.123)	(0.842)	(.)	(0.213)	(0.122)	(0.258)	(0.072)	(0.182)	(0.062)	(0.195)
γ^Y (y-coordinate)	360.5***	359.8***	359.8***	360.1***	359.1***	334.2***	360.1***	360.2***	360.1***	359.9***	360.1***	360.1***	360.0***
	(0.234)	(0.056)	(0.051)	(0.091)	(0.654)	(103.61)	(0.18)	(0.101)	(0.066)	(0.061)	(0.13)	(0.068)	(0.134)
Observations	17	90	90	309	66	18	110	271	167	131	99	314	55
R^2	0.281	0.279	0.515	0.372	0.512	0.233	0.361	0.207	0.225	0.316	0.393	0.505	0.345
AIC	30.3	92.7	52.2	284.5	80.9	16.1	56.6	261	239.4	214.2	201.9	509.9	115.4

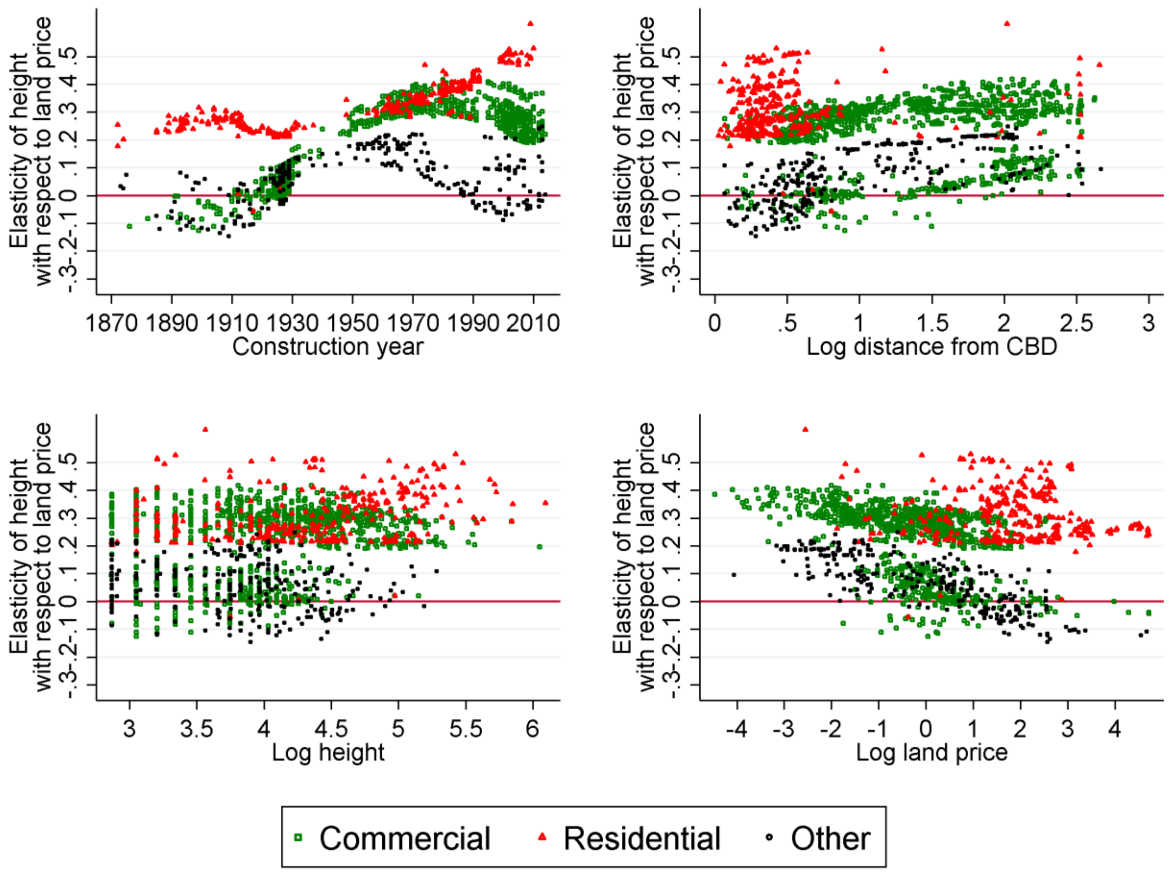
Notes: Unit of observation is new constructions. Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

3.2 The elasticity of height with respect to land price: LWR-IV estimates

As discussed in the main paper in Section 3.3 there is a concern that assessors may have been influenced by the announcement of tall buildings and assigned high land values not because of a fundamental locational advantage but because they knew a tall building was under construction. Using the lagged land price as an instrument for the land price, we do not find evidence for such a reverse causality in the parametric models reported in Table 5 (column 2 and 6) in the main paper. We therefore estimate the fundamental height using non-instrumented locally weighted regressions (LWR) whose estimates we summarize in Figure 8 in the main paper.

As a robustness check we replicate these LWR using the lagged land price as an instrument for the actual land price. The resulting estimates of the elasticity of height with respect to land price are summarized in Figure A6. The results are qualitatively and quantitatively very similar to the baseline results reported in the main paper (Figure 8). The only notable difference is that the increase in the elasticity over time estimated for commercial buildings shows some non-linearity in the IV estimates. Up until the 1930s, the elasticity remains relatively constant, and then increases at a more or less linear rate, whereas in the baseline estimates it increases approximately linearly throughout the study period.

Fig. A6. LWR-IV Estimates



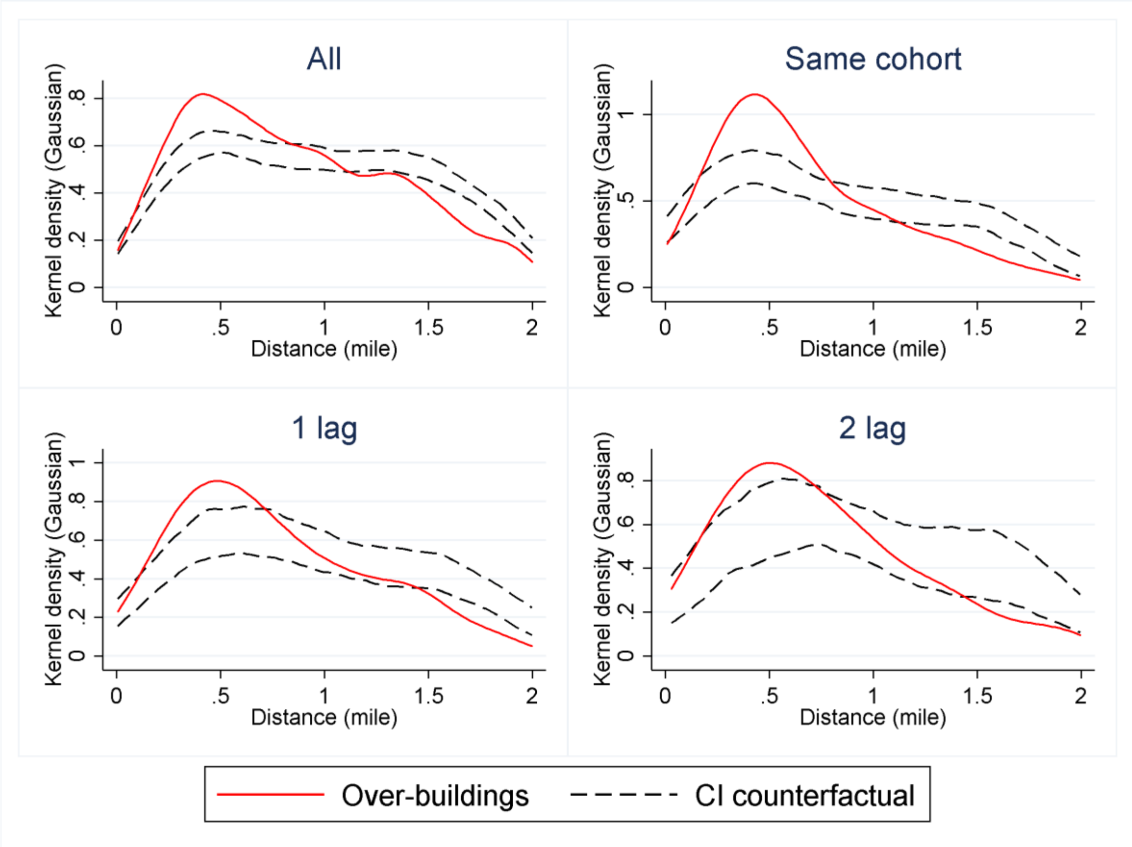
Notes: Each icon represents a LWR estimate of the elasticity of height with respect to land price for a given building $\tilde{\imath}$ built in year $\tilde{t}$. The regression model in the same as in Table 5, column (6). Observations are weighted using Gaussian Kernel weights based on the geographic distance from $\tilde{\imath}$ and the time distance from $\tilde{t}$. The bandwidth is selected according to the Silverman (1986) rule. Lagged land prices (by one decade) are used as an instrument for actual land prices.

4 Spatial interactions in excess height

4.1 Top decile over-buildings: All buildings and "Other" buildings

Figure 10 and 11 in the main paper compare the distribution of bilateral distances between commercial and residential over-buildings to counterfactual distributions based on random draws from bilateral distances between all buildings in the same category (commercial or residential). In Figure A7 we show similar distributions for the category of "other" buildings, which includes non-commercial non-residential buildings such as churches, stadia, or water towers. In keeping with intuition, we find no evidence for dissipative height competition for these buildings.

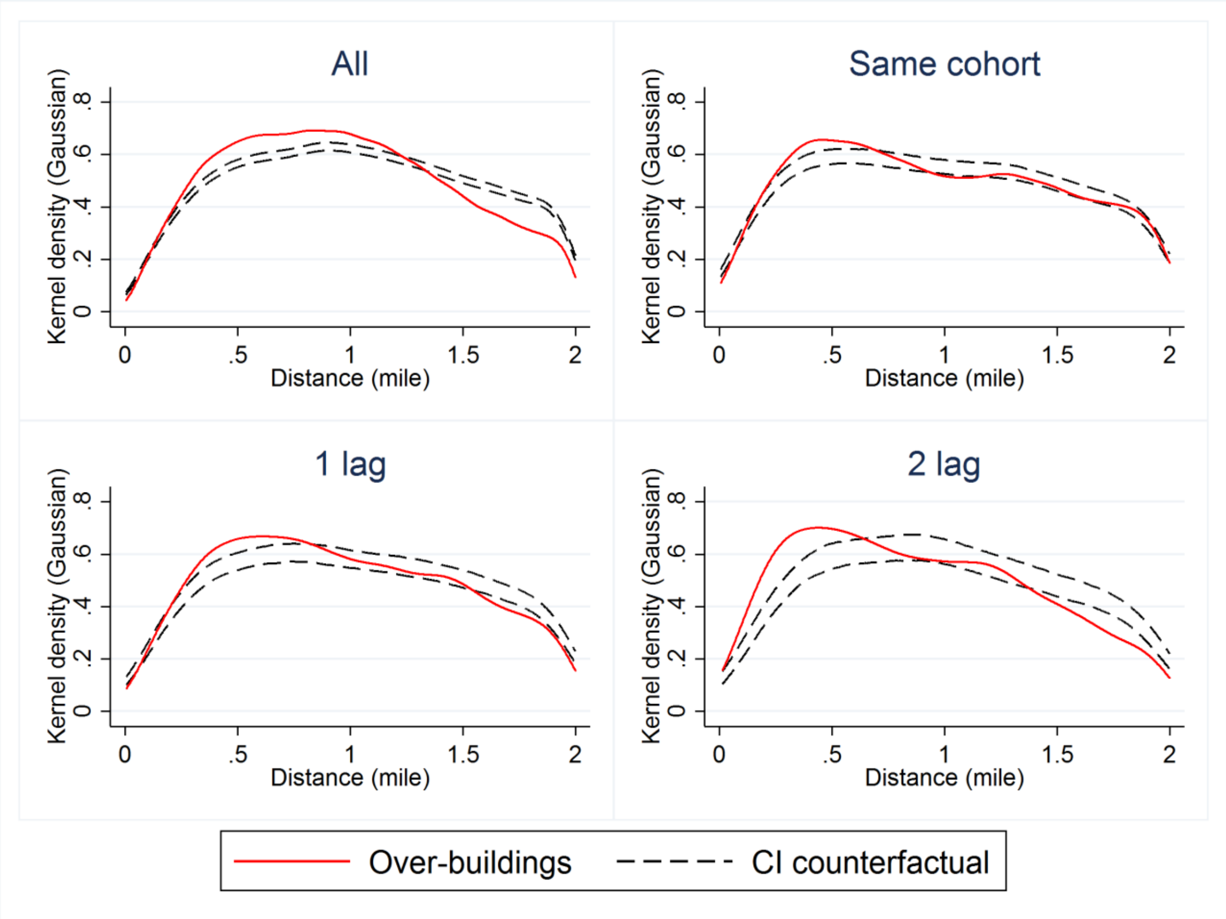
Fig. A7. Bilateral distances between non-commercial and non-residential over-buildings



Notes: Over-buildings are the top quartile in the distribution of the relative excess height across non-commercial and non-residential buildings. Kernel density estimator uses a Gaussian kernel and a bandwidth set according to the Silverman (1986) rule. Confidence bands are generated based on 100 random draws of samples of commercial or residential buildings of the same size as the respective sample of over-buildings. Upper and lower bounds represent the 95% and the 5% percentile in the distribution of counterfactual densities at a given year or height.

Figure A8 shows the same density distributions taking all buildings as a basis. As expected, the relative distance distributions resemble a mix of the three land use categories, with weak signs of dispersion of over-building at short distances.

Fig. A8. Bilateral distances between non-commercial and non-residential over-buildings



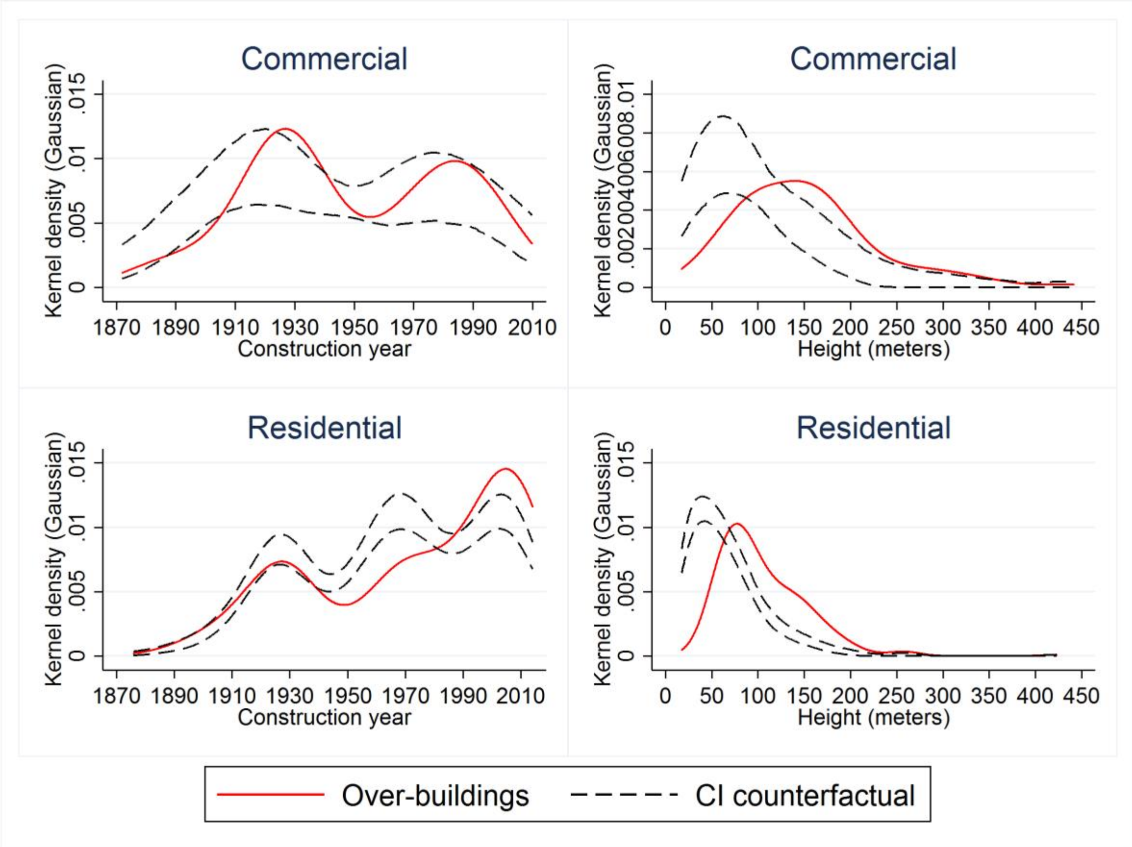
Notes: Over-buildings are the top quartile in the distribution of the relative excess height across all buildings. Kernel density estimator uses a Gaussian kernel and a bandwidth set according to the Silverman (1986) rule. Confidence bands are generated based on 100 random draws of samples of commercial or residential buildings of the same size as the respective sample of over-buildings. Upper and lower bounds represent the 95% and the 5% percentile in the distribution of counterfactual densities at a given year or height.

4 . 2 Top quartile over-buildings

In the analyses reported in Section 4 of the main paper we define over-buildings as the buildings in the top decile of the distribution of excess heights. Because this threshold is arbitrary we replicate the main stages of the analysis defining over-buildings as the top quartile in the same distribution.

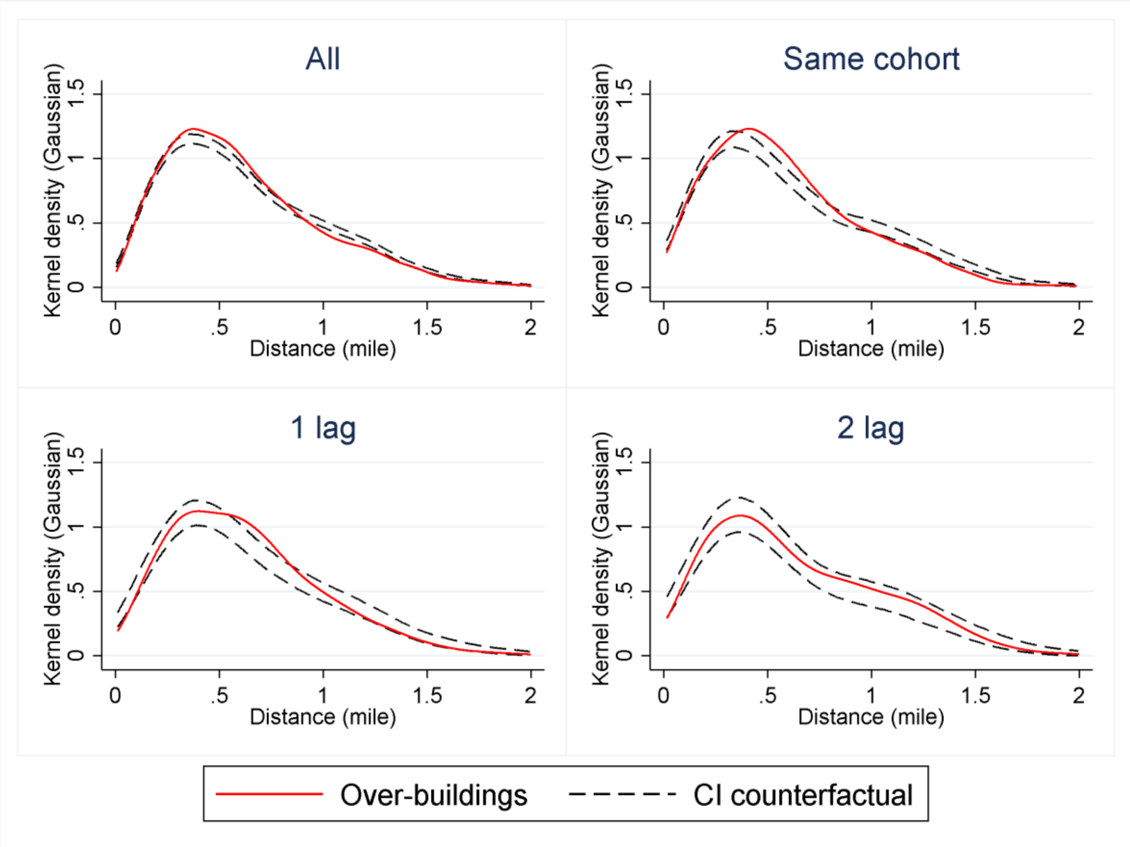
Apart from this different definition of over-buildings, Figures A9-A12 are exact replications of Figures 9-12 in the main paper. The confidence intervals are generally narrower because as the number of over-building increases, the sample size of the randomly drawn comparison samples also increases. Other than that, the figures are virtually identical to the respective figures in the main papers so that all interpretations provided in the main paper apply.

Fig. A9. Over-buildings by height and construction year



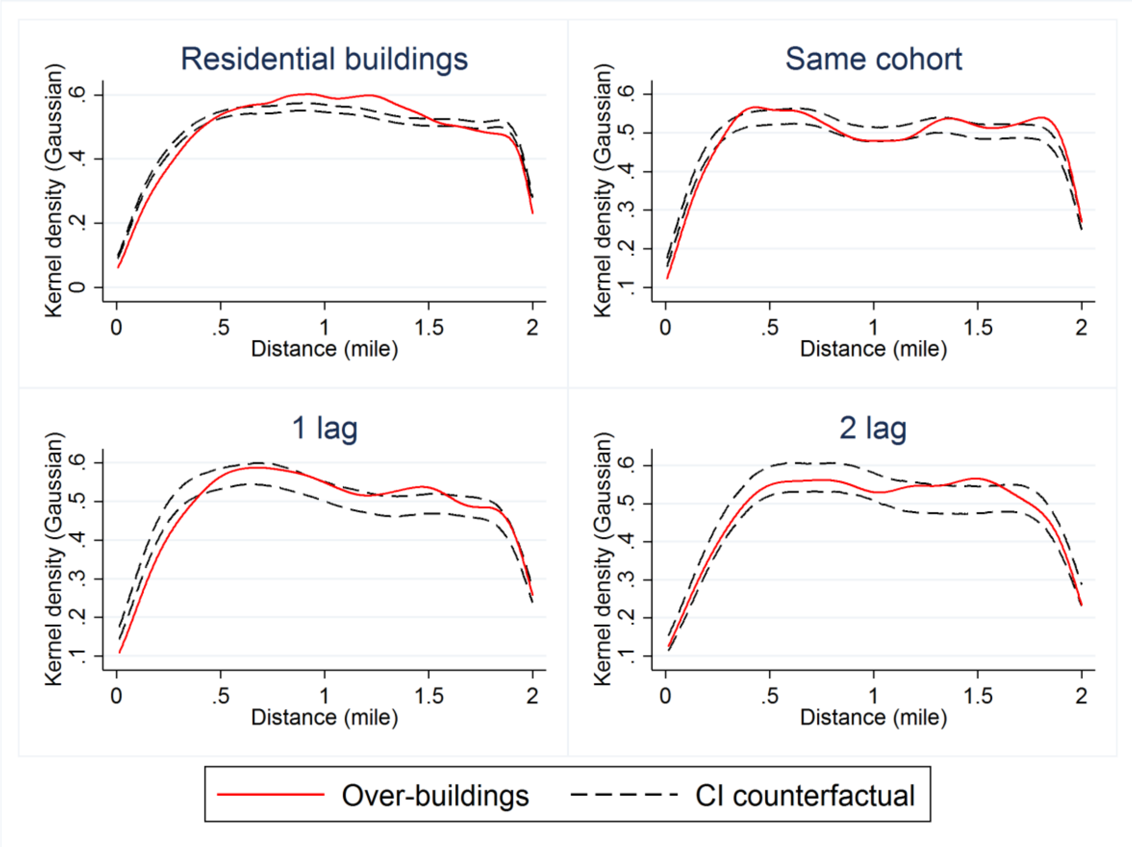
Notes: Over-buildings are the top quartile in the distribution of relative excess heights across commercial or residential buildings. Kernel density estimator uses a Gaussian kernel and a bandwidth set according to the Silverman (1986) rule. Confidence bands are generated based on 1000 random draws of samples of commercial or residential buildings of the same size as the respective sample of over-buildings. Upper and lower bounds represent the 95% and the 5% percentile in the distribution of counterfactual densities at a given year or height.

Fig. A10. Bilateral distances between commercial over-buildings



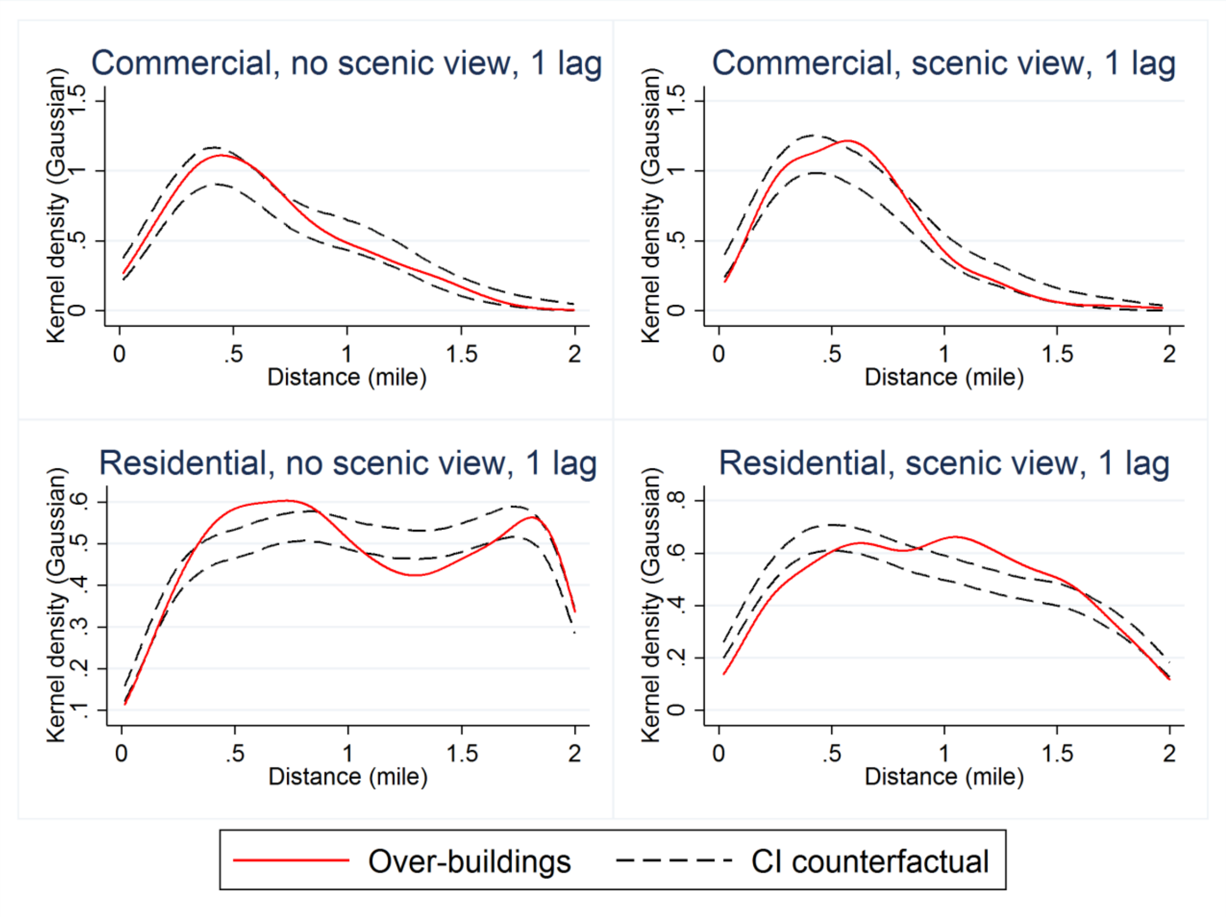
Notes: Over-buildings are the top quartile in the distribution of the relative excess height across commercial buildings. Kernel density estimator uses a Gaussian kernel and a bandwidth set according to the Silverman (1986) rule. Confidence bands are generated based on 1000 random draws of samples of commercial or residential buildings of the same size as the respective sample of over-buildings. Upper and lower bounds represent the 95% and the 5% percentile in the distribution of counterfactual densities at a given year or height.

Fig. A11. Bilateral distances between residential over-buildings



Notes: Over-buildings are the top quartile in the distribution of the relative excess height across residential buildings. Kernel density estimator uses a Gaussian kernel and a bandwidth set according to the Silverman (1986) rule. Confidence bands are generated based on 1000 random draws of samples of commercial or residential buildings of the same size as the respective sample of over-buildings. Upper and lower bounds represent the 95% and the 5% percentile in the distribution of counterfactual densities at a given year or height.

Fig. A12. Bilateral distances between commercial or residential over-buildings with or without a scenic view



Notes: Over-buildings are the top quartile in the distribution of the relative excess height across residential buildings or commercial buildings. With (without) scenic view includes constructions within 0.1 (beyond 0.2) miles from Chicago River or Lake Michigan. Kernel density estimator uses a Gaussian kernel and a bandwidth set according to the Silverman (1986) rule. Confidence bands are generated based on 1000 random draws of samples of commercial or residential buildings of the same size as the respective sample of over-buildings. Upper and lower bounds represent the 95% and the 5% percentile in the distribution of counterfactual densities at a given year or height.

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