

The Economic Dynamics of City Structure: Evidence from Hiroshima's Recovery*

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ABSTRACT: We provide new theory and evidence on the resilience of internal city structure after a large shock, analyzing the atomic bombing of Hiroshima. Exploiting newly digitized data, we document that the city structure recovered within five years after the bombing. Our new dynamic quantitative model of internal city structure incorporates commuting, forward-looking location choices, migration frictions, agglomeration forces, and heterogeneous location fundamentals. Strong agglomeration forces in our estimated model explain Hiroshima's recovery, and we find an alternative equilibrium where the city center did not recover. These results highlight the role of agglomeration forces, multiple equilibria, and expectations in urban dynamics.

KEY WORDS: agglomeration, history, expectations, atomic bombing, spatial dynamics

JEL classification: C73, N45, O18, R12, R23

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1 Introduction

Cities have faced a host of shocks throughout history. Wars, natural disasters, pandemics, and technological shocks have all impacted city structure – the spatial distribution of economic activities within cities. However, there remains substantial debate about whether city structure is resilient to large shocks and what mechanisms are behind this resilience ([Glaeser 2022](#)). Theoretically, resilience of city structure after temporary shocks emerges from exogenous locational fundamentals that uniquely determine the distribution of economic activities, or the presence of strong agglomeration forces by which the city structure is determined via a coordination of expectations around the focal point. However, the empirical importance of these different mechanisms remains an open question ([Lin and Rauch 2022](#)).

Understanding the mechanisms that underlie the resilience of city structure would aid the reconstruction of war-torn cities, improve urban revitalization efforts, and inform planning for future shocks. Nevertheless, there are two important challenges in answering these questions. First, we rarely observe a large shock to city structure that allows us to capture spatially-granular data on economic activities over a long period of time. Second, we need a quantifiable model of the dynamics of internal city structure that allows us to disentangle the mechanisms underlying the resilience of city structure.

In this paper, we provide new theory and evidence on the resilience of city structure by analyzing the atomic bombing of Hiroshima, one of the most remarkable examples of urban resilience in human history. The atomic bombing completely destroyed the city center while sparing its outskirts. This distinctive and massive shock provides a unique laboratory for studying the dynamics of city structure. We collect and digitize new granular historical data on the distribution of economic activities within Hiroshima. Using this data, we first document that the city structure of Hiroshima recovered to its pre-war state within five years after the bombing. We then construct and calibrate a new dynamic quantitative model of internal city structure, which explains this observed recovery. In our estimated model, strong agglomeration forces created by population and employment density yield better local amenities and increase productivity. This provided the key incentive for people to again live and work in the city center. Finally, we show that these agglomeration forces induce multiple equilibria. In particular, there exists an alternative equilibrium in which the city center did not recover, in contrast to the observed recovery equilibrium. We argue that self-fulfilling expectations of recovery might have played an important role in realizing the recovery equilibrium.

We begin by describing the historical context and our newly collected data on the distribution of economic activities within Hiroshima. As of 1945, most the administrative region of Hiroshima lay within 6 kilometers of the city center. On August 6, 1945, the atomic bomb hit near

the city center and destroyed almost all structures within 2 kilometers of the city center, but many structures on the outskirts of the city were much less affected. Some areas on the outskirts even experienced an increase in population due to inflows of survivors from the city center. Consequently, the atomic bombing was an extremely large shock to city structure; the pre-war city center now had the lowest population and employment density in the city. To conduct our quantitative analysis at a spatially granular level, we collect and digitize new historical data on population, employment, wartime destruction, and fundamental characteristics at the city block level within Hiroshima. Importantly, our dataset covers both the pre-bombing and immediate post-bombing periods, allowing us to investigate the recovery of central Hiroshima in detail.

Through descriptive and reduced-form analyses, we reveal that the city structure of Hiroshima was resilient to this unprecedented shock. Our findings are twofold: (i) the destroyed city center again became the main hub of economic activity within five years of the atomic bombing; and (ii) the recovery of central Hiroshima is not explained by various observed fundamental location characteristics, which could directly affect amenities and productivity independently of the local density of economic activities (e.g., altitude, access to natural water). There are two possible explanations for these findings. First, while our results suggest that the recovery of the city center is not explained by its observed locational advantages and our results also hold even within a small homogeneous area, it is still possible that the destroyed city center retained some unobserved locational advantages that survived the bombing (e.g., scenic views). Second, people may have expected the recovery of the destroyed city center when making location choices, and the incentive to again live and work in the city center came from agglomeration forces due to expected high density as in the pre-war period. We analyze these two possible explanations using our structural model.

We develop a new dynamic quantitative model of internal city structure. Our model is the first quantitative urban model that accommodates commuting, forward-looking location choices, migration frictions, agglomeration forces, and heterogeneous location fundamentals. The commuting patterns within a city are endogenously determined by individual choices of workplace and residence. Individuals correctly anticipate the future path of the economy when making location decisions, and neighborhood amenities and productivity depend on population and employment density. Location-specific fundamental amenities and productivity capture the heterogeneous advantages of locations in a city that are independent of population and employment density. In addition, our model incorporates migration frictions, which induce history-dependence in city structure. These model elements are necessary to capture alternative possible determinants of the dynamics of internal city structure.

We calibrate our model and evaluate its ability to explain the recovery of central Hiroshima. We estimate the model using the observed location choices of Hiroshima residents from 1955 to

1975, after the period of rapid recovery, because sufficient data for calibrating our model are only available for this time period. We leverage the structure of the model to estimate model parameters and compute unobserved location characteristics. Our key parameters describe how the agglomeration forces increase amenities and productivity as population and employment density rise. We estimate these forces under the identification assumption that exogenous changes in the amenities and productivity of each block over time are uncorrelated with distance from the city center, while allowing for arbitrary heterogeneity in location-specific amenities and productivity. We find strong agglomeration forces in both amenities and productivity. We then assess how well our calibrated model fits the location choice data for 1950 when people had returned to the destroyed city center. The endogenous mechanisms of our model successfully account for the resurgence observed in the data for 1950.

We highlight that agglomeration forces play a key role in explaining the recovery of central Hiroshima. To this end, we simulate a counterfactual population and employment distribution in which agglomeration forces in amenities and productivity are absent and fundamental productivity and amenities for 1950 are equal to their estimated averages from the 1955–1975 data. We find that our calibrated model without agglomeration forces cannot predict the recovery of the city center, consistent with the idea that agglomeration forces played an important role in the resurgence of the center. Theoretically, in the presence of strong agglomeration forces, there is potential for multiple equilibria because the city center would not be attractive if its recovery were not expected in the near future. To investigate this, we numerically solve the model for an alternative rational expectations equilibrium in which the population and employment densities of the city center do not recover. This suggests that the observed pattern of recovery is one equilibrium selected from multiple, and that self-fulfilling expectations of recovery might be crucial in selecting this equilibrium. We argue that certain factors, such as government recovery plans, the anchoring effect of salient location characteristics in the city center (e.g., tram networks, the destroyed Hiroshima castle), property rights, and popular narratives of rebuilding, may have induced expectations that the destroyed city center would return to its high density as in the pre-war period. Our results suggest the importance of these factors in the rapid recovery of city structure through fostering the formation of such recovery expectations.

Overall, our analysis of Hiroshima highlights the role of agglomeration forces, multiple equilibria, and expectations in the economic dynamics of city structure. For cities recovering from a large shock, our findings indicate the importance of agglomeration forces and creating potentially self-fulfilling expectations for recovery. Our results further suggest that policymakers could substantially change the dynamics of city structure if they could influence expectations about a city’s future.

This paper contributes to studies on the determinants of the concentration of economic ac-

tivity in space, which is at the core of urban economics and economic geography. A theoretical literature has uncovered the importance of fundamental location characteristics and agglomeration forces in shaping the spatial distribution of economic activities, including Fujita and Ogawa (1982), Fujita and Thisse (1996), Fujita, Krugman, and Venables (1999), Lucas and Rossi-Hansberg (2002) and Ahlfeldt, Redding, Sturm, and Wolf (2015). Moreover, when agglomeration forces are important relative to heterogeneity in location characteristics so that there are multiple equilibria, initial conditions (“history”) or self-fulfilling expectations may determine the spatial distribution of economic activities by selecting a particular equilibrium. Krugman (1991) and Matsuyama (1991) show that self-fulfilling expectations can induce a transition from one steady state to another when multiple equilibria exist, implying that the initial conditions determined by history can be overcome by expectations.¹ We empirically contribute to this discussion by analyzing the atomic bombing of Hiroshima as a large exogenous shock to city structure and showing the importance of agglomeration forces, multiple equilibria, and expectations in the economic dynamics of city structure.²

Many empirical studies have investigated the importance of historical shocks as determinants of the spatial distribution of economic activities. Previous studies exploiting war-time destruction across cities and regions have typically found that large shocks have only temporary impacts, including Davis and Weinstein (2002, 2008), Brakman, Garretsen, and Schramm (2004), Bosker, Brakman, Garretsen, and Schramm (2007), Miguel and Roland (2011), Feigenbaum, Lee, and Mezzanotti (2022). Among others, Davis and Weinstein (2002) finds that the population distribution across Japanese cities after World War II converged with its pre-war trend, including Hiroshima. Yet, studies that exploit shocks other than war-time destruction often find that large shocks can have persistent or permanent effects on the spatial distribution of economic activities, including Redding, Sturm, and Wolf (2011), Bleakley and Lin (2012), Schumann (2014), Siodla (2015), Hornbeck and Keniston (2017), Michaels and Rauch (2018), Brooks and Lutz (2019), Ambrus, Field, and Gonzalez (2020), Hebllich, Trew, and Zylberberg (2021), Allen and Donaldson (2022), Brooks, Rose, and Veuger (2022) and Yamagishi and Sato (2023).³ Our paper is distinctive from these studies in three important ways. First, we analyze the spatial distribution of economic activities *within* a

¹Among others, see Fukao and Bénabou (1993), Rauch (1993), Holmes (1999), Baldwin (2001), Ottaviano (2001), Oyama (2009), and Barreda-Tarazona, Kundu, and Østbye (2021) for developments in self-fulfilling expectations and economic geography. Self-fulfilling expectations also matter in other important economic contexts with multiple equilibria, including structural transformation in economic development (Murphy, Shleifer, and Vishny 1989).

²Fujita and Thisse (1996) states “[a]nother reason for [a spatial structure’s] inertia...is the formation of self-fulfilling prophecies about the development of some areas. Indeed, it seems reasonable to consider existing cities as focal points that help agents coordinate their spatial decisions. In such a context, reshaping the urban landscape would then require major changes in agents’ expectations.”

³Harada, Ito, and Smith (forthcoming) and Redding and Sturm (2023) estimate the long-run impact of bombing on neighborhood quality within Tokyo and London. Compared to them, we do not analyze neighborhood quality as such data is unavailable and instead focus on the dynamics of the re-emergence of city structure.

city using new spatially granular data. Second, we use the atomic bombing of Hiroshima as an exogenous and unprecedentedly large shock to the internal structure of a city. Third, and most importantly, we develop and apply a novel dynamic quantitative urban model to this historical shock to investigate why we observe such resilience in Hiroshima, highlighting the importance of agglomeration forces and self-fulfilling expectations in overcoming the catastrophe. In particular, their importance can reconcile the aforementioned empirical studies that are split on the persistence of historical shocks: we often observe history independence in the distribution of economic activities because expectations of recovery to the pre-event situation tend to emerge after wartime destruction. History dependence may arise in other contexts where such expectations are absent.

Our structural analysis also relates to recent advancements in quantitative spatial models, as reviewed in [Redding and Rossi-Hansberg \(2017\)](#). To analyze the resilience of city structure, we develop a new quantitative urban model with commuting, forward-looking location choices, migration frictions, agglomeration forces, and heterogeneous location fundamentals. Studies that consider commuting and agglomeration forces within cities ([Ahlfeldt et al. 2015](#); [Monte, Redding, and Rossi-Hansberg 2018](#); [Dingel and Tintelnot 2020](#); [Tsivanidis 2022](#)) do not accommodate forward-looking migration decisions and migration frictions, while those with forward-looking migration decisions ([Caliendo, Dvorkin, and Parro 2019](#); [Balboni 2021](#); [Heblich, Trew, and Zylberman 2021](#); [Warnes 2021](#); [Allen and Donaldson 2022](#); [Almagro and Domínguez-Iino 2022](#); [Kleiman, Liu, and Redding 2023](#)) do not incorporate commuting or agglomeration forces. Among others, [Monte, Porcher, and Rossi-Hansberg \(2023\)](#) presents a model for one-dimensional cities on the real line with forward-looking individuals who choose work arrangements and commuting patterns. In contrast, our model allows for an arbitrary number of discrete locations within cities and location fundamentals, which are tractable when mapping the data to the model.⁴ Importantly, we integrate commuting, forward-looking location choices, migration frictions, agglomeration forces, and heterogeneous location fundamentals into a single framework that is otherwise parsimonious since data availability in historical contexts is often limited. The tractability of the model is particularly useful in data-scarce environments.

Lastly, this paper relates to studies on the recovery of Hiroshima from the atomic bombing ([Hiroshima City Government, 1971; 1983](#)). There is little econometric analysis on the distribution of economic activities within the city and the resurgence of the city center. Our paper formally analyzes the recovery pattern using newly-digitized granular historical data and a novel quantitative economic model. This provides new evidence on the resilience of Hiroshima's city structure and a new approach to understanding the economic mechanisms behind the resilience.

⁴As an early theoretical contribution, [Rossi-Hansberg \(2004\)](#) presents the canonical urban model with shocks to internal city structure.

The rest of the paper is structured as follows. Section 2 describes the historical context and data. Section 3 presents the reduced-form analysis and Section 4 introduces the theoretical framework. Section 5 calibrates the model and demonstrates that our model accurately fits the recovery of central Hiroshima. In Section 6 we undertake a counterfactual analysis to show the roles of agglomeration forces and expectations in the recovery. Section 7 explores the potential factors contributing to the formation of expectations. Section 8 concludes.

2 Historical Background and Data

This section briefly describes the history of Hiroshima prior to the atomic bombing and the impact of the bombing on the city (Subsection 2.1) and how we construct new granular spatial data on population, employment and other characteristics of Hiroshima (Subsection 2.2).

2.1 *Historical Background*

The development of Hiroshima started in the late 16th century when Terumoto Mōri, a local samurai lord, built Hiroshima castle.⁵ Hiroshima has been a major city in the *Chugoku* region of Japan since then thanks to its proximity to the sea and rivers. Early in the 20th century, the city grew quickly. In 1935, 310,118 people lived in Hiroshima, which made it the seventh-largest city in Japan by population. As Japan gradually transitioned to a war economy through the Second Sino-Japanese War (1937–1945) and Pacific War (1941–1945), growth slowed and then reversed. Before the atomic bombing, the city had an estimated population of 350,000. As the U.S. overwhelmed Japan during World War II, most Japanese cities endured extensive non-atomic air raids (Davis and Weinstein 2002). However, the U.S. avoided bombing Hiroshima to preserve the city as the “best laboratory” for demonstrating the effects of the atomic bomb.⁶ Consequently, the atomic bombing was essentially the only direct destruction the city experienced during WWII.

On August 6, 1945, the U.S. Air Force dropped the atomic bomb “Little Boy” near the center of Hiroshima. The damage to people and buildings was unprecedentedly catastrophic. The city government of Hiroshima estimates that 140,000 people died by the end of 1945 as a result of the atomic bombing, although it is difficult to determine the exact number.⁷ The death rate was near

⁵In this paper we use the word “Hiroshima” to refer to the administrative Hiroshima City (*Hiroshima-shi*). We sometimes explicitly state Hiroshima City to clearly distinguish it from Hiroshima Prefecture.

⁶Based on “Minutes of the Second Meeting of the Target Committee Los Alamos, May 10-11, 1945” (<http://www.dannen.com/decision/targets.html>, last accessed on October 28, 2023), the target of the bombing was determined based on the city’s size and its flat terrain to best measure the damage from the bombing. Notably, local economic conditions were not considered in selecting targets.

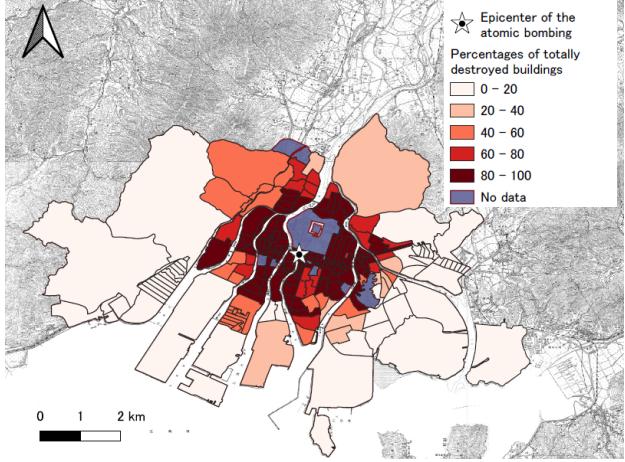
⁷The real death toll is likely to be even higher because the atomic bombing caused severe injuries and diseases that killed many after 1945. Source: <https://www.city.hiroshima.lg.jp/site/english/9803.html> (last accessed on October 28, 2023). This damage was much more severe than in other cities that endured extensive air raids. For example, the population of Tokyo was approximately 7 million in 1940. U.S. air raids on Tokyo killed over 100,000 civilians and

Figure 1: Destruction of the atomic bombing in Hiroshima

(a) Total destruction near the epicenter



(b) Block-level destruction rate of buildings



Note: Panel (a) is a photograph from the United States Strategic Bombing Survey made available by the U.S. National Archives and Records Administration. Panel (b) shows a map of Hiroshima at the time of the bombing, along with block-level data (197 blocks in total) on the fraction of completely destroyed buildings and the epicenter ([Hiroshima City Government 1971](#); [Takezaki and Soda 2001](#)). Remote islands (*Nino-shima*, *Kanawa-jima*, *Touge-shima*) are omitted for better visibility. We use as the background image the 1950 topographic map taken from the Time Series Topographic Map Viewer of Japan ([Tani 2017](#), <https://ktgis.net/kjmapw>).

100 percent for those within 1 kilometer of the epicenter. The bomb also destroyed a large number of buildings: 51,787 out of 76,237 buildings in Hiroshima were completely destroyed and 18,720 were partly destroyed. The vast majority of buildings within 2 kilometers of the city center were completely destroyed. This can be seen in Figure 1a, which was taken near the epicenter of the bombing. The population of Hiroshima dropped to 136,518 as of November 1945, about one-third of the pre-war population.

In contrast to the total destruction in central Hiroshima, the outskirts of the city were much less damaged. Figure 1b shows the fraction of completely destroyed buildings at the block level ([Hiroshima City Government 1971](#); [Takezaki and Soda 2001](#)). While nearly all buildings in the dark-colored areas close to the epicenter were destroyed, buildings in the light-colored areas away from the epicenter were much less damaged. As a result, the outskirts of Hiroshima experienced a significant increase in population as survivors from the city center flooded in. As of November 1, 1945, Hiroshima beyond 3 kilometers from the epicenter had 142 percent of its pre-bombing population.

The war ended on August 15, 1945. People initially doubted whether Hiroshima could recover.

damaged approximately 700,000 housing units. Source: <https://tokyo-sensai.net/about/tokyoraids/> (In Japanese, last accessed on October 28, 2023). While the absolute numbers are large in Tokyo, the percentage rates in Hiroshima are substantially greater than in Tokyo due to its smaller population.

Despite then-limited scientific knowledge, radioactive contamination was a major concern immediately after the bombing. Rumors circulated that “nothing will grow here for 75 years.”⁸ However, the serious radioactive contamination caused by the bombing decayed rapidly. According to the Hiroshima City government, radiation at the epicenter was 1/1,000th a day after the bombing and 1/1,000,000th a week later.⁹ Furthermore, a large typhoon hit Hiroshima on September 17, 1945, about six weeks after the bombing. According to the U.S. Atomic Bomb Casualty Commission, the typhoon probably washed away much contaminated material, bringing radioactivity down to a relatively safe level ([Takahashi 2008](#)). Given this evidence, we do not consider potential radioactive contamination in analyzing the recovery of Hiroshima because living in Hiroshima was unlikely to be meaningfully unhealthy after this typhoon.

Despite initial pessimism, people gradually became optimistic about Hiroshima’s destroyed city center ([Hiroshima City Government 1971](#)). Although it is difficult to identify one single factor, several may have contributed to such optimism. First, the city government of Hiroshima published a recovery plan. Even though the government faced a serious budget shortage and could not implement most of its plan for several years after the bombing, the plan might have induced optimism about Hiroshima’s future.¹⁰ Second, the presence of salient location characteristics in the city center, such as the transportation network and the destroyed Hiroshima castle, may have anchored people’s expectations for recovery despite the severe damage. Third, pre-war private property ownership was preserved, though almost all homeowners near the city center lost their homes and many landowners and homeowners close to the city center were killed by the bombing. Finally, rebuilding narratives may have been shared by people and coordinated their expectations. We revisit the discussion about the formation of expectations in Section 7.

Notwithstanding the lack of strong public actions, Hiroshima experienced a strong recovery due to private efforts. In 1955, Hiroshima had a population of 357,287, larger than the 1935 population. Hiroshima continued to grow and physically expanded along the way.¹¹ Today, Hiroshima has a population of approximately 1.2 million, making it the 10th largest Japanese municipality and the largest in the *Chugoku* region of Japan.

⁸Source: <https://www.bbc.com/news/world-asia-53660059>, last accessed on October 28, 2023.

⁹Source: <https://www.city.hiroshima.lg.jp/site/english/9809.html>, last accessed on October 28, 2023.

¹⁰The recovery council was formed in February 1945 and consisted of 26 members, including the former mayor, city councillors, and local business leaders. However, despite the exceptionally catastrophic damage, Hiroshima could not get special budgetary treatment until the enactment of the Hiroshima Peace Memorial City Construction Law in 1949. In 1947, the budget for the reconstruction of Hiroshima City was 0.56 billion JPY, which was only 2.5 percent of the estimated total budget of 23 billion JPY ([Shinoda 2008](#)). The city focused on providing public housing, but it could only provide 3,000 units during 1945–1950, relative to the over 70,000 buildings destroyed. The restoration of pre-war infrastructure was also prioritized, but this did provide a particular advantage to the city center as the city outskirts also had comparable infrastructure.

¹¹As shown in [Davis and Weinstein \(2002\)](#), the aggregate city population recovered its pre-war trend around twenty years after the atomic bombing.

2.2 Data

We have collected and digitized various sources of information on economic activity in Hiroshima before and after the war. Here, we provide a brief overview of our data sources. Appendix A provides further details.

Spatial Units The spatial unit of our analysis is a city block (*cho-cho-moku*) in Hiroshima. As our primary definition of city blocks, we use the block boundaries as of the bombing constructed by [Takezaki and Soda \(2001\)](#). In comparing the pre-war and post-war periods, we focus on areas that were part of Hiroshima as of the bombing.¹² Throughout this paper, we use the block definitions of 1945. The pre-war central business district (CBD) is defined as the mid-point of the *Kamiya-cho* block and *Hacchobori* blocks, which were the two prominent central areas of pre-war Hiroshima. Note that the recovery of the city center documented below implies that the pre-war city center corresponds to the post-recovery city center. We address the revisions of the block boundaries over time by converting all data to the 1945 block definitions based on areal weighting interpolation, and we digitize the block boundaries of 1966 and 1976 to implement this. Throughout the paper, the number of blocks is 174 and the average size of blocks is 0.32 square kilometers.¹³

Destruction by the Atomic Bombing We primarily use the fraction of completely destroyed buildings as a measure of the severity of destruction. The block-level destruction rate is reported in [Hiroshima City Government \(1971\)](#). We augment the digitization of [Takezaki and Soda \(2001\)](#) by consulting [Hiroshima City Government \(1971\)](#) to correct typos in their data and obtain additional information on missing values. Panel (b) of Figure 1 in the previous section illustrates the share of completely destroyed buildings in each block.

Population We collect and digitize population data at the block level. We refer to the Statistical Handbook of Hiroshima (*Hiroshima-shi toukei sho*) for 1933–1936 and the Statistical Abstract of Hiroshima (*Hiroshima shisei youran*) for 1945–1953.¹⁴ From 1955, the population data is taken from the Population Census. Panel (a) of Figure 2 provides a visualization of Hiroshima’s population over time. The population of Hiroshima was increasing prior to the atomic bombing, dropped significantly after the bombing, and resumed growth again after WWII. We also observe that the

¹²The city boundaries gradually expanded since 1955 through municipal mergers as the Hiroshima metropolitan area grew. The administrative Hiroshima as of 1945 roughly corresponds to the four central wards (*Naka-ku*, *Nishi-ku*, *Minami-ku*, *Higashi-ku*) of Hiroshima today. The expansion of the administrative boundaries and commuting zones of Hiroshima implies that our data is more concentrated within the relatively central locations as time elapses.

¹³A Japanese city block is generally smaller than a U.S. census tract, which has a population of around 4,000, but larger than a U.S. census block, which has 40 housing units. In our data on Hiroshima, the average area size for blocks is 0.04 (0.13) square kilometers within 1 (3) kilometer of the CBD, and the average block area is 2.19 square kilometers among blocks more than 3 kilometers from the CBD.

¹⁴For 1945–1950, population is reported using a more aggregated block definition. We combine this information with the block-level destruction rate of buildings to predict the block-level population distribution.

center of Hiroshima declined as a share of the population over time, reflecting the suburbanization of the city that absorbed most post-war population growth. Note that this declining trend was already observed pre-WWII, suggesting that a smaller central population share after WWII does not necessarily mean that recovery was incomplete.

Employment We collect and digitize employment data at the block level from various sources.¹⁵ For 1938, we refer to the Survey of Commerce and Industry in Hiroshima (*Hiroshima-shi shoukougyou keiei chousa*) which records the number of establishments at the block level. The number of commercial buildings right after the bombing is available in the Statistical Abstract of Hiroshima (*Hiroshima shisei youran*). For 1953, we exploit the Survey on the Daytime Population of Hiroshima (*Hiroshima-shi chukan jinko chosa*), where we assume that the daytime population approximates employment. From 1957 to 1975, we use the Business Establishment Statistical Survey (*Jigyousho toukei chousa*).¹⁶ Based on these data, we approximate block level employment every five years from 1950 to 1975. Panel (b) of Figure 2 shows employment in Hiroshima over time. Total employment dropped significantly in 1945 after the bombing, but increased again post-war, and the number of workers employed in the central area recovered to its pre-war level. The share of employment in the city center rose throughout the post-war period, implying an increased concentration of employment.

Commuting and Transportation Networks We use trip-level microdata from the 1987 Hiroshima City Person-Trip Survey to analyze commuting patterns. The data captures the workplace, residence, and representative travel mode for each commuting trip. We also collect and digitize road networks, bus networks, and train networks in Hiroshima and compute bilateral travel time between blocks for different modes: walk, bike, car, bus, and train. Although Hiroshima's public transportation networks were generally stable after the war, there were some changes, notably the discontinuation of the *Ujina* line in 1966.¹⁷ To address this, we use the public transportation networks of 1950 for years prior to 1966 and those of 1987 for later years.

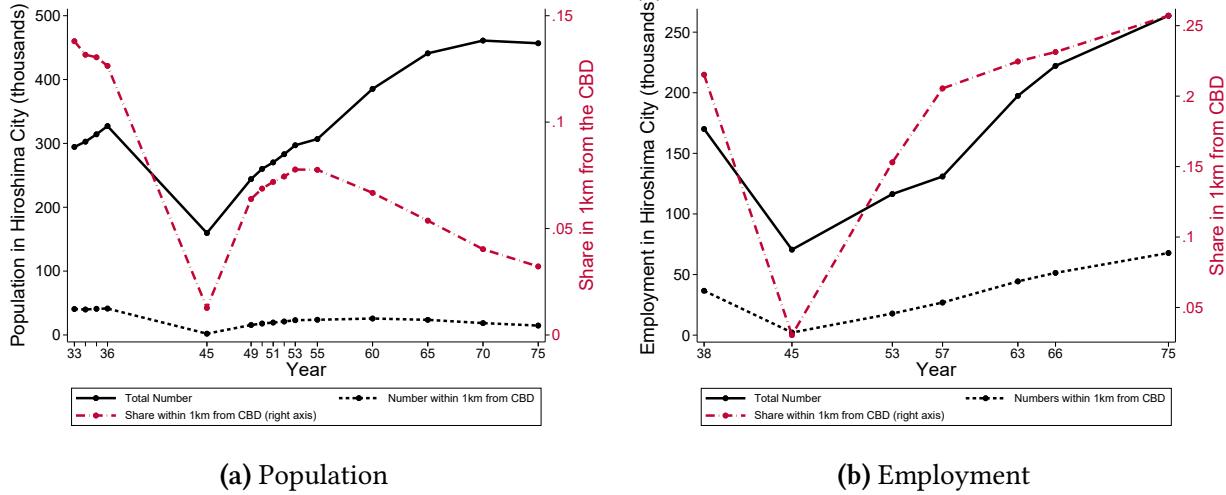
Location Characteristics We collect various information on the location characteristics of each block. In particular, we exploit data on altitude, ruggedness, soil condition, geographical coordinates, distance to the pre-war CBD, distance to train stations, distance to Hiroshima port (*Ujina*

¹⁵While we do not distinguish employment by sector, available evidence suggests that the locations of manufacturing and service sector employment are highly correlated in Hiroshima (see Figure A.5 in the Appendix). We also abstract from agricultural employment. Even in 1950, when agricultural employment was large in the Japanese economy, the Population Census indicates that less than 10 percent of workers in Hiroshima City engaged in agriculture.

¹⁶For 1953–1963, employment is reported using less geographically granular units than blocks. We address this by combining the best available block-level information to approximate the block-level employment distribution. When employment data is unavailable but establishment data is available, we follow Ahlfeldt et al. (2015) and assume that the number of establishments is proportional to employment.

¹⁷The *Hijiyama/Minami* line and *Eba* line) opened in 1944 for military purposes, and these lines have been maintained after the war. These lines improved transportation access in the outskirts.

Figure 2: Population and employment over time in Hiroshima City



Note: The figures show total population and employment within the entire city and within 1 kilometer of the CBD (left axis), as well as the shares of population and employment within 1 kilometer of the CBD (right axis).

port), distance to bodies of water, and distance to cultural assets for each block. Distances are calculated using the centroid of each block shape.

3 Reduced-form Evidence

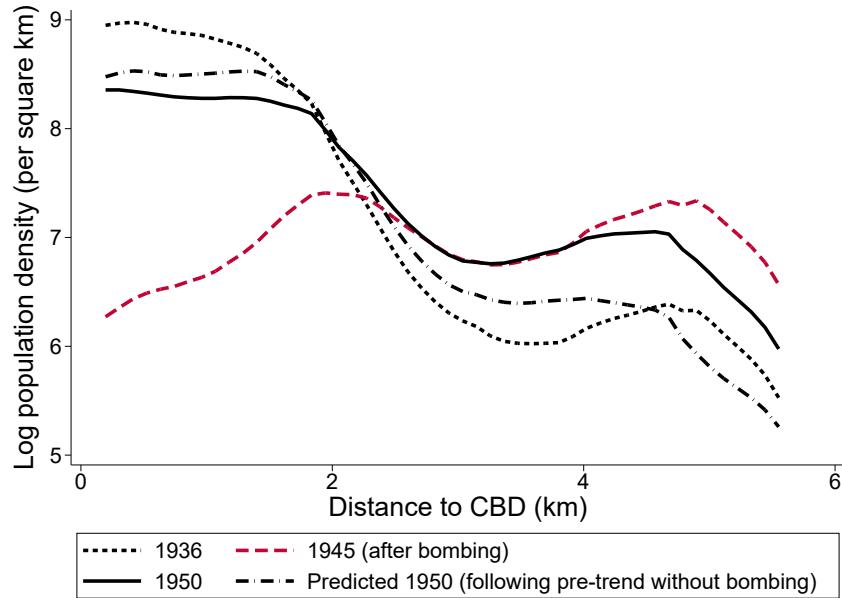
In this section we analyze population density to illustrate the pattern of destruction and recovery of the city structure of Hiroshima. Subsection 3.1 describes how the atomic bombing destroyed central Hiroshima and how the city subsequently recovered to its pre-war city structure. In Subsection 3.2, we formalize this recovery result in a regression analysis. We also find that the recovery tendency is robust to controlling for observable prominent location characteristics, which refer to characteristics of a location that directly affect amenities and productivity independently of the local density of economic activities (e.g., altitude, access to natural water).

3.1 Descriptive Evidence on the Destruction and Recovery of City Structure

In Figure 3 we non-parametrically plot population density within Hiroshima by distance to the CBD, where we normalize the total population of the city to 100,000 each year to facilitate comparisons of the inner-city structure over time. The figure shows that the city structure of Hiroshima was completely changed by the atomic bombing but quickly recovered to the pre-WWII city structure. In 1936, the city had a typical monocentric structure: the city center had the highest population density and density fell as one moved away from the center. This monocentric pattern was completely reversed by the atomic bomb hitting the densely populated city center.

Figure 3 shows that, after the bombing, the city center was wholly destroyed and consequently had the lowest population density in the city. In contrast, areas two kilometers away from the center, which avoided total destruction (see Figure 1b), became the most crowded places in the city. Areas further away from the city center also experienced significant increases in population density as many survivors from the center escaped to the outskirts.

Figure 3: Population density by distance to city center



Note: The figure shows the local polynomial regression of log population density on distance to the CBD for different years. To eliminate the effect of changes in the total population, we normalize the total population each year to 100,000. The predicted population distribution of 1950 is computed based on the 1936 population distribution, assuming that each block experienced annual population growth rate equal to the pre-war (1933–1936) rate.

Despite the “reversal” of the monocentric city pattern after the bombing, the monocentric structure had already re-emerged in 1950, just five years after the bombing. The rate of population recovery in the city center was remarkable. While the recovery from total destruction is qualitatively clear, the recovery may not have been perfect, as the concentration of population around the CBD appears to be less dense in 1950 than in 1936. However, this does not necessarily imply that the recovery was incomplete because the city center already had a slow rate of population growth prior to the war. This can be illustrated by comparing the actual population distribution in 1950 and a predicted 1950 distribution, based on extrapolating pre-war population growth trends from 1936 to 1950. The next section formalizes this recovery result via a regression analysis, which allows us to consider the statistical significance of our findings and incorporate various location characteristics as controls.

3.2 Regression Analysis of the Recovery of Central Hiroshima

We now analyze the magnitude of the recovery at the spatially granular level of blocks. Note that recovery implies that the set of blocks that lost more population due to the atomic bombing grew faster in the post-war period. We operationalize this idea with the following regression model:

$$\ln \left(\frac{\text{Popdens}_{i,t}}{\text{Popdens}_{i,1945}} \right) = \gamma \ln \left(\frac{\text{Popdens}_{i,1945}}{\text{Popdens}_{i,1936}} \right) + \eta X_i + v_i, \quad (1)$$

where i is the block, t is the post-war year, e.g. 1950, X_i is the vector of location characteristics, and v_i is the error term. We regress the post-war log change in population density on the log change in population density from 1936 to 1945, reflecting the damage from atomic bombing.¹⁸ The estimated coefficient γ represents the degree of recovery back to the pre-war city structure.¹⁹ If $\gamma = 0$, the population density lost during the war did not recover in the post-war period. This would imply that the shock of atomic bombing has permanent effects on the city population distribution. In contrast, if $\gamma = -1$, the lost population density completely recovered in the post-war period, so the shock had only temporary effects on population distribution. To check robustness, we also consider an alternative regression specification at the end of this section.

In some specifications we control for location characteristics X_i such as altitude and distance to bodies of water, allowing us to investigate how the degree of recovery γ changes after conditioning on location characteristics. We interpret these regressions as capturing the correlation between population density lost during the war and post-war population growth, either unconditional or conditional on location characteristics X_i . It does not necessarily have a causal interpretation.

Panel (a) of Figure 4 illustrates the relationship between the wartime and post-war population density growth rates for each block as of 1950, along with the regression line. The fitted line is somewhat less steep but already close to a slope of -1 , implying a strong resurgence among destroyed areas just five years after the bombing. Panel (b) of Figure 4 demonstrates that a similar result is obtained when examining the population distribution in 1960, suggesting that the recovery was essentially complete by 1950. Therefore, for brevity, we confine our regression analysis to the recovery from 1945 to 1950.

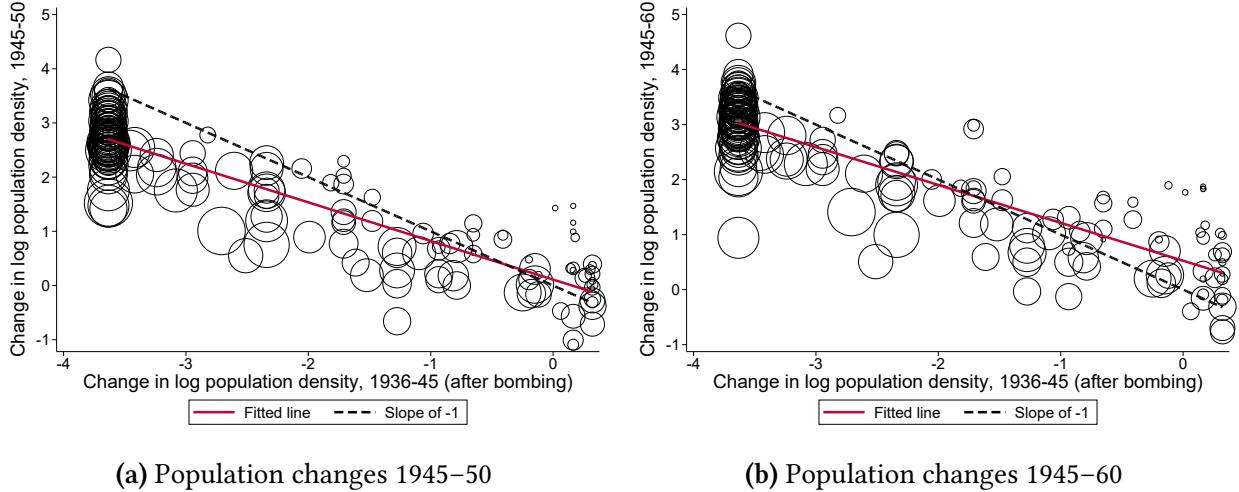
Column (1) of Table 1 provides the regression result for growth of population density in 1950, as depicted in Panel (a) of Figure 4. The coefficient is -0.712 , which is statistically distinguishable

¹⁸We use 1936 population density because it is the closest observation we have before 1945. In our data, population density in 1945 is measured in November 1945 and is positive for all blocks.

¹⁹Since we include a constant in X_i , γ is invariant to population level in year t . Put differently, the coefficient γ captures the degree of convergence to the pre-war population distribution, where the total city population is normalized to the pre-war one.

from zero and the null hypothesis of complete persistence is rejected.²⁰ Although we can also statistically reject the null hypothesis of purely temporary shocks ($\gamma = -1$), the results suggest a strong recovery within just five years.

Figure 4: Relationship between population changes from 1945–1950 and population changes due to the atomic bombing by block



Note: The figures plot changes in the log of population density from 1945 to 1950 or 1960 with those from 1936 to 1945, which are largely driven by the atomic bombing. Each circle represents a block, where the size of the circle is proportional to the population density in 1936. We plot the (unweighted) linear fit between these two variables (solid line) as well as a line of slope -1 (dashed line), which would be obtained if population changes from the bombing were completely reversed in the post-war period.

Accounting for Location Characteristics We have documented the quick recovery of Hiroshima’s city center. We now examine the extent to which the recovery of the city center can be explained by observed location characteristics that could directly affect amenities and productivity independently of the local density of economic activities, such as altitude and access to natural water.

Before proceeding with the regression analyses, we discuss heuristically why the locational advantage of central Hiroshima may not account for its resurgence. Following Krugman (1993), we consider two types of location characteristics: natural location characteristics (known as “first nature”) and built location characteristics (known as “second nature”). For the first, natural conditions within the city, such as altitude and distance to water, are homogeneous because our geographic scope is limited and most of the city lies within 6 kilometers of the city center.²¹ For

²⁰The spatial autocorrelation of error terms is unlikely to affect this conclusion. First, using Conley’s (1999) standard error to accommodate the spatial autocorrelation within 1 kilometer of each observation does not alter the statistical significance. Second, the residuals do not have a statistically significant correlation with distance from the CBD. Similarly, we also find that the potential spatial autocorrelation of errors would also be inconsequential after controlling for location characteristics.

²¹In particular, the majority of Hiroshima is located in the delta of the *Ota* river, characterized by flat terrain with

Table 1: Change in population density and war-time damage

	(1)	(2)	(3)	(4)	(5)	(6)
Change in log population density 1945–1950						
Change in log population density 1936–1945 (γ)	-0.7124 ^a (0.0271)	-0.7443 ^a (0.0343)	-0.8004 ^a (0.0424)	-0.8383 ^a (0.0560)	-0.8307 ^a (0.0533)	-0.9034 ^a (0.0465)
<i>p</i> -value from testing $\gamma = -1$	0.000	0.000	0.000	0.004	0.002	0.040
Natural location characteristics (first nature)		Yes		Yes	Yes	Yes
Built location characteristics (second nature)			Yes	Yes	Yes	Yes
Pre-war trends in population					Yes	
Within 3 km of the city center						Yes
Number of blocks	174	174	174	174	174	158
R-squared	0.809	0.828	0.823	0.846	0.848	0.859

Note: We report the OLS estimates of equation (1). Natural location characteristics consist of log distance to nearest water, altitude and its square, ground slope and its square, geographical coordinates (latitude, longitude, and their interaction), and a dummy for bad soil conditions. Built location characteristics consist of log distance to the nearest station, log distance to Hiroshima port (*Ujina* port), log distance to the nearest cultural asset, and the initial housing stock condition (the fraction of moderately-destroyed or intact buildings). In column 5, we also control for the pre-war (1933–1936) population growth rate and its square. In column 6, we confine the sample to blocks within 3 kilometers of the city center. We report the *p*-value from testing the null $\gamma = -1$, meaning that the population density converged back to the 1936 city structure. Heteroskedasticity-robust standard errors in parentheses. ^a indicates significance at the 1 percent level.

the second, the built advantages of central Hiroshima were substantially damaged by the bombing. The city center of Hiroshima, areas around *Hachibori* and *Kamiya-cho*, is located next to Hiroshima castle, a historical amenity which had been a symbol of the city since the samurai period. The center was also adjacent to the former center, called *Nakajima-cho*, which developed during the samurai period due to its convenient access to the castle and water transportation. These advantages were lost following the bombing. Hiroshima castle was completely destroyed as was *Nakajima-cho*. Although the city center may have retained some transportation advantage, jobs and other economic amenities would have been eliminated as central neighborhoods were completely destroyed and other areas of the city likely enjoyed better conditions after the bombing, as can be seen in other Japanese cities.²²

We now use our regression model (1) to formally assess the role of locational advantages. Specifically, we control for the observable characteristics of each block. If the recovery were primarily driven by the attractive location characteristics of the destroyed areas, then γ would approach zero, such that the recovery tendency is no longer observed after conditioning on these

loose soil. The flat terrain was an important reason why the US chose Hiroshima as the target of the bombing (see footnote 6). Moreover, much of the city close to water, as the city is cut through by many branches of the *Ota* and faces the sea to the south.

²²The areas around Hiroshima station also provided convenient access to transportation but experienced much less destruction from the bombing, which could have made Hiroshima station the potential new center of Hiroshima. In Japan, some large cities did see their centers shift after the war (e.g., Yokohama, Kobe). In Yokohama, [Takano \(2023\)](#) documents that the city center moved to an area with transportation advantages after the requisition of the former city center by the U.S. Army for nearly ten years.

location characteristics. For natural location characteristics, we control for distance to nearest water, altitude and ruggedness, an indicator of bad soil conditions, and geographic coordinates.²³ As built location characteristics that can be considered as given right after the bombing, we control for distance to the nearest train station as of 1950, distance to Hiroshima port, distance to the nearest cultural asset, and the quality of housing stock after the bombing.²⁴

Columns (2)–(4) of Table 1 present the regression results when controlling for location characteristics. Column (2) controls for natural conditions. We find that natural characteristics do not account for the recovery as the coefficient γ actually moves closer to negative one. Column (3) controls for built conditions, again finding that γ gets closer to negative one relative to Column (1). In Column (4) we control for both natural and built location characteristics. We estimate $\gamma = -0.83$, which is even closer to negative one. This conclusion remains in Column (5) when controlling for pre-war trends in population. Note that in Columns (1)–(5), we can also reject the null of perfect path independence ($\gamma = -1$), meaning that the post-war city structure is somewhat different from the pre-war one. Nevertheless, we consistently find γ closer to negative one than zero, meaning that the city structure exhibited a strong recovery tendency. Moreover, observed location characteristics do not explain the recovery, as the degree of recovery γ becomes stronger after conditioning on observed location characteristics.

Column (6) of Table 1 replicates Column (4) while restricting our sample to blocks within 3 kilometers of the city center. Within such a small area, it is harder to attribute the recovery of the destroyed areas to unobserved fundamentals because location characteristics are likely more homogeneous.²⁵ Even within such a small homogeneous sample, we find that γ gets even closer to negative one relative to Column (4). This result suggests that unobserved location advantages of the destroyed areas may not be the main driver of the recovery. Taken together, our results suggest that the recovery was not driven by advantageous location characteristics of the destroyed areas.

Testing Recovery via Alternative Specification Besides our main specification (1), we use an alternative regression specification where we regress the logarithm of population density in 1950 on the logarithm of population density in 1936 and 1945 and observed location characteristics:

$$\ln \text{Popdens}_{i,t} = \eta X_i + \gamma_1 \ln \text{Popdens}_{i,1945} + \gamma_2 \ln \text{Popdens}_{i,1936} + v_i \quad (2)$$

²³Note that considering potential radioactive contamination would, if anything, reinforce the main finding of our reduced-form analysis that the city center recovered. Since radioactive contamination is a "bad" that makes the city center less attractive, failing to control for it would underestimate the strength of the recovery.

²⁴We measure the quality of housing stock by the fraction of moderately destroyed or intact buildings. As an additional control for housing conditions, we use the number of public housing units constructed between 1945 and 1950 in a robustness check. This has little impact on the regression results (see Appendix B.2 for details).

²⁵Table A.2 in the Appendix suggests that the standard deviations of observed location characteristics are smaller for blocks within 3 kilometers of the city center. A similar idea has been invoked in Schumann (2014) in a different context.

This alternative specification allows us to address two concerns.²⁶ First, measurement error in the 1945 population may introduce a negative bias into the coefficient γ in equation (1). Specifically, a positive measurement error reduces the outcome variable while increasing the explanatory variable in equation (1), but not in equation (2). Second, by regressing the 1950 population density on location fundamentals (X_i) exclusively, we can determine the extent to which city structure can be explained by location fundamentals. If fundamentals account for most of the variation in population density within a city, then the recovery tendency we found in Table 1 may not be economically important, and vice versa.

Table B.1 in the Appendix presents the results of estimating (2). Columns (1)–(3) of Table B.1 address the first concern of measurement error. We find that the 1936 population density, i.e. the pre-war city structure, is much more strongly associated with the 1950 population density than the 1945 population density, immediately after the bombing. Notably, the 1945 density is no longer significant when built location characteristics are controlled for. As in Column (6) of Table 1, Column (4) of Table B.1 restricts the sample to areas within 3 kilometers of the CBD to limit heterogeneity in location fundamentals. Reassuringly, the above conclusion remains valid in Column (4). Overall, the findings in Table 1 are robust to this alternative specification, and the city structure exhibits a strong recovery tendency.

Next, in Columns (5) and (6), we regress the 1950 population density solely on location fundamentals to determine the extent to which they account for the city structure. While there is some evidence suggesting a correlation between distance to nearest station and water and lower population density, the ability of the specification containing only fundamentals to explain population density is substantially worse than that of our baseline specifications in Columns (3) and (4), which include 1936 and 1945 population density.²⁷ Therefore, the city structure tends to recover to the pre-war city structure, above and beyond the tendency that blocks with advantageous location fundamentals achieve higher population density. This result aligns with our conclusion drawn from Table 1, which suggests that the recovery was not primarily due to advantageous location fundamentals and that other forces likely induced the recovery.

3.3 *Robustness*

We provide further reduced-form evidence on the recovery of the city center by exploiting other information and specifications. In addition, we show that recovery to the pre-war city structure was also observed in Nagasaki, the second city hit by atomic bombing, and discuss the implications. The results are in Appendix B.

²⁶This specification is equivalent to (1) if we impose that the sum of two coefficients ($\gamma_1 + \gamma_2$) equals one.

²⁷Indeed, the R-squared of Columns (3) and (4) is substantially larger than that of Columns (5) and (6)

Recovery of Employment Distribution In Section B.2 of the Appendix we analyze the impact of the atomic bombing on the distribution of employment. We find that the regression results are very similar to those in Table 1 for the population distribution. Recovery occurred not only for the residential population but also in the spatial distribution of commercial activity.

Recovery of Land Price Distribution While we do not have comprehensive land price data during our sample period, we are able to measure the location with the highest land price in the city, which could be interpreted as the center of the city. In both 1931 and 1959, the highest land price was observed near *Hacchobori*, the city center both before and after the war.²⁸ Thus, the resurgence of central Hiroshima is also observed in land prices.

Characteristics of Neighboring Blocks In Section B.2 of the Appendix, we consider the possibility that the post-war population growth rate of a block may depend not only on its own characteristics, but also on the characteristics of neighboring blocks. To consider the characteristics of neighbors, we adopt the so-called “SLX model” from the spatial econometrics literature (Halleck Vega and Elhorst 2015) and add spatial lags of the following three neighborhood characteristics to our main regression (1): (i) the log change in population induced by the bombing; (ii) the location characteristics; and (iii) the population distribution right after the war, which is meant to capture market access after the bombing.²⁹ Table B.3 shows that including these spatial lag variables has only a modest impact on our regression results.

The Recovery of Nagasaki In Section B.3 of the Appendix we examine population data for Nagasaki, the second city destroyed by an atomic bomb. As in Hiroshima, the damage in Nagasaki was catastrophic: around 70,000 people were killed and almost all buildings within 2 kilometers of the epicenter were wholly destroyed (Nagasaki City Government 1977). However, in Nagasaki, the atomic bomb hit the outskirts of the city (see Figure B.1a). This is in contrast to Hiroshima, where the atomic bomb hit the city center.³⁰ Despite this difference, recovery to the pre-war city structure was also observed in Nagasaki. Figure B.1b shows a fitted line from estimating equation (1) for Nagasaki. Our coefficient of interest is around -0.88 and statistically indistinguishable from -1, suggesting the complete recovery of the population distribution in Nagasaki. This similar pattern of recovery in Nagasaki offers two additional implications. First, it bolsters the external

²⁸The block containing the plot with the highest land price is the *Horikawa-cho* block adjacent to the *Hacchobori* block. Other available evidence on pre-war land prices suggests a similar conclusion (Nozawa 1934; Hayakawa and Nakaouji 1965).

²⁹In particular, the market access term addresses the possibility that the city center could recover as the “donut hole of the city”: it might still have relatively good market access thanks to its central location despite its destruction.

³⁰Nagasaki was selected by historical coincidence. The US initially intended to bomb Kokura, but changed to the city center of Nagasaki due to weather conditions. The weather conditions also prevented an attack on the city center of Nagasaki, and consequently the bomb was dropped on the outskirts of Nagasaki. See <https://www.peace-nagasaki.go.jp/abombrecords/b020101.html> (last accessed on October 28, 2023).

validity of our Hiroshima recovery result. Second, it may limit the importance of potentially lower development costs on large empty plots or creative destruction in our context because the center of economic activities could have shifted toward the completely destroyed periphery of Nagasaki if these factors had been crucial, but we do not find such a shift.³¹

Summary of Reduced-form Analysis Taken together, our reduced-form analysis has revealed that (i) the population distribution in the city recovered back to its pre-war state within five years after the bombing, and (ii) the recovery was not driven by the prominent location characteristics we have controlled for. There are two possible explanations for these findings. First, there could be some unobserved locational advantages in the destroyed city center that persisted through the bombing (e.g., scenic views). Second, people may have expected the recovery of the destroyed city center when making location choices, and the incentive to again live and work in the city center came from agglomeration forces due to expected high density as in the pre-war period. To analyze these possibilities, we develop and calibrate a quantitative spatial model that incorporates both agglomeration forces and unobserved location characteristics as potential explanations for the recovery.

4 Theoretical Framework

In this section we present a dynamic quantitative spatial model to understand the mechanisms of the recovery. To account for the impact of the atomic bombing on the dynamics of internal city structure during the recovery, the model incorporates forward-looking location choice, migration frictions, commuting, agglomeration forces, and heterogeneous location fundamentals.

First, individuals make decisions about their residence and workplace subject to migration frictions. They do so taking into account continuation values, defined by the expected future value of living and working in their chosen locations. Second, their residence and workplace are potentially different, which defines the equilibrium commuting patterns within the city. Finally, locations differ in productivity and amenities that are determined by both agglomeration forces and location fundamentals. Our model is the first tractable dynamic quantitative model of internal city structure that possesses these elements in a unified framework. Appendix C provides the details of the derivations.

Time is discrete and indexed by t . We consider a single city (Hiroshima City) embedded in a large economy (Hiroshima Prefecture or Japan). The city consists of a discrete set of locations rep-

³¹The limited importance of large empty lots or creative destruction in our context may be due to construction technology. While the demolition of old buildings facilitates high-rise buildings by providing a large vacant lot and may enhance productivity (Hornbeck and Keniston 2017), Japanese technology for high-rise buildings right after WWII was relatively limited and the shortage of construction materials made high-rise buildings even more unavailable (Hiroshima City Government 1971).

resented by \mathcal{C} . We typically use subscripts n and n' to refer to the place of residence of a worker and subscript i and i' to refer to their place of work. The number of locations in the city $N = |\mathcal{C}|$ is fixed over time. The city is located within a larger economy that is modelled as a single location, denoted by o . Locations in the city correspond to blocks and are differentiated by fundamental productivity, amenities, land endowments, and geography. Fundamental productivity and amenities capture exogenous locational advantages for production and residence, respectively, and can change over time. The land endowment of each block is constant over time.

Individuals in the economy live for a finite time, T . The mass of the population in the larger economy is denoted by M and is exogenous. While we assume that M is time-invariant, the total population of the city changes over time through migration flows. This allows us to focus on the distribution of individuals within the city. Individuals are endowed with one unit of labor that is supplied inelastically and they are geographically mobile across locations in a city. They commute from their residential block to their workplace block subject to commuting costs. Individuals outside the city (o) are prohibited from commuting into the city for work. Production occurs in every location in the economy and firms produce a homogeneous final good that can be freely traded across locations. In each period, an individual may receive an opportunity to change their residence and workplace. Individuals receive such an opportunity with some exogenous probability. Given an opportunity to change locations, individuals choose their locations in a forward-looking way, taking into account the expected future values of living and working in particular locations. These forward-looking location choices allow us to characterize the transitions of the population and employment distributions in the city, which depend on agents' expectations about the future.

4.1 *Production*

Firms in the economy are competitive and produce a homogeneous final good. The production technology of a representative firm in location $i \in \mathcal{C}$ is:

$$Y_{it} = A_{it} L_{it}, \quad (3)$$

where Y_{it} is production in location i , A_{it} is productivity and L_{it} is employment in location i at time t . Productivity (A_{it}) is determined by fundamental productivity and employment density in the location:

$$A_{it} = a_{it} \left(\frac{L_{it}}{S_i} \right)^\alpha, \quad (4)$$

where a_{it} represents the exogenous component of productivity and S_i is the area size of location i that is time-invariant. The parameter α controls the contemporaneous productivity agglomeration forces with respect to employment density, and a positive value of α implies higher employment

density increases productivity.³²

The homogeneous good is freely traded and chosen as the numeraire.³³ The zero-profit condition implies that the wage rate at location i in period t is $w_{it} = A_{it}$. Therefore, the wage rate in any particular location is a function of exogenous productivity and employment density in that location.³⁴

4.2 Preferences

Individuals live for finite periods, consume only a homogeneous tradable good, and inelastically supply one unit of labor. Individuals are hand-to-mouth, always spending their wage w_{it} in period t . Their period utility from living in location n and working in location i at period t is:

$$\ln u_{int} = \ln B_{nt} + \ln w_{it} - \ln \kappa_{int}, \quad (5)$$

where B_{nt} is the common utility benefit from residential amenities at residential place n in period t , w_{it} is labor earnings in workplace i , and κ_{int} is the utility cost due to commuting from n to i .

The value of amenities in a residential place (B_{nt}) depends on the fundamental value of amenities and population density:

$$B_{nt} = b_{nt} \left(\frac{R_{nt}}{S_n} \right)^\beta, \quad (6)$$

where b_{nt} is an exogenous component in the value of amenities for each location and R_{nt} is the population of location n in period t . In this specification, the elasticity of amenities with respect to population density (β) captures the strength of the net agglomeration effect in a residential place. Specifically, we capture net residential agglomeration forces through housing prices and consumption amenities. In Appendix C.5, we provide a microfoundation for this specification.³⁵

Outside of the city (o), individuals receive common utility u_{ot} in period t , which is exogenous in every period. Because u_{ot} governs the attractiveness of living in Hiroshima City relative to the outside economy, it captures aggregate shocks that affect the whole city of Hiroshima.

³²This is in line with numerous empirical findings (Ciccone and Hall 1996; Arzaghi and Henderson 2008) and microfounded by different mechanisms in agglomeration economies (Duranton and Puga 2004). In addition, this may also reflect congestion forces from land prices that are increasing in density. We do not explicitly include land in production for simplicity, as we do not observe block-level land prices in the data.

³³We can incorporate block-specific costs of transporting the homogeneous good to the outside world. Suppose that the numeraire produced in block i is exported to the outside world subject to iceberg trade cost: $\tau_i \geq 1$ units of goods must be shipped to sell one unit. This is isomorphic to the case with productivity A_{it}/τ_i in our model.

³⁴Given the linear technology and perfect competition, producers always earn zero profit. Thus, considering dynamic incentives does not change our arguments as long as firms correctly expect that future profits will always be zero. In addition, no firm has an incentive to enter or exit in any location.

³⁵We do not explicitly model consumption of land for simplicity since we do not observe block-level land prices in the data.

4.3 Forward-looking Location Choices

Workers are forward-looking in making migration decisions subject to the exogenous migration frictions. At the end of period t , share $\theta_t \in (0, 1)$ of workers in the economy can change their locations and share $1 - \theta_t$ of workers will remain in their current locations next period $t + 1$. If $\theta_t = 1$, all workers are able to change their location pairs. A low value of θ_t leads to stickiness in workers' location decisions.³⁶ Intuitively, due to the high fixed cost of moving, migration happens when an exogenous event arrives, such as job loss or life-cycle shocks. θ_t is interpreted as the probability of experiencing such an event.

When a worker obtains the opportunity to change their locations at the end of period t , they draw idiosyncratic shocks related to location choice in period $t + 1$. For an individual worker, the idiosyncratic shock is independently drawn from a time-invariant independent Type-I extreme distribution $F(\varepsilon) = \exp(-\exp(-(\varepsilon + \Gamma)))$ where Γ is the Euler-Mascheroni constant. At the end of period t , workers decide their residence and workplace for the next period considering the option value $\{V_{int+1}\}$ associated with each workplace and residence pair.

Consider a worker ω living in n and working in i at period t . When the worker can move to a different location pair next period, they solve the following location choice problem:

$$v_{int}(\omega) = \ln u_{int} + \max \{ \rho V_{i'n't+1} + \sigma \varepsilon_{i'n't+1}; \rho V_{ot+1} + \sigma \varepsilon_{ot+1} \} \quad (7)$$

for $t = 1, 2, \dots, T - 1$. $V_{i'n't+1}$ refers to the value function implied by choosing a different residence n' and workplace i' in period $t + 1$ and V_{ot+1} is the option value of choosing to live outside the city. $\rho \in (0, 1)$ is the discount factor governing the importance of the future values and σ is a positive constant governing the variance of the idiosyncratic shocks. An individual makes a forward-looking migration choice of residence and workplace at $t + 1$ given a path of the exogenous and endogenous variables. In particular, an individual correctly anticipates the path of the population distribution (R_{nt}) and employment distribution (L_{it}) that are endogenously determined in equilibrium. As we focus on migration within a city, we assume away bilateral mobility costs as they are likely sufficiently small and homogeneous relative to inter-city migration costs.³⁷

With the idiosyncratic shocks following a Type-I extreme value distribution and migration frictions, we can express the option value of living in n and working in i in period t by:

$$V_{int} = \ln u_{int} + (1 - \theta_{t+1})\rho V_{int+1} + \theta_{t+1}\sigma \ln \left[\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \exp(\rho V_{i'n't+1})^{1/\sigma} + \exp(\rho V_{ot+1})^{1/\sigma} \right], \quad (8)$$

³⁶This Calvo-style migration friction is also adopted in other recent quantitative spatial models to capture the persistence of migration decisions (Caliendo, Dvorkin, and Parro 2019 Section 5.3; Heblitch, Trew, and Zylberberg 2021). This approach is attractive in a setting such as ours in which bilateral migration flows are unobserved.

³⁷Unlike Caliendo, Dvorkin, and Parro (2019) we do not observe bilateral migration flows. This is likely inconsequential as Gechter and Tsivanidis (2023) estimates that in a within-city setting, the fixed cost of moving is substantially larger than the moving cost that increases with moving distance.

for $t = 1, 2, \dots, T - 1$. The first term is the current utility from residence n and workplace i . The second term is the expected value of staying at the same location pair next period when no migration opportunity realizes, with probability $1 - \theta_{t+1}$. The third term is the expected value when a worker is able to change their location pair, with probability θ_{t+1} .

For workers residing outside of the city, their option value for $t = 1, 2, \dots, T - 1$ is:

$$V_{ot} = \ln u_{ot} + (1 - \theta_{t+1})\rho V_{ot+1} + \theta_{t+1}\sigma \ln \left[\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \exp(\rho V_{i'n't+1})^{1/\sigma} + \exp(\rho V_{ot+1})^{1/\sigma} \right]. \quad (9)$$

When workers have an opportunity to migrate, they can choose any location pair. Therefore the last term in the value function is the same as in equation (8). For the last period $t = T$, equations (8) and (9) are written as $V_{inT} = \ln u_{inT}$ and $V_{oT} = \ln u_{oT}$ because future considerations are absent.

Using our assumption that the idiosyncratic shocks are independent and follow a type-I extreme value distribution $F(\varepsilon)$, we derive the share of workers that live in n and work in i in the next period $t + 1$ when they have a migration opportunity:

$$\lambda_{int+1} = \frac{\exp(V_{int+1})^{\rho/\sigma}}{\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \exp(V_{i'n't+1})^{\rho/\sigma} + \exp(V_{ot+1})^{\rho/\sigma}}, \quad i, n \in \mathcal{C}. \quad (10)$$

This probability λ_{int+1} characterizes the location dynamics of workers in the city for period $t + 1$. Workers choose their pair of residence and workplace, correctly anticipating future changes in commuting costs, wages, and residential amenities. Since there is no residence-workplace specific migration cost, equation (10) applies to all workers with a migration opportunity in period t . In addition, the share of workers that live outside of the city in period $t + 1$ conditional on being able to change their location pair is given by probability $\lambda_{ot+1} = 1 - \sum_{i \in \mathcal{C}} \sum_{n \in \mathcal{C}} \lambda_{int+1}$.

Using these choice probabilities for workers, we can express the mass of workers in the city who live in n and work in i in period $t + 1$ as:

$$L_{int+1} = (1 - \theta_{t+1})L_{int} + \theta_{t+1}\lambda_{int+1}M. \quad (11)$$

This is the number of commuters within the city. On the right-hand side, the first term is equal to the number of commuters who retain the same workplace and residence from the last period, and the second term is the total number of workers who either move in from outside of the city or change location pairs within the city. Since the commuting market clears, the mass of workers in workplace i becomes:

$$L_{it+1} = (1 - \theta_{t+1})L_{it} + \theta_{t+1} \left[\sum_{n \in \mathcal{C}} \lambda_{int+1} \right] M, \quad (12)$$

where the mass of workers in workplace i is the sum of workers who have no opportunity to change locations and those who join workplace i in period t . Analogously, the mass of workers residing in n becomes:

$$R_{nt+1} = (1 - \theta_{t+1})R_{nt} + \theta_{t+1} \left[\sum_{i \in \mathcal{C}} \lambda_{int+1} \right] M. \quad (13)$$

Lastly, the total population in the city in period $t + 1$ is given by $L_{t+1} = \sum_{i \in \mathcal{C}} \sum_{n \in \mathcal{C}} L_{int+1}$.

Conditional on the wage variation and exogenous location characteristics, the mobility of workers in our model is controlled by the parameter of Calvo-style stickiness θ_t and taste shocks σ . We emphasize that they have different interpretations. Calvo-style migration frictions capture the immobility of workers even if they would like to change their locations. Intuitively, this reflects any constraint that prevents workers from relocating. In contrast, the dispersion of taste shocks captures the individual valuation attached to the location pair and controls the degree of sorting in response to utility differences. In the present model, we introduce both migration frictions and idiosyncratic shocks to capture both mobility constraints and the sorting of workers into their residence and workplace choices. We discuss how we can identify these two parameters from the data in Subsection 5.1 below.

4.4 General Equilibrium

We now define a forward-looking competitive equilibrium in this economy. The economy starts with the initial distributions of population (R_{n0}) and employment (L_{i0}). The exogenous variables of the model are block-level fundamental productivity (a_{it}) and amenities (b_{nt}), the sizes of blocks (S_n), bilateral commuting costs (κ_{int}), the degree of worker location stickiness (θ_t) and utility outside the city (u_{ot}). The economy-wide parameters in the model are the agglomeration forces in productivity (α), agglomeration forces in amenities (β), the discount factor of workers (ρ), the variance of idiosyncratic shocks in location choices (σ) and the mass of workers in the economy (M). Then, a forward-looking equilibrium is defined as follows:

Definition 1. *Given the exogenous variables of the model and economy-wide parameters, a forward-looking equilibrium is characterized by the sequences of wages $\{w_{it}\}$, population $\{R_{nt}\}$, employment $\{L_{it}\}$, and value functions associated with location choices $\{V_{int}\}$ such that (i) the value functions of workers for their location choices $\{V_{int}, V_{ot}\}$ satisfy (8) and (9) with $V_{inT} = \ln u_{inT}$ and $V_{oT} = \ln u_{oT}$ for the last period T , (ii) the commuting market clears in the city and the masses of workers in workplace and residential locations are given by (12) and (13), and (iii) firms maximize their profits and the zero-profit condition leads to a wage rate equal to (4).*

Since productivity and amenities evolve with employment density and population density, we can summarize the forward-looking equilibrium by population, employment, and the value

function adjusted by the value of living outside of the city. Equations (4), (8), (9), (12), and (13) constitute $N^2 + 3N$ equations for each t , which can be solved for $N^2 + 3N$ endogenous variables for each t . Location choices are based on current real income but also the option values associated with each pair of locations, and they determine the future path of location choices taking into account future shocks.

We define a steady-state equilibrium for the economy as one where the population and employment distributions are constant. The steady state equilibrium in this economy exists and is unique when the net agglomeration forces are small for both productivity and amenities. We summarize these results in the following proposition:

Proposition 1. *(i) Given the initial state and exogenous factors, a forward-looking competitive equilibrium such that, for all periods $t = 1, 2, \dots, T$, $R_{nt} \geq (1 - \theta_t)R_{nt-1}$ and $L_{it} \geq (1 - \theta_t)L_{it-1}$, exists; (ii) A steady-state equilibrium exists when $\alpha \neq \sigma/\rho$ and $\beta \neq \sigma/\rho$; (iii) Sufficient conditions for the existence of a unique steady state are negative net agglomeration forces: $\alpha \leq 0$ and $\beta \leq 0$.*

Appendix C.3 provides the proof. While Proposition 1 (i) and (ii) show the existence of an equilibrium and a steady state, there may be multiple steady states and multiple equilibrium paths. Proposition 1 (iii) shows that the steady state is unique if agglomeration forces (α, β) are negative, which implies that the net dispersion forces dominate the agglomeration forces both in productivity and amenities. In this case, the economy will converge to this unique steady state in the long run, although there could be multiple paths toward the steady state. In other cases, there can be multiple steady states, which can happen when net agglomeration forces are positive according to Proposition 1 (iii). After a shock that affects the initial condition, both the initial conditions and expectations about the future distribution of population and employment matter in determining which steady state or path realizes (Krugman 1991; Matsuyama 1991).

In our calibration, we solve the model backward for the observed changes in population and employment. We do not require that the economy is exactly in the steady state in the last period T , but we assume that it is sufficiently close to the steady state so that the commuting gravity equation approximately holds, which we estimate in our calibration. Our calibration does not require the uniqueness of the steady state nor a unique path to the steady state because it relies only on the observed equilibrium. This feature allows us to calibrate the model when there are multiple steady states so that different expectations may lead to different steady states. When we undertake counterfactuals, we explicitly acknowledge the potential for multiple equilibria.

5 Quantitative Analysis

Our goal in this section is to show how the present model can be matched to the observations in Hiroshima. Our quantification proceeds in three steps which we discuss in turn. Appendix D

presents further details on the calibration.

In Subsection 5.1 we first obtain commuting costs (κ_{int}) by estimating a model of travel mode choice. Our model accommodates two aspects of migration frictions. We calibrate each using different information. The dispersion of idiosyncratic taste shocks (σ) is calibrated based on the calibrated discount factor (ρ) and the commuting elasticity (ρ/σ) estimated by a gravity equation for commuting. We infer the stickiness (θ_t) from additional data on the share of people who remain in the same residence over time. The outside utility (u_{ot}) is chosen to match the observed total population of the city.

Given the parameters, in Subsection 5.2, we leverage the structure of the model to back out the composites of amenities and productivity that rationalize the observed population and employment changes over time. Intuitively, changes in population and employment by block allow us to invert the option values associated with each location. These option values reflect the attractiveness of each location as a residence or workplace, which is a composite of location fundamentals and agglomeration forces.

In Subsection 5.3, we estimate the key parameters that govern the strength of the agglomeration forces in productivity (α) and amenities (β). We first recover the unobserved fundamentals in productivity and amenities based on the recovered option values and variations of population density and employment density over time. For these fundamentals, we then define the moment conditions and estimate the agglomeration force parameters. In the estimation, we use the location choice data from 1955 to 1975. In Subsection 5.4 we discuss the robustness of our estimated values for agglomeration forces.

Having fully quantified our model, in Subsection 5.5 we investigate how well our model fits the observed changes in population and employment distributions in the recovery period. To this end, we first use the location choice data for 1950, which is not used for calibration, to back out the locational advantages in the recovery period. We then decompose these advantages into two components: (i) advantages in productivity and amenities explained by the model, and (ii) structural residuals in productivity and amenities. We demonstrate that our model predicts the central recovery only with the first model-based component.

5.1 Step #1: Parameter Calibration ($\rho, \sigma, \kappa_{int}, \theta_t, u_{ot}$)

Travel mode choice and commuting costs (κ_{int}) To estimate commuting costs, we extend the model to incorporate choice of travel modes following Ahlfeldt et al. (2015) and Tsivanidis (2022). There are five modes of transportation: walk, bicycle, car, bus, and train. In each period, a worker chooses the mode of transportation that minimizes the realization of observed and idiosyncratic travel costs, given their workplace and residence. We assume that the idiosyncratic travel cost follows a Gumbel distribution with two nests: (i) public modes: walk, bus and train; and (ii)

private-vehicle modes: bicycle and car. We estimate this nested discrete choice model of travel mode by exploiting the 1987 Hiroshima City Person Trip Survey and compute the expected commuting cost for two types of workers who may or may not use cars.³⁸ We then estimate the overall expected travel cost for residence n and workplace i before the realization of the idiosyncratic travel costs, using information on the car ownership rate in Japan in different years. We discuss the details in Appendix D.1.

Commuting gravity (ρ/σ) We suppose that the economy approximately reaches a steady state in the last period and estimate the commuting elasticity of workers using the 1987 Hiroshima City Person Trip Survey.³⁹ Plugging the average commuting time in 1987 from above into the equilibrium commuting pattern in the steady state yields the gravity equation:

$$\ln L_{in} = -\frac{\rho}{\sigma} \bar{c}_{in} + \phi_i + \eta_n + \chi, \quad (14)$$

where \bar{c}_{in} is the log bilateral commuting costs determined by travel time, ϕ_i and η_n are workplace and residence indicators and χ is a constant. ρ/σ corresponds to the commuting elasticity with respect to commuting cost in our model, which is decreasing in σ (the dispersion parameter of the idiosyncratic shock) and increasing in ρ (the discount factor). Lower σ and higher ρ imply a higher sensitivity of migration decisions to utility differentials. We estimate (14) using Pseudo-Poisson Maximum Likelihood to allow for heteroskedasticity and zero bilateral commuting flows for some pairs. Our baseline parameter estimate of ρ/σ is 8.019, which is close to estimates of the elasticity of commuting flows with respect to commuting costs in Dingel and Tintelnot (2020). In the following, we set ρ/σ to be 8 for all t . See Appendix D.1 for the detailed estimation results.

Discount factor (ρ) We assume that the annual discount rate is 8.5 percent. This value is consistent with the discount rate widely used in the context of developing countries (e.g., Garcia-Cicco, Pancrazi, and Uribe 2010), which is consistent with the relatively low GDP per capita of Japan right after the war.⁴⁰ Since one period in our calibration corresponds to five years, we set $\rho = (1/1.085)^5 \simeq 0.66$.

Migration frictions (θ_t) Individuals can change their residence and workplace in period t with probability θ_t . We assume that people change their residence when obtaining a migration opportunity and match this migration friction parameter to the probability that people change their residence during five years, the length of one period in calibration. The 1960 Population Census reports that around 86 percent of people stayed in the same residence from the prior year. Thus, we set the parameter $\theta_t = 1 - (0.86)^5 \simeq 0.53$ for all $t \geq 1955$.⁴¹

³⁸When a car is unavailable, the nest of private vehicle modes is reduced to a single choice (bicycle).

³⁹Alternatively, we can suppose that individuals can always migrate ($\theta_t = 1$) after the last period.

⁴⁰Japan's GDP per capita in 1950 was less than one-fifth that of the U.S.

⁴¹Although in a different context, this value is very close to the value used in Hebllich, Trew, and Zylberberg (2021).

Utility outside the city (u_{ot}) We set the outside utility (u_{ot}) for each period to match the total population of Hiroshima City. Formally, we choose the outside value to match the observed total population in the city, \mathbb{M}_t . The model predicted population of the city is $(1 - \lambda_{ot})M = \mathbb{M}_t$, where λ_{ot} is the probability of choosing to live and work outside the city computed in the model. Since location choice is independent of the outside utility conditional on living in the city, the value of the outside option only affects the total population of Hiroshima in our model so we can focus on analyzing the internal city structure.

5.2 Step #2: Inversion of the Option Values

When individuals are forward-looking, their location choices depend on current real income and the option value associated with each location. In this step, we back out the option values by leveraging the population and employment dynamics of the model. Specifically, for $t = 1, 2, \dots, T - 1$, the option value of location n as a residential place can be summarized by the continuation value of amenities in the location:

$$\Xi_{nt} = b_{nt} \left(\frac{R_{nt}}{S_n} \right)^\beta \prod_{\tau=t+1}^T \left[b_{n\tau} \left(\frac{R_{n\tau}}{S_n} \right)^\beta \right]^{\prod_{s=t+1}^{\tau} \rho_s (1 - \theta_s)}. \quad (15)$$

Analogously, the option value of location i as a workplace can be written as:

$$\Omega_{it} = a_{it} \left(\frac{L_{it}}{S_i} \right)^\alpha \prod_{\tau=t+1}^T \left[a_{i\tau} \left(\frac{L_{i\tau}}{S_i} \right)^\alpha \right]^{\prod_{s=t+1}^{\tau} \rho_s (1 - \theta_s)}. \quad (16)$$

These option values express the attractiveness of each location as a residence and workplace. They are a composite of amenities and productivity that include both fundamental amenities (b_{nt}) and productivity (a_{it}), and the agglomeration forces from future population and employment density.

When $\theta_t = 1$, all workers can change locations every period and therefore the future values of their choices are independent of current location choices. In contrast, rare migration opportunities (small θ_t) lead to more weight placed on the future evolution of amenities and productivity since workers are less likely to change their locations. In sum, these option values reflect the value of amenities and productivity for each location when workers choose locations in a forward-looking way.

Equations (12) and (13) imply that the option values (Ξ_{nt}, Ω_{it}) satisfy the following equations:

$$\begin{aligned} R_{nt} - (1 - \theta_t)R_{nt-1} &= \sum_{i \in \mathcal{C}} \frac{K_{int}\Xi_{nt}^{\rho/\sigma}}{\sum_{n' \in \mathcal{C}} K_{in't}\Xi_{n't}^{\rho/\sigma}} (L_{it} - (1 - \theta_t)L_{it-1}), \\ L_{it} - (1 - \theta_t)L_{it-1} &= \sum_{n \in \mathcal{C}} \frac{K_{int}\Omega_{it}^{\rho/\sigma}}{\sum_{i' \in \mathcal{C}} K_{i'nt}\Omega_{i't}^{\rho/\sigma}} (R_{nt} - (1 - \theta_t)R_{nt-1}), \end{aligned} \quad (17)$$

where K_{int} summarizes current and future commuting costs (see equation D.3 in the Appendix for the definition). Intuitively, equation (17) states that the number of residents that actively choose to live in block n for period t ($R_{nt} - (1 - \theta_t)R_{nt-1}$) is written as the sum of the products of the number of workers that actively choose to work in block i for period t ($L_{it} - (1 - \theta_t)L_{it-1}$) and their conditional residential choice probabilities for location n ($K_{int}\Xi_{nt}^{\rho/\sigma}/(\sum_{n' \in C} K_{in't}\Xi_{n't}^{\rho/\sigma})$).

We solve the system of equations (17) for the option values (Ξ_{nt}, Ω_{it}) conditional on observed population (R_{nt}), employment (L_{it}), commuting costs (K_{int}), and migration frictions (θ_t).⁴² We can recover unique (Ξ_{nt}, Ω_{it}) that rationalize the observed changes in the mass of workers without using any information on the unobserved characteristics and without making assumptions about the strength of agglomeration forces.

5.3 Step #3: Estimation of Agglomeration Parameters (α, β)

Next, we back out fundamental productivity (a_{it}) and amenities (b_{nt}) by using observed employment and population density, according to the inverted option values (Ξ_{nt}, Ω_{it}) . Given the agglomeration forces (α, β) , we use (15) and (16) to derive the fundamentals by location for each period $t = 1955, 1960, \dots, 1975$. Then, we assume that fundamental productivity and amenities consist of location-fixed components $(\{a_i^F\}, \{b_n^F\})$, time-trend components $(\{a_t^*\}, \{b_t^*\})$, and time-varying errors $(\{a_{it}^{\text{Var}}\}, \{b_{nt}^{\text{Var}}\})$:

$$\ln a_{it} = \ln a_i^F + \ln a_t^* + \ln a_{it}^{\text{Var}}, \quad \ln b_{nt} = \ln b_n^F + \ln b_t^* + \ln b_{nt}^{\text{Var}}. \quad (18)$$

The location-specific productivity and amenities capture the fundamental advantages of locations and the trends of productivity and amenities reflect the change in their levels over time within the city. $(\{a_{it}^{\text{Var}}\}, \{b_{nt}^{\text{Var}}\})$ are the structural residuals in our model that allow us to perfectly match the observed population and employment distributions.

Averaging out the trend terms and taking differences between two consecutive periods, we have:

$$\Delta \ln \left(\frac{a_{it}}{\tilde{a}_t} \right) = \Delta \ln \left(\frac{a_{it}^{\text{Var}}}{\tilde{a}_t^{\text{Var}}} \right), \quad \Delta \ln \left(\frac{b_{nt}}{\tilde{b}_t} \right) = \Delta \ln \left(\frac{b_{nt}^{\text{Var}}}{\tilde{b}_t^{\text{Var}}} \right), \quad (19)$$

where we denote the geometric mean across locations as $\tilde{a}_t = \exp(\frac{1}{N} \sum_{i \in C} \ln a_{it})$.

The structural residuals of productivity and amenities in (19) difference out both common trends across all blocks in the city in each year and time-invariant locational advantages. Using

⁴²The solution is up to scale because equations (17) exploit only information on the relative migration probabilities across blocks within the city. Since we take the total population of Hiroshima City from the data and assume that the outside utility (u_{ot}) adjusts to rationalize it (see Subsection 5.1), we do not need to determine the absolute levels of $\{\Xi_{nt}\}$ and $\{\Omega_{it}\}$ governing migration between Hiroshima City and the outside world. We normalize the geometric mean of $\{\Xi_{nt}\}$ and $\{\Omega_{it}\}$ to one.

(19), we consider the following moment conditions:

$$\begin{aligned}\mathbb{E}[\Delta \ln(a_{it}/\tilde{a}_t) \times \mathbb{1}_i(k)] &= 0, \\ \mathbb{E}[\Delta \ln(b_{nt}/\tilde{b}_t) \times \mathbb{1}_n(k)] &= 0,\end{aligned}\tag{20}$$

where $\mathbb{1}_n(k)$ is an indicator such that location n is in grid k , where the grid is defined based on the distance from the CBD. We define five grid cells based on the distance from the CBD and equally allocate blocks into these grid cells in our baseline specification.⁴³ We use the moment conditions (20) to estimate the parameters for agglomeration forces.

Our identification assumption for using the moment conditions (20) is that log changes in the idiosyncratic fundamental productivity and amenities terms are not correlated with distance from the city center. In other words, the systematic change in the gradient of economic activity relative to the distance from the CBD is explained, on average, by the mechanisms of the model rather than by systematic changes in the pattern of structural residuals (19). This identification assumption seems plausible in post-recovery Hiroshima because the spatial extent of our study is small and all blocks in the data experienced similar changes in the economic and political environment.⁴⁴

We assess the validity of our moment conditions in the following two ways. First, to confirm that changes in fundamental amenities and productivity are not correlated with distance from the city center, we plot them against the distance from the city center. Figure D.2 plots the changes during our estimation sample period (1955–1975) and Figure D.3 plots the changes for the period 1950–1955, which are not used for our estimation. In both figures, the moment conditions appear plausible as the changes are generally independent of the distance from the CBD. Second, since the fundamental amenities and productivity are likely to be more homogeneous within a small geographic area, we also estimate the set of parameters using only blocks within 3 kilometers of the CBD. In particular, this addresses the potential concern of post-recovery suburbanization driven by systematic increases in attractiveness for either production or residence further away from the CBD.⁴⁵

Table 2 reports the estimation results using the two-step generalized method of moments (GMM). Columns (1) and (2) report our baseline estimates of the agglomeration parameters for productivity (α) and amenities (β), respectively. Overall productivity (A_{it}) in the workplace rises by around 19 percent when current employment density doubles. Turning to amenities, doubling population density is associated with an 18 percent increase in the value of amenities. In Columns

⁴³We carry out a robustness check for the sensitivity of estimates to the number of grid cells (using ten cells). See Table D.2 in Appendix D.5.

⁴⁴The effect of radioactivity faded away quickly (see Section 2.1), and hence is unimportant for changes in amenities and productivity, as our estimation data start in 1955.

⁴⁵We also show that fundamental productivity and amenities were not dramatically changed by the atomic bombing by comparing the 1930s and 1975. We assume that the population distribution in 1930 is in a steady state and fundamental productivity and amenities in the 1930s are estimated to rationalize the population distribution in 1936 and employment distribution in 1938. See Figure D.4 for the results.

Table 2: Generalized method of moments estimates for agglomeration parameters

	(1) Productivity	(2) Amenities	(3) Productivity	(4) Amenities
Elasticity of employment density (α)	0.193 ^a (0.0001)		0.196 ^a (0.0002)	
Elasticity of population density (β)		0.184 ^a (0.0009)		0.203 ^a (0.0007)
Sample of blocks	All blocks in the city		Blocks within 3 km of CBD	
Sample of periods	Every 5 years from 1955 to 1975		Every 5 years from 1955 to 1975	
Instruments	5 grids for CBD distance		5 grids for CBD distance	

Note: This table reports two-step generalized method of moments (GMM) estimates exploiting the moment conditions (20). The Eicker-Huber-White heteroskedasticity-robust standard errors are in parentheses. We use data for five periods (1955, 60, 65, 70 and 75). We define five grid cells according to the distance to the CBD for the moment conditions. In Columns (1) and (2) we use all 174 blocks in the city. In Columns (3) and (4) we use 158 blocks that lie within 3 kilometers of the CBD. ^a indicates significance at the 1 percent level.

(3) and (4) in Table 2 we show similar results when we restrict our sample to blocks within 3 kilometers of the CBD.

Since we estimate strong positive agglomeration forces in both amenities and productivity, the model could have multiple equilibria in light of Proposition 1. Although the direct comparison is difficult due to differences in models and empirical contexts, our estimates of agglomeration forces are broadly in line with those in the existing literature. Our estimated elasticity of productivity with respect to employment density is 0.19. While larger than the 0.03–0.08 from the survey by Rosenthal and Strange (2004), this is relatively close to several recent estimates (e.g., Kline and Moretti 2014; Hebligh, Redding, and Sturm 2020; Tsivanidis 2022; Allen and Donaldson 2022) and also well within the range of estimates in the meta-analysis by Melo, Graham, and Noland (2009). Our estimated elasticity of amenities with respect to population density is 0.18. This value is close to the estimates of Ahlfeldt et al. (2015) and Hebligh, Redding, and Sturm (2020), while smaller than Tsivanidis (2022).

5.4 Robustness of Agglomeration Parameter Estimates

Instruments based on Pre-war Population Density A potential concern with defining instruments based on distance to the CBD is that the results could be sensitive to the definition of the city center. To address this, we instead use population density in 1936 to define the grid cells. We report the estimation results in Table D.2 in Appendix D.5. We find similar results: the agglomeration parameters for productivity and amenities are 0.178 and 0.165, respectively.

Spatial Spillovers in Productivity and Amenities So far, we have assumed that agglomeration forces in productivity and amenities are at work only in the local block. While this is consistent with empirical evidence that agglomeration forces are highly localized (e.g., Arzaghi and Hender-

son 2008; Ahlfeldt et al. 2015; Gechter and Tsivanidis 2023), productivity in each block may also depend on employment of surrounding blocks. To consider the spatial spread of spillovers, we estimate the agglomeration forces when productivity and amenities are a function of employment and population density, with weights decreasing exponentially with travel time. Specifically, following Ahlfeldt et al. (2015), productivity in block i is: $A_{it} = a_{it} \left[\sum_{i' \in C} e^{-\delta \tau_{ii'}} \left(\frac{L_{i't}}{S_{i'}} \right) \right]^\alpha$, where δ is a parameter characterizing the spatial decay of productivity and τ_{in} is travel time between blocks. When $\delta \rightarrow \infty$, there is no spatial spread of spillovers as in our baseline specification. We specify amenities in an analogous way. Figure D.5 in Appendix D.5 shows the estimated values of the agglomeration parameters (α, β) given different values of spatial decay (δ). As we can see in the figure, the estimated values of the agglomeration parameters range from 0.18 to 0.26 for productivity and from 0.17 to 0.22 for amenities, which are close to the baseline estimates.

Lagged Effects of Agglomeration Forces Our main model assumes that the amenities and productivity of each block depend on its current population and employment densities. However, they could also depend on its past population or employment densities. First, current productivity could reflect the histories of capital, public goods and innovation as determined by past economic activities; second, current amenities could depend on the stock of housing or local infrastructure that is related to past population.⁴⁶ In addition to migration frictions, these effects may also induce history dependence. To take this into account, we specify productivity and amenities in period t as a function of current employment and population densities and the previous employment and population densities in period $t - 1$, following Allen and Donaldson (2022). We estimate the parameters characterizing both the current and lagged spillover effects using similar moment conditions. Table D.3 in Appendix D.5 shows the results. The elasticity of productivity with respect to current employment density is 0.228 and historical employment density is -0.064. The elasticity of amenities with respect to current population density is 0.175 and historical population density is 0.015. Overall, the influence of lagged population and employment density is small relative to that of current density, and the strength of contemporaneous density remains similar to our baseline estimates.⁴⁷

⁴⁶Allen and Donaldson (2022) provide microfoundations for these specifications. In a previous version of this paper, we also provided alternative microfoundations in the within-city context.

⁴⁷Our estimates of agglomeration forces in productivity are broadly similar to those in Allen and Donaldson (2022), which uses long-run county-level data from the U.S. Yet, they find negative contemporaneous agglomeration forces in amenities. This difference may arise from the difference in spatial extent. The negative agglomeration forces in amenities may capture congestion in a local housing market, while our estimates of positive agglomeration forces may capture consumption externalities or neighborhood network effects.

5.5 Accounting for the Recovery: Location Choice for 1950

We are now in position to assess how well our calibrated model fits population and employment changes during the recovery period from 1945 to 1950, data which were not used for calibration. To this end, we evaluate how well the endogenous component of location advantages and the time-invariant unobserved characteristics can fit the workplace and residence choices of 1950, the first location choices made in our model after the atomic bombing. Intuitively, we evaluate how much of the incentive to work or live in a given location during the recovery period can be explained by our model. See Appendix D.6 for more details.

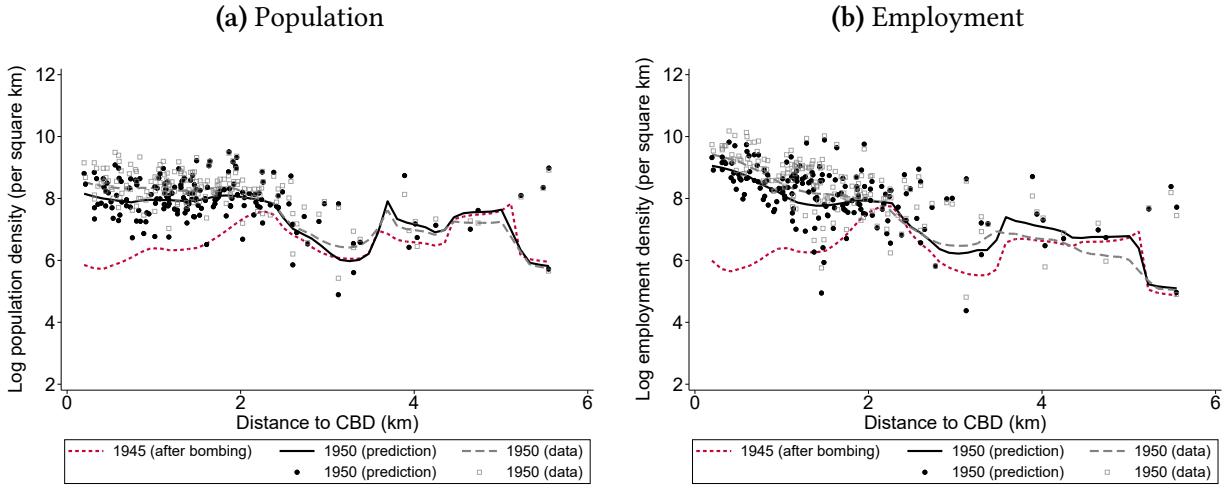
We first use equations (15) and (16) to construct the predicted option values of each location as a residence ($\Xi_{n,1950}^F$) and workplace ($\Omega_{i,1950}^F$), then substitute them into equation (17) to solve for predicted population and employment in 1950. By construction, the option values in our model are a composite of (i) location-fixed advantages, (ii) the endogenous components of agglomeration forces, (iii) future option values associated with the location, and (iv) idiosyncratic shocks. Among these, factors (i) – (iii) capture the location advantages that our model can explain. In contrast, the idiosyncratic terms (iv), corresponding to ($\{a_{it}^{\text{Var}}\}$, $\{b_{nt}^{\text{Var}}\}$) in equation (19), are structural residuals required perfectly match the model prediction with the observed data, which absorb any other characteristics unrelated to the model specification.

Therefore, to evaluate how well our model can fit the recovery, we exclude the structural errors when constructing the model-predicted option values for residence $\{\Xi_{n,1950}^F\}$ and workplace choices $\{\Omega_{i,1950}^F\}$. In obtaining the predicted location decisions for the recovery period (1945–1950), we use the parameter values from our main calibration except we set a higher migration opportunity $\theta_{1950} = 0.9$ as available evidence suggests the mobility rate was substantially higher, possibly for war-related reasons such as job loss, housing destruction, or the end of temporal reallocation during the war (see Appendix A for more details). Importantly, we assume the block-fixed amenities and productivity, (a_{i1950}, b_{n1950}) , equal the averages estimated for the post-recovery period 1955–1975.⁴⁸

Figure 5 illustrates the population and employment distributions predicted by our model for 1950. The horizontal axis is distance to the CBD, and the vertical axis shows population and employment density after the bombing in 1945, as observed in 1950 and as predicted by the model for 1950. For both population and employment, we find that our calibrated model successfully predicts the recovery of the city center, which we indeed observe in the data. The linear regression of the log of observed population (employment) density in 1950 on predicted population (employment) density by the model yields a coefficient of 0.88 (1.01) with a high R-squared around

⁴⁸The validity of this assumption can be checked by comparing the 1955–1975 fixed amenities and productivity with the 1950 exogenous amenities and productivity, which we can compute by netting out the agglomeration forces and future values from the option values ($\{\Xi_{n,1950}^F\}$, $\{\Omega_{i,1950}^F\}$). We find they are quite similar, with correlation coefficients of 0.98 for productivity and 0.99 for amenities.

Figure 5: Recovery of population and employment: Endogenous part explained by our model



Note: Each figure overlays observed log population density (Panel a) and employment density (Panel b) with local polynomial regressions using each on distance from the CBD. We estimate three separate regressions: the 1945 population and employment densities (small dashed line); the observed 1950 population and employment densities (long dashed line); and the 1950 population and employment densities inferred under the counterfactual scenario in which we exclude the structural error components of amenities and productivity (solid line). Each dot represents a block, with different colors for the predicted density and the observed density.

0.88 (0.91).⁴⁹ This result shows that our calibrated model successfully explains the fast and strong recovery from 1945 to 1950.⁵⁰

6 The Role of Agglomeration Forces

Having demonstrated that our calibrated model can account for the recovery of central Hiroshima, we now analyze the role of agglomeration forces in the recovery. In Subsection 6.1 we undertake a counterfactual experiment in which we exclude agglomeration forces in both productivity and amenities from our calibrated model. In Subsection 6.2 we investigate the existence of multiple equilibria. Consistent with the importance of agglomeration forces, we numerically find an alternative equilibrium in which the city center did not recover. This suggests that expectations can be self-fulfilling by selecting the recovery equilibrium among multiple equilibria.

⁴⁹Note that the prediction of our model is substantially more accurate than just capturing the general tendency that blocks closer to the city center tend to have higher density in 1950. Indeed, regressing log population (employment) density on the log distance from the city center yields R-squared around 0.20 (0.49), which is considerably lower than the R-squared from our model prediction.

⁵⁰Note that we exclude idiosyncratic components of locational fundamentals that may capture factors such as the recovery plan or property rights. Yet, these shocks may not be essential in inducing the recovery (see also Section 7).

6.1 Agglomeration Forces as the Key Driver of the Recovery

The city center recovers when individuals regard it as an attractive residence and workplace. Strong agglomeration forces can be a primary source of attractiveness. These forces operate by increasing the expected population and employment density, which in turn leads to improved amenities and productivity. An alternative possibility is that the city center has attractive location fundamentals so that it attracts population and employment regardless of agglomeration forces. Which forces induced the recovery of central Hiroshima in our calibrated model? To investigate this, we compute counterfactual population and employment distributions for 1950 when spillovers in amenities and productivity are absent.

We solve the model for counterfactual equilibrium 1950 population and employment distributions, using the same parameter values as Subsection 5.5 but setting both agglomeration parameters, α and β , to zero.⁵¹ As in the baseline, individuals make forward-looking migration decisions taking into account future fundamental productivity, amenities, and commuting costs. Notably, as in Subsection 5.5, we assume that the fundamental amenities and productivity during the recovery period equal the average amenities and productivity during 1955–1975.⁵² If agglomeration forces play the key role in explaining the attractiveness of the city center in our model, then this counterfactual exercise would not be able to predict the recovery.⁵³

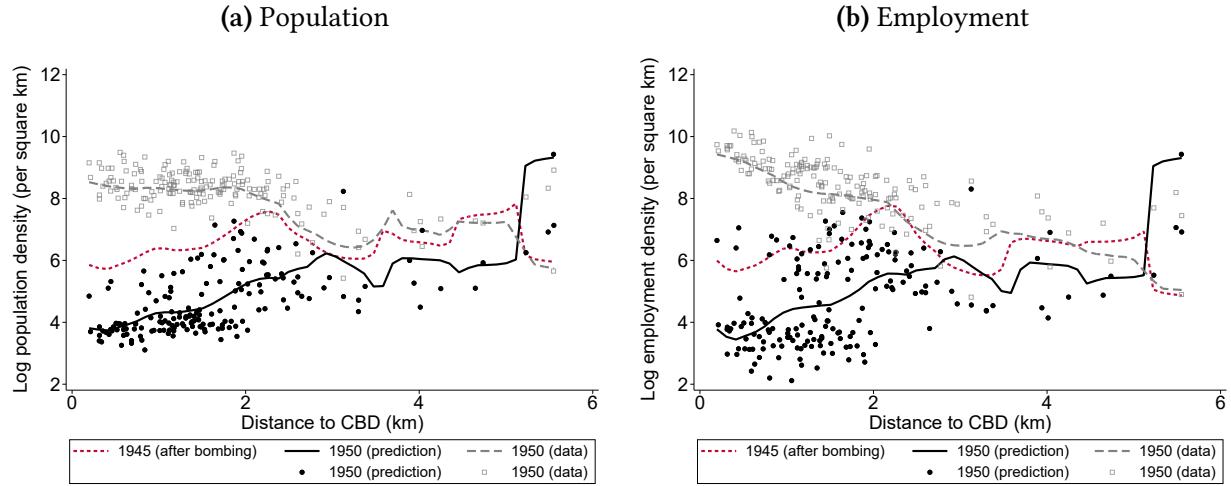
Figure 6 shows the counterfactual population and employment densities in the absence of agglomeration forces. The model no longer predicts the recovery of population and employment in central Hiroshima. This is in stark contrast to our main calibrated model in Figure 5. Given that the only deviation from our main calibrated model is the shutdown of agglomeration forces, this result highlights that agglomeration forces play the key model role in explaining the recovery of the city center. Note that as discussed in the last paragraph of Section 3, the importance of agglomeration forces is in line with our reduced-form results that the observed fundamental location characteristics, which are independent of agglomeration forces, do not explain the recovery.

⁵¹To focus on the population and employment distributions within the city, we assume in this counterfactual that the total population matches the observed data.

⁵²This assumption on fundamental amenities and productivity is important because even without agglomeration forces our model can fit any population and employment distribution in 1950 as long as the structural errors (a_{i1950}, b_{n1950}) can take any value. Therefore, the role of agglomeration forces highlighted in this subsection presumes that the levels of fundamental amenities and productivity are similar to those in the post-recovery period 1955–1975. Consistent with this assumption, we find that the values of the structural errors (a_{i1950}, b_{n1950}) are similar to the 1955–1975 fundamentals. See previous discussion in Subsection 5.5.

⁵³The parameters (α, β) capture not only pure externalities of density but also other channels through which population or employment density affects productivity and amenities. In this counterfactual, we turn off all these density effects simultaneously.

Figure 6: Population and employment distributions with no agglomeration forces



Note: Each figure overlays log population density (Panel a) and employment density (Panel b) with local polynomial regressions of each on distance from the CBD. We run three separate regressions: one for the observed 1945 population and employment densities (small dashed line), one for the observed 1950 population and employment densities (long dashed line), and one for the inferred 1950 population and employment densities when we shut down agglomeration forces in both productivity and amenities (solid line). Each dot represents a block, with different colors for the predicted density and the observed density.

6.2 Multiple Equilibria and Self-fulfilling Expectations of Recovery

This section examines an alternative equilibrium in which the recovery does not occur. When agglomeration forces are important, the model may have multiple equilibria because whether the city center remains attractive depends on whether people expect a high density city center in the near future. There could exist an alternative equilibrium in which central Hiroshima does not recover. If so, the selection of the recovery equilibrium among multiple equilibria might be crucial in explaining the recovery of central Hiroshima.

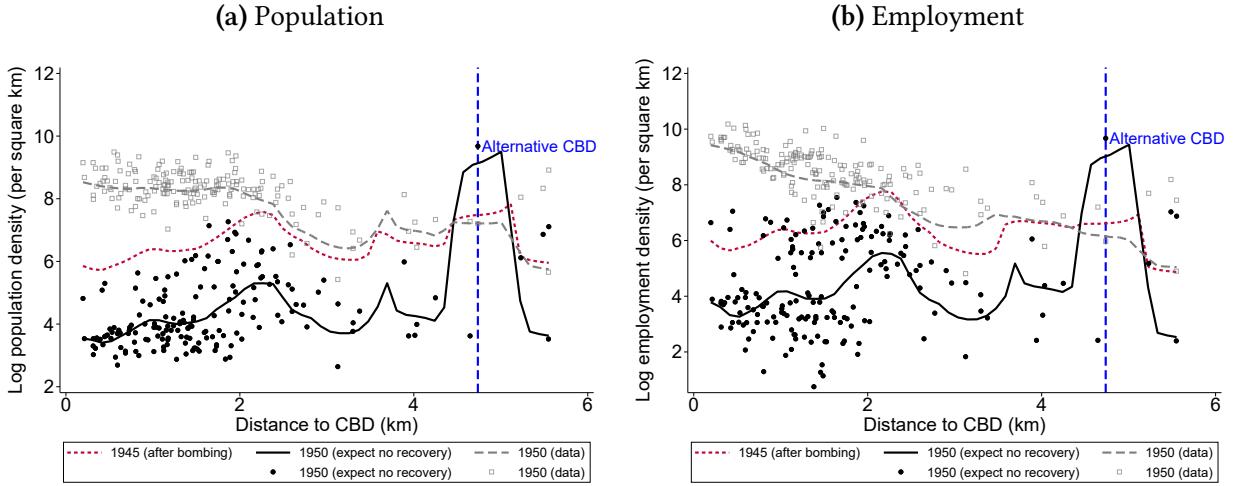
Specifically, we present an example of an alternative rational-expectations equilibrium in which the city center does not recover. We use the parameters values and fundamentals estimated in Section 5 and assume that the total population matches the observed data. To find an alternative equilibrium, we start off with guesses of population and employment in 1975 that are different from the observed data.⁵⁴ We then solve for the dynamics of population and employment consistent with equilibrium conditions dating back to 1945. Subsequently, we update our initial guess for 1975 until the backward solution in 1945 converges to the initial conditions observed in 1945.

Figure 7 provides a visualization of population and employment densities in an alternative

⁵⁴To construct initial guesses for the population and employment distributions in 1975, we simulate population and employment dynamics forward in time from 1950, assuming that people have a myopic expectation that the population and employment distribution in period $t + 1$ will be the same as in period t .

equilibrium. We compare these with the realizations of population and employment in 1950 and the initial pattern of 1945. We label a block with a high concentration of population and employment in this counterfactual as an alternative CBD.⁵⁵ In Panel (a) we find that pre-war central Hiroshima does not recover, and its population density is even lower than the initial level in 1945. In Panel (b) we find a similar pattern for employment. These results are consistent with the idea that a totally different city structure could have emerged as an alternative equilibrium.

Figure 7: Population and employment distribution in an alternative equilibrium



Note: Each figure plots log population density (Panel a) and employment density (Panel b) with local polynomial regressions of each on distance from the CBD. We run three separate regressions: one for the observed 1945 population and employment densities (small dashed line), one for the observed 1950 population and employment densities (long dashed line), and one for the inferred 1950 population and employment densities in an alternative equilibrium (solid line) when people expect that the pre-war CBD will not recover and an alternative block located at the vertical dashed line will grow. Each dot represents a block, with different colors for the predicted density and the observed density. The location with growing population and employment density is labeled “alternative CBD”.

This multiplicity of equilibria highlights the potential importance of self-fulfilling expectations as an equilibrium selection device (Krugman 1991; Matsuyama 1991). In our rational-expectations model, if people expect the recovery, then the recovery equilibrium realizes because such expectations make the city center an attractive residence and workplace due to agglomeration forces. In contrast, if people do not expect the recovery of the city center, then no recovery equilibrium realizes as the city center remains unattractive. Therefore, our result highlights that the formation of expectations in recovery might be crucial in inducing the recovery of central Hiroshima after the bombing.

⁵⁵This block (*Niho machi*) is a plausible candidate for an alternative CBD as it hosts high productivity firms such as *Toyo Kogyo* (currently known as a large automotive manufacturer, *Mazda Motor*) and is close to Hiroshima port.

7 Discussion on the Origin of Expectations in the Recovery

Our analysis has demonstrated that the expectation that blocks with high pre-war density would regain high density post-war is crucial in explaining the recovery of central Hiroshima. We now discuss the potential factors contributing to the formation of expectations, while we remain agnostic about *why* the expectations of recovery emerged.

Government Recovery Plan First, the presence of a government recovery plan would have facilitated the formation of expectations, despite the fact that publication of the plan lagged the onset of the recovery.⁵⁶ Moreover, the government was substantially underfunded, as discussed in Subsection 3.3, and implementation of the plan faced substantial difficulty.⁵⁷

Land Ownership Land ownership is an additional factor to consider. Yet, the recovery is unlikely to be explained by a strong tendency of original landowners to return to their prior homes. In particular, personal land ownership was quite rare in pre-WWII Japan; the rate of land ownership in pre-WWII urban area in Japan was likely less than 10 percent (Kato 1988).⁵⁸ In our context, unlike conventional air raids, the death rate near the epicenter of the atomic bombing was nearly 100 percent, implying that the number of surviving landowners was small.⁵⁹ To further analyze the influence of land ownership on the recovery quantitatively, we carry out a counterfactual analysis in which we assume that landowners consisted of 20 percent of the total population in 1936 and those who survived the bombing returned to their pre-bombing block by 1950 due to personal attachment. Without agglomeration forces, however, we do not find a strong recovery of central Hiroshima relative to the observations (see details in Appendix D.6). That said, even the small number of surviving landowners that returned to their original locations may have played an important role in forming expectations in the recovery.

Salient Location Characteristics Another possibility is that the tangible presence of some location characteristics in the city center may have induced an anchoring of expectations. The first example is the transportation system, especially the tram network. While the direct benefit of access to trains does not appear to be essential to the recovery as we control for transportation

⁵⁶It is unlikely that zoning laws contributed to the recovery in 1945–50 because the first post-war zoning of Hiroshima was published in 1949, when the recovery was nearly complete. In addition, there were only four types of zones (commercial, residential, industrial, and unspecified), and the zoning allowed substantial mixed land use (Asano 2012).

⁵⁷Appendix B.2 reports that controlling for the number of public housing units supplied during 1945–1950 does not alter our regression results, which would be plausible given the limited supply due to the budget shortage.

⁵⁸The fraction of households owning a home was also quite low in pre-WWII urban Japan at around 25 percent (Hinokidani and Sumita 1988).

⁵⁹The turnover of business owners was also high. According to Hiroshima City Government (1983), in 1958, approximately 28 percent of stores on a notable shopping street, *Hondori*, remained in the same location as before the war, while the remaining 72 percent of stores had begun operating only after the bombing.

access in both the reduced-form and structural analyses, the relatively quick restoration of the pre-war train network may have anchored people’s expectations of reconstruction. Another example is Hiroshima castle. Although the castle itself was completely destroyed by the bombing and was unlikely to provide direct amenity value, its historical salience may have made it difficult for people to expect a situation in which the city center moves away from the castle.

Narratives Lastly, the narrative of “rebuilding from the atomic bombing” may have sounded like a compelling success story and been shared widely (Shiller 2017).⁶⁰ As long as individuals were aware that many others shared this narrative, they could expect that the city structure would look like the pre-war Hiroshima in their memory, thereby inducing the recovery of the pre-war city center.⁶¹

Summary These underlying factors may influence the attractiveness of each location by either directly improving location-specific amenities (b_{nt}) and productivity (a_{it}), or via expectation channels. However, as discussed in Subsections 5.5 and 6.1, the ability of our calibrated model to explain the recovery comes from agglomeration forces, not location-specific amenities and productivity. In the expectations channel, several factors may alter expectations regarding the future population and employment distributions after the bombing, thereby affecting the attractiveness of each location via agglomeration forces. The self-fulfilling nature of expectations found in Subsection 6.2 suggests the possibility that the above-mentioned factors may have played a key role in inducing the recovery through the expectations channel.

8 Conclusion

A major source of public policy debate is the resilience of cities in the face of large shocks. To shed light on this question, we examine the atomic bombing of Hiroshima, which drastically changed the city’s structure by completely destroying the city center while sparing the city’s outskirts. We collect and digitize new historical data on Hiroshima’s population, employment, wartime destruction, and fundamental location characteristics at the city block level. Then, we document the strong resilience of Hiroshima’s city structure: the destroyed city center recovered its population density just five years after the atomic bombing. Our reduced-form analysis reveals that controlling for prominent observable location characteristics, such as altitude, access to natural water

⁶⁰Although it is challenging to empirically assess how powerful and widespread such a narrative was, the 1946 Statistical Abstract of Hiroshima is suggestive in stating ‘... rumors like “nothing will grow here for 75 years” immediately disappeared among people with their burning desire to rebuild...’ (p. 4, translated by the authors).

⁶¹This relates to the idea of “memory-based expectations,” in which people form expectations based on their past experiences (Malmendier and Wachter 2022). To gauge its potential importance, we simulate the model as in Subsection 5.5 assuming that workers expect the population distribution in 1936 and employment distribution in 1938 to be realized again in 1950. The simulation shows that such purely memory-based expectations also induce the recovery of the city center, suggesting that such expectations are comparable to rational expectations in our context.

and train stations, does not explain the recovery.

To identify the mechanism behind the recovery, we develop and calibrate a novel dynamic quantitative model of internal city structure that incorporates commuting, forward-looking migration decisions, migration frictions, agglomeration forces, and heterogeneous fundamentals across locations. Estimating the model with post-recovery data (1955–1975), we find strong agglomeration forces in productivity and amenities. The calibrated model successfully explains the resurgence of population and employment in the city center after the bombing (1945–1950), and agglomeration forces are essential for this success.

In the presence of strong agglomeration forces, multiple equilibria may exist because the city center does not become attractive if it is not expected to achieve high density. We find that there exists an alternative forward-looking equilibrium where the city center fails to recover. This suggests that the recovery crucially depended on people's expectations, as they can be self-fulfilling and select the equilibrium of recovery. We argue that certain factors, such as government recovery plans, the anchoring effect of salient location characteristics in the city center, property rights, and popular narratives of rebuilding, may have led people to expect that the destroyed areas would once again achieve high density as in the pre-war period. Taken together, our quantitative findings highlight the role of agglomeration forces, multiple equilibria, and expectations in the resilience of city structure.

Beyond the context of Hiroshima's resilience, agglomeration economies and expectations are important determinants of the dynamics of city structure. Therefore, our findings suggest that policymakers may be able to substantially change the dynamics of city structure if they could influence expectations about future city structure. Our theoretical framework developed in this paper could serve as a useful starting point for performing quantitative analyses to understand how the organization of economic activities within cities evolves over time. However, our model does not incorporate an explicit process in which people form expectations. Developing additional understanding of the ways in which agents can form expectations about a city's future structure is an interesting area for further research.

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Online Appendix for “The Economic Dynamics of City Structure: Evidence from Hiroshima’s Recovery” (Not for publication)

Kohei Takeda

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Appendix A describes the details of data construction. Appendix B provides additional reduced form results, including additional analysis on Nagasaki. Appendix C presents detailed derivations of model elements. Appendix D provides details for Sections 5 and 6 in the main text.

A Data Appendix

A.1 Basic Data

Maps, Spatial Units and Sample Selection The city block (*cho cho moku*) is our spatial unit of analysis. As our main source of geographic and city block data, we use GIS data on block boundaries as of the bombing constructed by [Takezaki and Soda \(2001\)](#). We make several adjustments to create our final sample. First, although [Takezaki and Soda \(2001\)](#) follows the map of officially-published block boundaries (*Hiroshima shin-shi*), it was constructed after the war, and a few blocks do not correspond to our population data. We address this issue by aggregating a handful of blocks in [Takezaki and Soda \(2001\)](#).¹ Second, we drop some blocks that experienced exceptional events that are outside the scope of our model. We drop blocks that later became Hiroshima Peace Memorial Park, Hiroshima-shi Chuo Park, and Hijiyama Park. Second, we drop three blocks that exhibit unusually large changes in population or employment in certain periods, which is likely due to idiosyncratic events outside of the model.² Third, we drop observations that have missing observations for the destruction rate of buildings or establishment counts in 1938. Finally, to ensure that our geographical scope is small, we drop two blocks whose centroids are more than 6 kilometers from the city center. We also drop an unpopulated remote island (*Touge-shima*) from our sample.³ In our final sample, there are 174 blocks.

We also digitize the block boundaries as of 1966 and 1976 to deal with changes in the block boundaries. For 1966, we use the map found in a 1965 block-level population report on Hiroshima

¹We aggregate two blocks (*Akebomo-machi* and *Kougo kita-machi*) that are recorded in a disaggregated way in [Takezaki and Soda \(2001\)](#). We also combine the *Yaga machi* and *Yaga shin-machi*, and *Funairi minami-machi* and *Funairi kawaguchi-machi*.

²We drop *Hakushima kita-machi*, *Iwamiya-cho*, and *Toriya-cho*. While we are not completely sure of why these blocks exhibit sudden changes in population or employment, we speculate that the presence of schools in *Hakushima kita-machi* and *Iwamiya-cho*, and a very small size of *Toriya-cho* (less than 0.0025km^2) made them prone to idiosyncratic shocks.

³We keep a remote island called *Kanawa-jima*, belonging to the *Niho machi* block in our sample because it is relatively close to the mainland and had a major shipyard.

(*Hiroshima-shi machi-betsu jinkou setai shiryou shouwa 40-nen kokusei chosa yori*). For 1976, we use the Hiroshima City map (*Hiroshima shigai chizu*) issued by a private publisher (*Shobun-sya*) in 1976.

Destruction by the Atomic Bombing The severity of destruction can be measured primarily in two ways: the ratio of buildings destroyed and the ratio of people killed. In this paper, we primarily focus on the building data for two reasons. First, the kill ratio is less reliable because it was extremely difficult to check who was killed in the destroyed city. [Hiroshima City Government \(1971\)](#) contains many missing values for the kill ratio due to the absence of reliable data on the kill rate. In contrast, the destruction rate of buildings was easier to record after the bombing and hence has way fewer missing values. Second, [Hiroshima City Government \(1971\)](#) records the “immediate” death rate following the bombing; however, the definition of “immediate” is unclear and seemingly inconsistent across blocks in [Hiroshima City Government \(1971\)](#). This is important in the context of Hiroshima because many people died days, months, or even years after the bombing due to radiation illnesses. Third, previous research on the impact of bombing on the city population ([Davis and Weinstein 2002](#); [Brakman, Garretsen, and Schramm 2004](#)) indicates that damage to buildings is a better measure of the damage level than casualties.

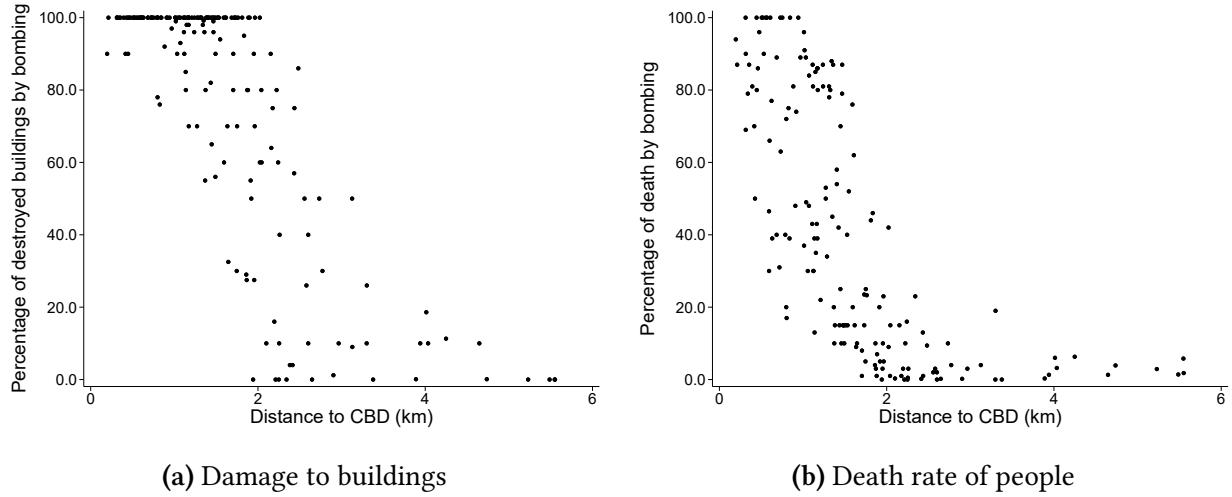
We base our analysis on the digitization of [Hiroshima City Government \(1971\)](#) by [Takezaki and Soda \(2001\)](#), but we consulted [Hiroshima City Government \(1971\)](#) to (i) correct errors in [Hiroshima City Government \(1971\)](#) or [Takezaki and Soda \(2001\)](#) and (ii) obtain the building destruction rate or the kill rate when they can be credibly inferred from the texts. We plot the building destruction rate against distance from the CBD in Figure A.1a. Blocks within 2 kilometers of the CBD were almost entirely destroyed, while those further than 2 kilometers from the CBD tended to experience much less damage. A similar plot for the kill rate is in Figure A.1b. The severest damage tends to concentrate in a smaller area (particularly within 1 kilometer of the CBD), and the data has more variation conditional on the same distance from the CBD, partially because the data is noisier.

A.2 Population and Employment

Population We collect and digitize block-level population data. For 1933–1936, we use the Statistical Handbook of Hiroshima City (*Hiroshima-shi toukei sho*) that reports population at the block level. For 1945–1953, we use the Statistical Abstract of Hiroshima City (*Hiroshima shisei youran*). From 1955, we use the population census data. Two issues must be addressed to make the population data comparable from 1933 to 1975. First, the block boundaries changed over time and the city’s shape also changed due to landfills and flood control. Second, prior to 1951, population data is available only at a less spatially granular level than blocks.

To address these issues, we first base our definition of blocks on the 1945 boundaries and focus

Figure A.1: Damage to buildings and death rate



Note: The left panel plots the percentage of completely destroyed buildings in each block. The right panel plots the percentage of people killed by the atomic bombing in each block. Source is [Hiroshima City Government \(1971\)](#).

on block areas that existed from 1945 to 1975. Then, when a block boundary changes within this period, we evenly distribute the population based on the overlapping area. We also need to address changes in the size of blocks due to landfills and flood control. The flood control, especially the redesign of the *Ota* river, which started in earnest in 1961 and was almost completed by 1965, is still an issue because parts of some 1945 blocks were later submerged, leaving some blocks in our data smaller than their original 1945 size. To address this, we calculate the percentage change in the area before and after this flood control operations and multiply this percentage by all population variables prior to 1965, which again implicitly assumes that population is evenly distributed within each block.

Second, prior to 1951, population data is available only at a less spatially granular level than blocks. To construct the block-level population data in 1945, we combine the block-level information on the rate of wholly destroyed buildings from [Hiroshima City Government \(1971\)](#) and population changes from the pre-bombing period to November 1, 1945, from the Statistical Abstract of Hiroshima City for each distance bin from the epicenter of the atomic bomb. We first calculate the fraction of destroyed buildings by distance to the city center by aggregating the data from [Hiroshima City Government \(1971\)](#). We then regress the population change ratio on a quadratic function of the fraction of completely destroyed buildings. As seen in Figure A.2a, the regression model fits the data well. Note also that the predicted populations in November 1945 are strictly positive even for blocks with a 100% destruction rate.

We use this model to predict population change ratios by block using the block-level destruction rate of buildings. Finally, we multiply this ratio and the 1936 block-level population to ap-

proximate the 1945 block-level population. We also validate our method of imputing the 1945 population distribution after the bombing using other data. The 1946 edition of *Hiroshima shisei youran* provides a map with population before (August of 1945) and after (August of 1946) the bombing for each school district. While we do not know the exact border of school districts, we can compute population change ratios between the two periods, which we expect to be highly correlated with population changes due to the atomic bombing. We then compare the population change of each school district with that of the census block that appears closest to the relevant school district. Figure A.3 shows the scatter plot and the fitted line. We obtain a very high correlation (around 0.86) between these two measures despite the population being measured at different times and the imperfect correspondence between school districts and blocks.

To construct the block-level population data in 1949 and 1950, we use population data that is recorded at a less spatially granular level, called *shucchojo*, taken from the 1949 and 1950 Statistical Abstract of Hiroshima.⁴ *Shucchojo* divides the city into 18 districts based on the administrative area of each branch of the city government. In principle, each *shucchojo* district is aggregated from blocks.⁵ Assuming that within each *shucchojo*, the population share is the same as in 1951, we approximate block-level population by multiplying this share by the population of the *shucchojo*.

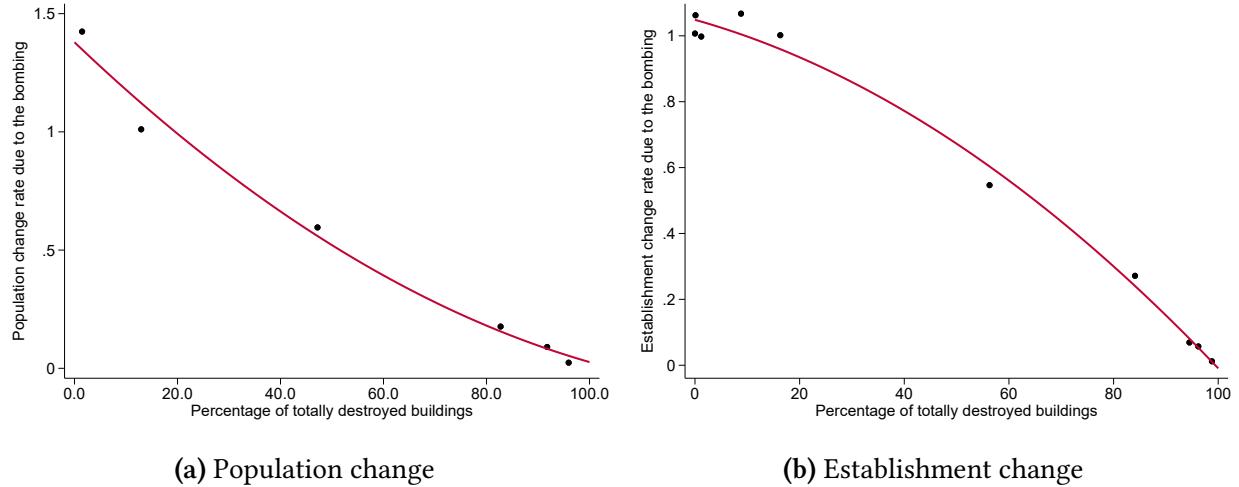
Our main analysis does not use population data from 1946–1948 because the block-level data is hard to construct. However, population data for 1946, 1947, and 1948 is available in the Statistical Abstract of Hiroshima City for distance categories from the epicenter of the bombing. In Figure A.4, we plot the time series of the population share of areas within 1 kilometer of the epicenter using this data. The figure shows that the recovery process had already started strongly in 1946, although the recovery was relatively slow until April 1946. Moreover, the recovery was complete in the sense that the population share of the central area exceeded the predicted share based on the pre-war trend.

Employment We collect and digitize block-level employment data from various historical sources. The Survey of Commerce and Industry in Hiroshima City (*Hiroshima-shi shoukou-gyou keiei chousa*) records the number of establishments (factories and commercial stores) at the block level for 1938. For 1946, the number of buildings used for business purposes is taken from the Statistical Abstract of Hiroshima City (*Hiroshima shisei youran*). For 1953, we rely on the Survey on the Daytime Population of Hiroshima (*Hiroshima-shi chukan jinko chosa*), assuming that the daytime population approximates employment. From 1957 to 1975, we use the Business Establishment Statistical Survey (*jigyousho toukei chousa*).

⁴Similar to the block-level data, we have also adjusted for shrinkage in *shucchojo* districts by defining the area of each district before and after the *Ota* river flood control. We multiply the original population by the percentage change of area to obtain estimates for *shucchojo* level population.

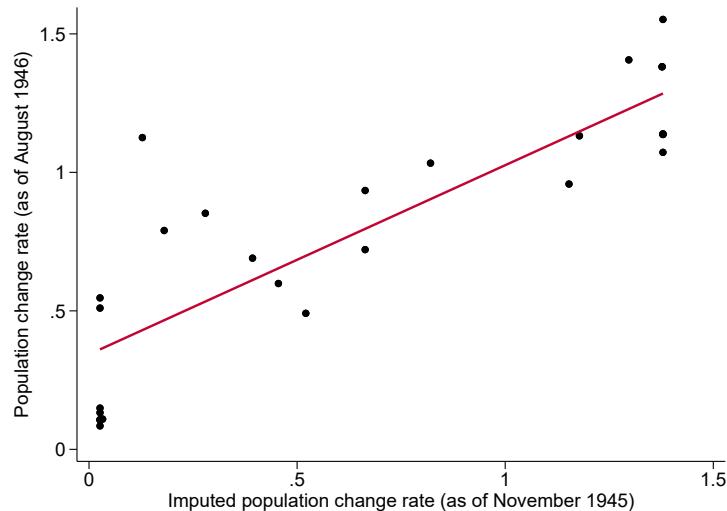
⁵There are a few exceptions in which a block overlaps multiple *shucchojo* districts. In this case we assume that a block belongs to the district in which more of the block residents live.

Figure A.2: Population and establishment changes relative to building destructions



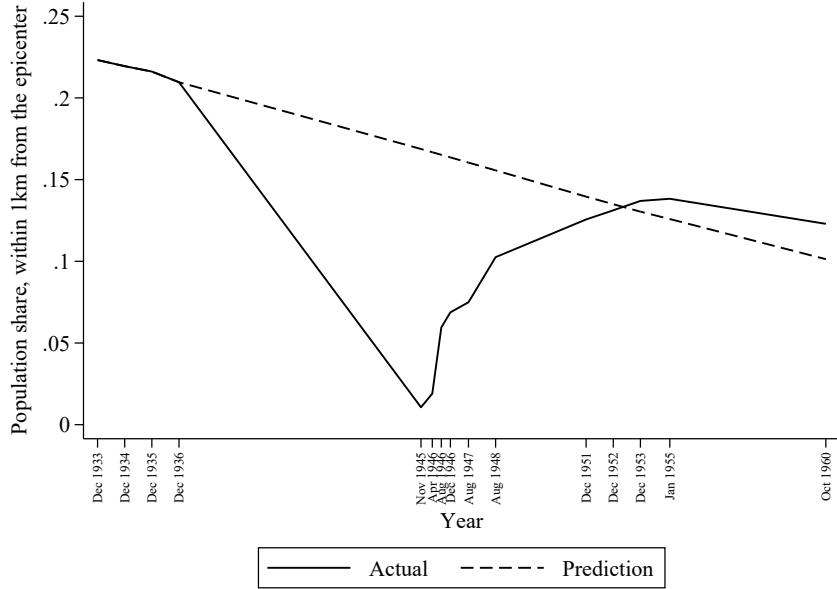
Note: The left panel shows a scatter plot of the percentage of completely destroyed buildings and population change ratios due to the bombing for distance categories from the epicenter (within 1km, 1-1.5km, 1.5-2km, 2-2.5km, 2.5-3km, more than 3km away). Population change is from the 1946 Statistical Abstract of Hiroshima City and the destruction rate is a population-weighted average of the block-level destruction rate from [Hiroshima City Government \(1971\)](#). The right panel shows a scatter plot of the percentage of completely destroyed buildings and establishment change ratios due to the bombing for distance categories (0.5km grids up to 5km). Establishment changes are from the 1946 Statistical Abstract of Hiroshima City. In both panels, we fit a quadratic model and plot it.

Figure A.3: Validation of our 1945 population data using alternative population data in 1946



Note: We validate our method of imputing the 1945 population after the bombing using different population data taken from the 1946 edition of *Hiroshima shisei youran* at the school district level. The horizontal axis shows the predicted population change rate as of November 1945 based on the imputed destruction rate of buildings for each school district. The vertical axis shows the population change as of August 1946, taken from the data. We also plot a linear regression line. The correlation coefficient is 0.8547.

Figure A.4: Actual and predicted population share within 1 km of the epicenter



Note: This figure shows the population share of areas within 1 kilometer of the epicenter. For 1945–1948, we observe the population in the Statistical Abstract of Hiroshima. For the remaining years, we aggregate block-level population to distance bins from the epicenter according to the definitions of [Hiroshima City Government \(1971\)](#). The predicted population share extrapolates the pre-war linear trend to the post-WWII period, analogous to Figure 2 of [Davis and Weinstein \(2002\)](#).

Throughout this paper, we focus on employment in the manufacturing or service sectors and ignore agricultural employment. This is a relatively moderate restriction because we focus on an urban area throughout our sample period.⁶

Three issues must be addressed to make the block-level employment data comparable between 1938 and 1975. First, similar to population, block boundaries and land area changed over time. Second, the employment information for 1945–1963 is only available at a less spatially granular level than blocks. Third, for 1938 and 1945, we know the number of establishments but not the number of workers. For the first issue, we address it using the same strategy as the population data.

We now describe how we address the second issue. We calculate the number of establishments

⁶While most of our data already focus on non-agricultural employment, the 1953 data report total employment, including agricultural employment. To account for this, the number of agricultural workers in 1953 is estimated using the following method. First, we obtain the share of agricultural households from the 1950 Statistical Abstract of Hiroshima. Using the number of agricultural workers from the 1950 Population Census, we estimate that roughly half of agricultural household members are counted as employed. This allows us to calculate the fraction of agricultural workers in the overall population. We multiply this by the block-level population in 1953 to approximate agricultural employment at the block level in 1953. Even in 1950, when agricultural employment was still significant in the Japanese economy, less than 10 percent of workers were in the agricultural sector in Hiroshima City.

as of November 1945, when our first post-war population data is available. We first extract the number of buildings for shops, restaurants, banks, hotels, associations, and entertainment facilities before and after the bombing (August 1946) from the 1946 Statistical Abstract of Hiroshima City. We also approximate the establishment distribution right after the bombing (August 1945) by multiplying the number of establishments before the bombing by the proportion of completely destroyed buildings.⁷ Using linear interpolation, we can approximate the number of establishments for each distance bin in November 1945 based on the data from August 1945 and 1946. Second, we regress the ratio of the number of pre-war establishments to those in November 1945 on the ratio of completely destroyed buildings and its square. Figure A.2b shows that the regression model fits the data well. Finally, we multiply the number of establishments in 1938 by the predicted change ratio using the block-level ratio of destroyed buildings and the estimated regression model shown in Figure A.2b.⁸

To construct the block-level employment distribution for 1950–1963, we rely on an employment distribution that is recorded at a less spatially granular level (*shucchojo*).⁹ Since our 1957 employment data aggregates seven peripheral districts into one, we define it as the “others” district and use the 12 *shucchojo* areas. The number of workers at the *shucchojo* level is available for 1953, 1957, and 1963. To calculate employment at the block level, we multiply the number of workers in the *shucchojo* and the employment share of that block in 1966. This procedure assumes that the employment share *within* the *shucchojo* district is approximated by the 1966 distribution, but allows for employment changes across *shucchojo* districts. Finally, to approximate the employment distribution in 1950, we assume that the employment distribution in 1950 is the same as in 1953 except for the total number of workers, which we scale down by the growth rate of the total population.

Finally, we need to construct block-level employment data from the block-level establishment data. Following prior studies (e.g., Ahlfeldt, Redding, Sturm, and Wolf 2015), we assume that employment is proportional to the number of establishments. To determine total employment in 1938 and 1945, we multiply the total population by the labor force participation rate in 1936, which is 44.2 percent according to the 1936 Statistical Handbook of Hiroshima City (*Hiroshima-shi toukei sho*).¹⁰

⁷We compute the average fraction of completely destroyed buildings for each bin from the block-level data on the fraction of completely destroyed buildings ([Hiroshima City Government 1971](#)), using the 1938 number of establishments as weights.

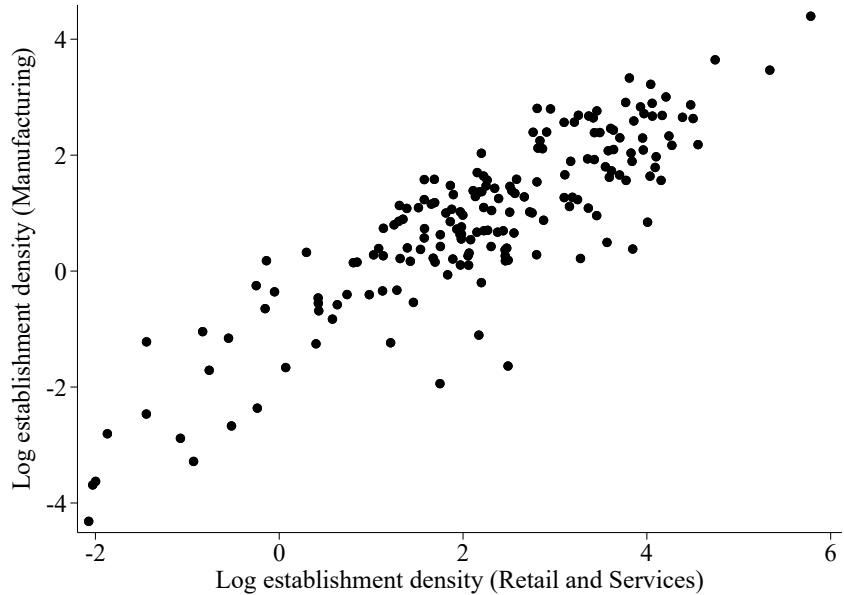
⁸The predicted model yields a negative rate of change in the number of establishments for a total destruction rate of 100 percent. To address this, we apply the predicted change rate for blocks with a 100 percent destruction rate to those with a 99 percent destruction rate.

⁹The issues of some blocks belonging to two *shucchojo* districts and changing land areas are addressed in the same way as for the population data.

¹⁰In our structural estimation, however, total employment equals total population because our model assumes that everyone works. We normalize the total population to the total employment.

While we focus on total employment in this paper, available evidence suggests that the location of employment is highly correlated across sectors. We digitize the 1952 Business Directory of Hiroshima City (*Hiroshima-shi shoko nenkan*). From this, we compute the number of establishments in each city block for both manufacturing and commerce (retail and services). Figure A.5 shows that establishment density is highly correlated across sectors. Therefore, analyzing the spatial distribution of total employment likely does not mask substantial sectoral heterogeneity.

Figure A.5: Geographic correlation of establishment counts by sector



Note: We plot the log establishment density of retail and services against the log establishment density of manufacturing. Each dot represents a city block. The data is taken from the 1952 Business Directory of Hiroshima City (*Hiroshima-shi shoko nenkan*).

A.3 Other Data

Commuting and Transportation Network We use trip-level microdata from the 1987 Hiroshima City Person-Trip Survey for metropolitan area residents. It is broad (about 7 percent of the population was surveyed) and representative. To further enhance representativeness based on residence, age, and gender, we use the sampling weights provided in the survey. The unit of observation is a trip, and for each trip, origin, destination, and mode(s) of transportation are recorded.¹¹ We use the following representative modes of transportation: walk, bicycle, car, bus, and train. The

¹¹As an alternative measure of a bilateral commuting time, we also try the geographical distance between blocks. We measure the bilateral distance by the geographical distance between the centroids of two areas. We estimate the gravity equation by constructing a bilateral commuting matrix between 66 areas within our sample area, using individual-level information on the residence and the workplace. The 66 areas are constructed by suitably aggregating blocks. Our main conclusions do not change.

Table A.1: Summary statistics for population and employment

	All blocks in the city (174 blocks)		Within 3km from CBD (158 blocks)	
	Mean	Standard deviation	Mean	Standard deviation
Population in 1936	1,880	2,153	1,642	1,103
--- per km^2 in 1936	23,761	14,104	25,752	13,138
Population in 1945	917	2,927	459	916
--- per km^2 in 1945	3,566	5,496	3,374	5,158
Population in 1950	1,495	2,683	1,026	1,091
--- per km^2 in 1950	11,877	6,616	12,583	6,374
Population in 1960	2,215	3,648	1,537	1,689
--- per km^2 in 1960	16,725	8,548	17,737	8,188
Population in 1975	2,625	5,423	1,501	2,694
--- per km^2 in 1975	12,758	5,046	13,065	4,906
Employment in 1938	978	835	949	626
--- per km^2 in 1938	42,517	41,449	46,512	41,422
Employment in 1945	405	1,056	259	420
--- per km^2 in 1945	5,507	8,035	5,602	8,072
Employment in 1953	669	965	505	465
--- per km^2 in 1953	7,358	6,083	7,909	6,099
Employment in 1966	1,277	1,516	1,060	792
--- per km^2 in 1966	18,499	17,408	20,111	17,463
Employment in 1975	1,515	1,880	1,211	993
--- per km^2 in 1975	21,017	21,948	22,821	22,243

representative mode is defined as follows. First, the representative mode is “train” if the trip uses a train or tram. Then, for trips that have not been coded, we code them as “bus” if they use buses. We code trips that have not been coded as “car” as such if they use a motorcycle or automobile. We code trips that have not been coded as “bicycle” if they use a bicycle. Finally, we code a trip as “walk” if it was walked.

To measure travel time between each workplace-residence pair, we also collect and digitize Hiroshima City’s road, bus, and train networks in 1987, and compute the bilateral travel time between the centroids of blocks for each mode: walk, bike, car, bus, and train.¹² Although public transportation networks were generally stable during our sample period, there were a few notable changes, including the discontinuation of the *Ujina* line in 1966. To address this, we also digitize the bus and train networks in 1950. Prior to 1966, we use the public transportation networks of 1950, and after that we use those of 1987. Throughout our sample period, we use the 1987 road network due to its data quality, which is reasonable given that the road network in Hiroshima has not changed significantly from the pre-war period. To formally verify this, we digitize the road

¹²We use QGIS to compute the travel time. Based on available evidence, we assume the following travel speeds: 5 km/h for walking, 12 km/h for bicycling, 25 km/h for driving a car, 15 km/h for bus, 12 km/h for tram, and 36 km/h for other trains. When calculating the travel time by bicycle, car, bus, and train, we assume walking occurs outside its network.

networks on published city maps prior to the bombing and in 1950.¹³ We then compare the travel times to the city center with these networks to the travel times using the road network of 1987. The correlation between the pre-bombing period and 1987 is 0.95, and the correlation between 1950 and 1987 is 0.97.

Location Characteristics (First Nature) Altitude and slope are taken from the Digital National Land Information (*kokudo suuchi joho*) database.¹⁴ For each 250 m × 250m square, the data record the average altitude and the average degree of slope. We assign the value at the centroid of each block. Second, we obtain the location of water areas for the pre-war and post-war periods. We use the digital map of [Takezaki and Soda \(2001\)](#) for the pre-war period and the Basic Geospatial Information (*kokudo kihon zu*) data for the post-war period. Finally, we take the soil condition from the Land Classification Basic Investigation data.¹⁵ We use the data on the surface strata and assign the soil condition to each block using the centroid location.

Other Location Characteristics We collect information on the location of train stations in 1950 from the Digital National Land Information data.¹⁶ The location of the city center is defined as the midpoint of the *Hacchobori* and *Kamiya-cho* blocks. The location of Hiroshima port (*Ujina* port) is taken from Google Maps. The list of cultural assets (*bunkazai*) in the city is taken from the Hiroshima Metropolitan Area and Hiroshima Prefecture Open Data Portal Site.¹⁷ We compute all distances using the centroid of each block. Finally, we digitize the location and number of units of each type of public housing from the 1949 and 1950 Statistical Abstract of Hiroshima City (*Hiroshima shisei youran*).¹⁸ The data cover all public housing units constructed in Hiroshima from 1946 to 1950.

Land Prices We obtain the location with the highest unit land price within Hiroshima.¹⁹ The 1931 Statistical Yearbook of Hiroshima City reports this location in 1931. The National Tax Agency reports the location with the highest land price in each prefecture in 1959, and the highest land

¹³For the pre-bombing map, we digitize a map created by the US Army based on pre-bombing resources (https://maps.lib.utexas.edu/maps/ams/japan_city_plans/). For 1950, we digitize the Geospatial Information Authority of Japan Map.

¹⁴Source: <https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-G04-d.html>, in Japanese. Last accessed on October 28, 2023

¹⁵Source is a map with a scale of 1 to 50,000; https://nlftp.mlit.go.jp/kokjo/inspect/landclassification/land/l_national_map_5-1.html, in Japanese. Last accessed on October 28, 2023.

¹⁶Source: https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-N05-v1_3.html, in Japanese. Last accessed on October 28, 2023.

¹⁷Source: <https://hiroshima-opendata.dataeye.jp/resources/9843>. Last accessed on October 28, 2023.

¹⁸In some cases, the location information in the data does not allow us to uniquely identify the block the public housing is located in. We still assign a single block based on our best guess of the location of that public housing unit.

¹⁹In Japan, to our knowledge, digitized comprehensive land price data in the pre-WWII period is available only for Tokyo and Kyoto ([Yamagishi and Sato 2023](#)).

Table A.2: Summary statistics for block characteristics

	All blocks in the city (174 blocks)		Within 3km from CBD (158 blocks)	
	Mean	Standard deviation	Mean	Standard deviation
Block area (km^2)	0.321	0.971	0.132	0.39
Distance to CBD (km)	1.66	1.06	1.4	0.652
Distance to Hiroshima port (km)	4.74	1.08	4.72	0.985
Distance to nearest station (m)	336	319	285	232
Distance to nearest water area (m)	248	229	226	185
Distance to nearest cultural asset (m)	808	637	684	412
Altitude (m)	5.91	14.4	4.25	7.56
Average slope (degree)	0.814	2.4	0.611	2.07
Indicator of bad soil condition	0.96	0.197	0.981	0.137
Latitude	34.4	0.0104	34.4	0.0091
Longitude	132	0.0167	132	0.0123
Annual population growth rate 1933–36	1.03	0.0355	1.03	0.0344
Share of fully destroyed buildings	74.5	35.4	81.1	29.8
Share of half-damaged buildings	18.6	26	15.2	23.6
Share of mildly-damaged buildings	6.65	17.7	3.38	12.1
Share of intact buildings	0.685	3.99	0.316	1.66

price in Hiroshima prefecture was in Hiroshima City.²⁰

Migration Rate Our primary data source for migration is the 1960 population census. It asks whether a respondent changed their address, including moves within the same municipality. In densely populated areas of Hiroshima prefecture, 85.9 percent of prime age residents answered they had not.²¹ Converting this into a 5-year interval, we calculate the rate of moving within five years as $\theta \simeq 0.53$. However, this migration probability seems too small for the period right after the war. Many people reallocated for wartime reasons, and they would have lower mobility costs (e.g., less attachment to their current residence and a higher probability of job switching). According to the city population registry (*Hiroshima shisei youran*), more than 50,000 people moved out of Hiroshima City in 1949. Since the population of Hiroshima City at the end of 1948 was about 24,000 (1952 *Hiroshima shisei youran*), this implies an annual migration rate of 21 percent even if intra-city migration is ignored. We assume that the relative frequency of intra-city migration and inter-city migration right after the war were similar to that in 1960.²² This suggests an annual rate of staying of 0.64, corresponding to a five year moving rate of $\theta \simeq 0.9$. Note that our migration rate for the period 1945–1950 is primarily based on the migration data from 1949. This might underestimate the migration rate if mobility right after the war was even higher than the 1949 migration rate.

²⁰This can be found in Weekly Tax Communication (*Shukan zeimu tsushin*), volume 444, issue of February 22, 1960.

²¹Prime-age means between the ages of 15 and 59. Data source: <https://www.e-stat.go.jp/stat-search/files?page=1&layout=datalist&toukei=00200521&tstat=000001036867&cycle=0&tclass1=000001038047&tclass2val=0>, in Japanese. Last accessed on October 28, 2023.

²²For prime-aged residents, this ratio in the densely-populated area of Hiroshima prefecture is around 7:10, implying that the annual migration rate is roughly 0.36.

B Additional Reduced-form Evidence

B.1 Testing Recovery in Alternative Specifications

Table B.1 presents the results of estimating equation (2) in the main text.

Table B.1: Testing recovery of population density in 1950

	(1)	(2)	(3)	(4)	(5)	(6)
	Log population density in 1950					
	Baseline			Only fundamentals		
	All blocks			Blocks in 3km of CBD	All blocks	Blocks in 3km of CBD
Log population density in 1936	0.4941 ^a (0.0415)	0.5222 ^a (0.0552)	0.5080 ^a (0.0675)	0.5474 ^a (0.0808)		
Log population density in 1945	0.0899 ^a (0.0317)	0.0553 (0.0383)	0.0288 (0.0400)	-0.0158 (0.0378)		
Log distance to nearest station		-0.0468 (0.0427)	-0.0169 (0.0491)	-0.0218 (0.0519)	-0.1803 ^b (0.0693)	-0.1318 ^c (0.0704)
Log distance to port		-0.0359 (0.1335)	0.8479 ^c (0.4463)	0.3643 (0.8525)	0.8226 (0.6924)	1.2200 (1.0585)
Log distance to cultural asset		0.1196 ^b (0.0552)	0.1057 ^c (0.0584)	0.1287 ^b (0.0546)	-0.0133 (0.0601)	-0.0214 (0.0529)
Fraction of moderately-destroyed buildings		0.0006 (0.0025)	-0.0018 (0.0039)	0.0017 (0.0041)	-0.0082 (0.0061)	-0.0051 (0.0057)
Log distance to water			0.0734 (0.0462)	0.0686 (0.0603)	-0.1325 ^c (0.0704)	-0.0879 (0.0819)
Altitude and slope			Yes	Yes	Yes	Yes
Soil conditions			Yes	Yes	Yes	Yes
Latitude and longitude			Yes	Yes	Yes	Yes
Number of blocks	174	174	174	158	174	158
R-squared	0.583	0.599	0.658	0.489	0.412	0.213

Note: We report the OLS estimates of equation (2) in the main text. The controls include the altitude and its square, the slope and its square, a dummy for bad soil conditions, and geographical coordinates (latitude, longitude, and their interaction). Heteroskedasticity-robust standard errors in parentheses. ^a, ^b and ^c indicates significance at the 1, 5 and 10 percent level, respectively.

B.2 Robustness Checks

Employment Table B.2 reports the regression results from estimating equation (1) for employment, in the same manner as Table 1 for population. The estimated coefficients are very similar to Table 1, but somewhat closer to -1. In Columns (3)–(6), we cannot reject the null hypothesis of $\gamma = -1$, implying complete recovery to the pre-war employment distribution.

Characteristics of Neighboring Blocks Post-war population growth of block i may depend not only on its own characteristics but also on the characteristics of adjacent blocks $i' \neq i$. To consider

Table B.2: Changes in employment density and war-time damage

	(1)	(2)	(3)	(4)	(5)	(6)
Change in log employment density 1945–1950						
Change in log employment density 1938–1945 (γ)	-0.7501 ^a (0.0363)	-0.8131 ^a (0.0403)	-0.8458 ^a (0.0409)	-0.8829 ^a (0.0533)	-0.9018 ^a (0.0499)	-0.9240 ^a (0.0336)
<i>p</i> -value from testing $\gamma = -1$	0.000	0.000	0.000	0.029	0.051	0.025
Natural location characteristics (first nature)		Yes		Yes	Yes	Yes
Built location characteristics (second nature)			Yes	Yes	Yes	Yes
Pre-war trends in population					Yes	
Within 3 km from the city center						Yes
Number of blocks	174	174	174	174	174	158
R-squared	0.757	0.795	0.775	0.814	0.823	0.877

Note: This table reports the OLS estimation results of estimating equation (1) for employment. The set of control variables is the same as in Table 1 in the main text. In Column (6), we confine the sample to blocks within 3 kilometers of the city center. We report the *p*-value from testing the null $\gamma = -1$. Heteroskedasticity-robust standard errors in parentheses. ^a indicates significance at the 1 percent level.

the characteristics of neighbors, we adopt the “SLX model” from the spatial econometrics literature (Halleck Vega and Elhorst 2015) and control for the spatial lag of the following three types of dependent variables in our main regression equation (1). The spatial lag of $\ln\left(\frac{\text{Popdens}_{i,1945}}{\text{Popdens}_{i,1936}}\right)$ summarizes the wartime destruction rate of surrounding blocks and the spatial lag of X_i summarizes the location characteristics of neighboring blocks. We use the exponential spatial weighting matrix by using geographical distance between centroids of blocks in kilometers, implying that the characteristics of blocks close to block i are given more weight.²³ We also construct the spatial lag of population right after the bombing, which is meant to capture the market access of a given block.²⁴ We additionally control for these spatial lag variables in our main regression analysis. Table B.3 shows that the inclusion of these spatial lag variables does not change our conclusion about the coefficient γ . In particular, we cannot reject the null of complete recovery ($\gamma = -1$) in all specifications.

Public Housing In many cities in Japan, the supply of public housing was a primary policy of government right after the war. In Table B.4 Column (1) reports the relationship between the number of public housing units and distance from the CBD. We additionally control for the number of public housing units in our baseline specification to assess how much the provision of public housing after the bombing influenced the recovery of central Hiroshima. Columns (2)–(4) in Table B.4 report the results, which are close to our estimate in Table 1 in the main text. This suggests that the provision of public housing alone did not meaningfully contribute to the recovery of the central city.

²³Following the decay of agglomeration forces in Ahlfeldt et al. (2015), we set the spatial decay parameter at 4.32.

²⁴We set the spatial decay parameter at 0.05 given the commuting cost estimate with respect to geographical distance in Hiroshima, which was reported in a previous version of this paper.

Table B.3: Controlling for characteristics of neighboring blocks

	(1)	(2)	(3)	(4)
	Change in log population density 1945–1950			
Change in log population density 1936–1945 (γ)	-0.9363 ^a (0.0541)	-0.9415 ^a (0.0433)	-0.8395 ^a (0.0778)	-0.9063 ^a (0.0510)
<i>p</i> -value from testing $\gamma = -1$	0.240	0.178	0.041	0.068
Location characteristics (first and second nature)	Yes	Yes	Yes	Yes
Spatial lag of change in log population density 1936–45	Yes			Yes
Spatial lag of control variables (block characteristics)		Yes		Yes
Spatial lag of population right after the bombing			Yes	Yes
Number of blocks	174	174	174	174
R-squared	0.847	0.889	0.846	0.891

Note: We report the OLS estimates of equation (1) when controlling for a spatial lag of dependent variables based on geographic distance between centroids of blocks. In Column (1) the spatial lags of the change in log population density between 1936–45 and block characteristics are constructed using exponential weights, where the decay parameter is set at 4.32. In Column (2), we construct the spatial lag of each control variable (except for latitudes and longitudes) with decay parameter 4.32 and use them as separate controls. In Column (3) the spatial lag of population right after the bombing is constructed using the decay parameter 0.05. In Column (4) we include all of them. We report *p*-values from testing the null $\gamma = -1$. Heteroskedasticity-robust standard errors in parentheses. ^a indicates significance at the 1 percent level.

Table B.4: Controlling for the supply of public housing

	(1)	(2)	(3)	(4)
	Log number of public housing units	Change in log population density 1945–1950		
Distance to CBD	0.0004 ^c (0.0002)			
Change in log population density 1936–1945 (γ)		-0.7270 ^a (0.0273)	-0.8403 ^a (0.0484)	-0.8875 ^a (0.0472)
Number of public housing units		0.0023 (0.0014)	0.0024 ^c (0.0012)	0.0019 (0.0026)
<i>p</i> -value from testing $\gamma = -1$	0.0000	0.0012	0.0184	
Location characteristics (first and second nature)		Yes	Yes	
Number of blocks	22	174	174	158
R-squared	0.234	0.816	0.854	0.866

Note: In Column (1) we regress log number of public housings units on distance to CBD. The number of blocks with public housing units is 22. In Columns (2)–(4), we report the OLS estimates of equation (1) when controlling for the number of public housing units. In Column (2) we do not include other location characteristics, while we include the same set of control variables in Column (3) as in Table 1 in the main text. In Column (4) we focus on 158 blocks within 3 kilometers of the CBD. We report the *p*-value from testing the null $\gamma = -1$. Heteroskedasticity-robust standard errors in parentheses. ^a and ^c indicate significance at the 1 and 10 percent level, respectively.

B.3 Nagasaki

We also analyze the atomic bombing in Nagasaki, the second and last city to experience an atomic bombing as of this writing. We exploit data on population at the school district level in Nagasaki for May 1945 (pre-bombing), October 1945 (post-bombing) and March 1954. The data is sourced

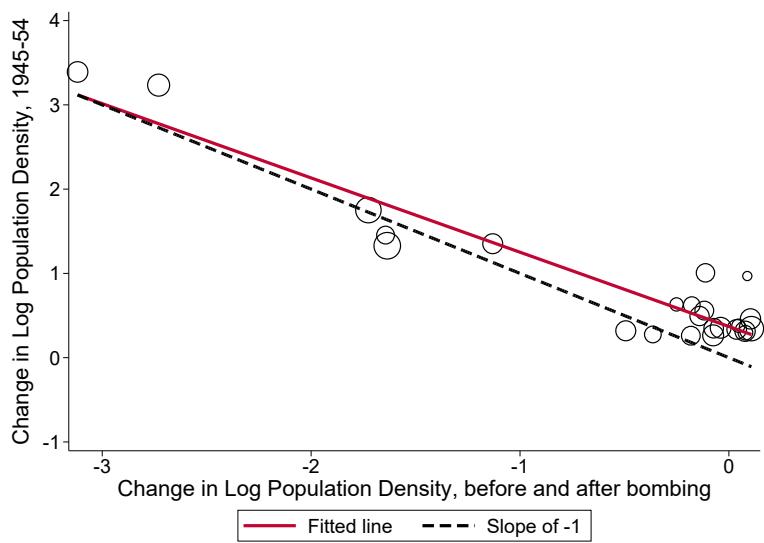
from Nagasaki City Government (1983).

Figure B.1: The map of Nagasaki and reduced-form results

(a) Map of physical damage caused by the atomic bombing (Nagasaki)



(b) Change in population density (Nagasaki)



Note: The map in Figure B.1a shows the epicenter of the bombing in Nagasaki, as well as major facilities and the extent of the damage to structures. This map is provided by the Atomic Bomb Disease Institute at Nagasaki University. Figure B.1b plots the change in the log of population density from 1945 to 1954 compared to changes from May 1945 to October 1945 in Nagasaki. Each circle represents a school district (i.e., an observation), where the size of the circle is proportional to the population density in May 1945. There are 23 school districts in our sample. We plot the (unweighted) linear fit between these two variables (solid line) as well as a line with slope of -1 (dashed line). Indeed, the destroyed areas may be advantageous in attracting more residents, and their population may be higher than in the pre-war period relative to intact areas.

Figure B.1a is the damage map of Nagasaki. The atomic bomb hit the outskirts of the city and the epicenter is more than 2 kilometers away from the city center, where Nagasaki City Hall and Nagasaki Prefectural Office were located. In Figure B.1b we show the relationship between the changes in log population density from 1945–54 (Vertical axis) and those from May 1945 to October 1945. This is the same as in Figure 4 for Hiroshima. Despite the fact that the atomic bomb hit a different part of the city in the case of Nagasaki, the figure shows a very similar pattern to the case of Hiroshima.

The estimated slope of the fitted line in the figure is -0.882 with a standard error of 0.101. We cannot reject the null hypothesis of $\gamma = -1$ at the conventional level. This is suggestive of the recovery of the pre-bombing city structure in Nagasaki, which reinforces the external validity of our results from Hiroshima. Moreover, in Nagasaki, the center of economic activities did not shift toward the destroyed area. This suggests the limited importance of low development costs or creative destruction in our context (Hornbeck and Keniston 2017) because the destroyed pe-

ipheral areas could attract more population and employment than the pre-war period if these factors were dominant.

C Theoretical Appendix

C.1 Value Function

When an individual is able to change their locations, she solves the problem of location choice (7) in the main text. The idiosyncratic taste shocks are drawn from a time-invariant and independent mean-zero Type I extreme distribution: $F(\varepsilon) = \exp(-\exp(-(\varepsilon + \Gamma)))$ where Γ is the Euler-Mascheroni constant: $\Gamma \equiv - \int_0^\infty \ln x e^{-x} dx$.

For $i, n \in \mathcal{C}$, we have distribution functions:

$$G_{int+1}(s) = \text{Prob}[\rho V_{int+1} + \sigma \varepsilon_{int+1} \leq s] = \exp \left[-\exp \left(-\left(\frac{s - \rho V_{int+1}}{\sigma} + \Gamma \right) \right) \right].$$

Therefore, $\rho V_{int+1} + \sigma \varepsilon_{int+1}$ follows the Gumbel distribution with mean ρV_{int+1} and scale parameter σ . The large value of σ leads to large variation. Define

$$V_{t+1}^* \equiv \max \{ \rho V_{int+1} + \sigma \varepsilon_{int+1} ; \rho V_{ot+1} + \sigma \varepsilon_{ot+1} \}$$

Then, we have

$$H_{t+1}(s) = \text{Prob}[V_{t+1}^* \leq s] = \left(\prod_{i \in \mathcal{C}} \prod_{n \in \mathcal{C}} G_{int+1}(s) \right) \times G_{ot+1}(s)$$

which corresponds to the maximum of the Gumbel random variables. It can be shown that this also follows a Gumbel distribution with mean

$$\mu_{t+1} = \mathbb{E}_{t+1}[s] = \sigma \ln \left[\sum_{i \in \mathcal{C}} \sum_{n \in \mathcal{C}} \exp(V_{int+1})^{\rho/\sigma} + \exp(V_{ot+1})^{\rho/\sigma} \right] \quad (\text{C.1})$$

Therefore, we have value functions (8) and (9) in the main text.

C.2 Location Choice

Let $z_{t+1} = \varepsilon + \sigma \Gamma$. When an individual can switch their locations, the probability that she chooses a location pair of workplace i and residential place n in period $t+1$ is

$$\begin{aligned} \lambda_{int+1} &= \int_{-\infty}^{\infty} \left[\prod_{i' \in \mathcal{C}} \prod_{n' \in \mathcal{C}} \exp \left(-e^{-\frac{1}{\sigma} (z_{t+1} + \rho(V_{int+1} - V_{i'n't+1}))} \right) \exp \left(-e^{-\frac{1}{\sigma} (z_{t+1} + \rho(V_{int+1} - V_{ot+1}))} \right) \right] \frac{e^{-z_{t+1}/\sigma}}{\sigma} dz_{t+1} \\ &= \int_{-\infty}^{\infty} \exp \left[-e^{-z_{t+1}/\sigma} \left(\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} e^{-\frac{\rho}{\sigma} (V_{int+1} - V_{i'n't+1})} + e^{-\frac{\rho}{\sigma} (V_{int+1} - V_{ot+1})} \right) \right] \frac{e^{-z_{t+1}/\sigma}}{\sigma} dz_{t+1} \end{aligned}$$

Letting $s_{t+1} = e^{-z_{t+1}/\sigma}$, this becomes

$$\begin{aligned}
& \int_0^\infty \exp \left[-s_{t+1} \left(\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \exp \left(-\frac{\rho}{\sigma} (V_{int+1} - V_{i'n't+1}) \right) + \exp \left(-\frac{\rho}{\sigma} (V_{int+1} - V_{ot+1}) \right) \right) \right] ds_{t+1} \\
&= \left[\frac{\exp(-s_{t+1} (\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \exp(-\frac{\rho}{\sigma} (V_{int+1} - V_{i'n't+1})) + \exp(-\frac{\rho}{\sigma} (V_{int+1} - V_{ot+1}))))}{-\left(\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \exp(-\frac{\rho}{\sigma} (V_{int+1} - V_{i'n't+1})) + \exp(-\frac{\rho}{\sigma} (V_{int+1} - V_{ot+1}))\right)} \right]_0^\infty \\
&= \frac{\exp(V_{int+1})^{\rho/\sigma}}{\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \exp(V_{i'n't+1})^{\rho/\sigma} + \exp(V_{ot+1})^{\rho/\sigma}}
\end{aligned} \tag{C.2}$$

Analogously, the probability that an individual worker lives outside of the city is:

$$\lambda_{ot+1} = \frac{\exp(V_{ot+1})^{\rho/\sigma}}{\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \exp(V_{i'n't+1})^{\rho/\sigma} + \exp(V_{ot+1})^{\rho/\sigma}} \tag{C.3}$$

An individual can change their residential place and workplace with exogenous probability, $\theta_{t+1} \in (0, 1)$. Using the location choice probabilities, the mass of workers choosing location i as a workplace and location n as a residential place in period $t + 1$ can be expressed by:

$$\begin{aligned}
L_{int+1} &= (1 - \theta_{t+1})L_{int} + \theta_{t+1}\lambda_{int+1}L_t + \theta_{t+1}\lambda_{int+1}(M - L_t) \\
&= (1 - \theta_{t+1})L_{int} + \theta_{t+1}\lambda_{int+1}M
\end{aligned}$$

We can use the same idea to derive the dynamics of population (12) and employment (13):

$$R_{nt+1} = \sum_{i \in \mathcal{C}} L_{int+1} = (1 - \theta_{t+1})R_{nt} + \theta_{t+1} \left[\sum_{i \in \mathcal{C}} \lambda_{int+1} \right] M \tag{C.4}$$

$$L_{it+1} = \sum_{n \in \mathcal{C}} L_{int+1} = (1 - \theta_{t+1})L_{it} + \theta_{t+1} \left[\sum_{n \in \mathcal{C}} \lambda_{int+1} \right] M \tag{C.5}$$

The total population of the city is

$$L_{t+1} = \sum_{i \in \mathcal{C}} \sum_{n \in \mathcal{C}} L_{int+1} = (1 - \theta_{t+1})L_t + \theta_{t+1}(1 - \lambda_{ot+1})M \tag{C.6}$$

C.3 Equilibrium

Let $\tilde{V}_{int} = V_{int} - V_{ot}$ and $\tilde{u}_{int} \equiv u_{int}/u_{ot}$. Our Bellman equations imply:

$$\tilde{V}_{int} = \ln \tilde{u}_{int} + (1 - \theta_{t+1})\rho \tilde{V}_{int+1}$$

Iterating this, we obtain:

$$\begin{aligned}
\tilde{V}_{int} &= \ln \tilde{u}_{int} + \sum_{\tau=t+1}^T \left\{ \prod_{s=t+1}^{\tau} \rho(1-\theta_s) \right\} \ln \tilde{u}_{in\tau} \\
&= \ln \left\{ \tilde{u}_{int} \prod_{\tau=t+1}^T (\tilde{u}_{in\tau})^{\prod_{s=t+1}^{\tau} \rho(1-\theta_s)} \right\} \\
&= \ln \left\{ \frac{a_{it} b_{nt}}{\kappa_{int} u_{ot}} \left(\frac{L_{it}}{S_i} \right)^{\alpha} \left(\frac{R_{nt}}{S_n} \right)^{\beta} \prod_{\tau=t+1}^T \left(\frac{a_{i\tau} b_{n\tau}}{\kappa_{in\tau} u_{o\tau}} \left(\frac{L_{i\tau}}{S_i} \right)^{\alpha} \left(\frac{R_{n\tau}}{S_n} \right)^{\beta} \right)^{\prod_{s=t+1}^{\tau} \rho(1-\theta_s)} \right\}.
\end{aligned} \tag{C.7}$$

The probability (C.2) can be expressed as:

$$\lambda_{int+1} = \frac{\exp(\tilde{V}_{int+1})^{\rho/\sigma}}{\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \exp(\tilde{V}_{i'n't+1})^{\rho/\sigma} + 1} \tag{C.8}$$

Therefore, we obtain the population in location n :

$$R_{nt+1} = (1 - \theta_{t+1})R_{nt} + \theta_{t+1} \left[\sum_{i \in \mathcal{C}} \frac{\exp(\tilde{V}_{int+1})^{\rho/\sigma}}{\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \exp(\tilde{V}_{i'n't+1})^{\rho/\sigma} + 1} \right] M \tag{C.9}$$

and employment in location i :

$$L_{it+1} = (1 - \theta_{t+1})L_{it} + \theta_{t+1} \left[\sum_{n \in \mathcal{C}} \frac{\exp(\tilde{V}_{int+1})^{\rho/\sigma}}{\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \exp(\tilde{V}_{i'n't+1})^{\rho/\sigma} + 1} \right] M \tag{C.10}$$

The equilibrium is characterized by $\{R_{nt}, L_{it}\}$ solving (C.7), (C.9) and (C.10) jointly.

We show the existence of a forward-looking competitive equilibrium in which population and employment satisfy $R_{nt+1} \geq (1 - \theta_{t+1})R_{nt}$ and $L_{it+1} \geq (1 - \theta_{t+1})L_{it}$ given θ_{t+1} . To simplify the notation, we suppose $(1 - \theta_{t+\tau})\rho \rightarrow 0$ for $\tau \geq 2$. Yet, our following argument can be applied to the general case. In this case the forward-looking equilibrium is characterized by $\{R_{nt}\}$ and $\{L_{it}\}$ solving the system of equations:

$$\begin{aligned}
R_{nt+1} &= (1 - \theta_{t+1})R_{nt} + \sum_{i \in \mathcal{C}} \frac{\mathcal{X}_{int+1} R_{nt+1}^{\beta \varkappa_{t+1}}}{\sum_{n' \in \mathcal{C}} \mathcal{X}_{in'n't+1} R_{n'n't}^{\beta \varkappa_{t+1}}} (L_{it+1} - (1 - \theta_{t+1})L_{it}), \\
L_{it+1} &= (1 - \theta_{t+1})L_{it} + \sum_{n \in \mathcal{C}} \frac{\mathcal{X}_{int+1} L_{it+1}^{\alpha \varkappa_{t+1}}}{\sum_{i' \in \mathcal{C}} \mathcal{X}_{i'nt+1} L_{i't+1}^{\alpha \varkappa_{t+1}}} (R_{nt+1} - (1 - \theta_{t+1})R_{nt}),
\end{aligned} \tag{C.11}$$

where $\varkappa_{t+1} \equiv \rho/\sigma$ and \mathcal{X}_{int+1} is exogenous factors.

We suppose that $R_{nt+1} \geq (1 - \theta_{t+1})R_{nt}$ and $L_{it+1} \geq (1 - \theta_{t+1})L_{it}$ for any $\{\theta_t\}$. Letting $\mathbf{X} = (\mathbf{R}, \mathbf{L})$ be a vector of population and employment, we define the operator $J(\mathbf{X})$ such

that the ι -th element $J_\iota(\mathbf{X})$ corresponds to the right-hand side of (C.11). When $R_{nt+1} \geq (1 - \theta_{t+1})R_{nt}$ and $L_{it+1} \geq (1 - \theta_{t+1})L_{it}$, we can define the convex subset of \mathbb{R}_{++}^{2N} where the operator J is mapping from the subset to itself. The operator J is a continuous mapping. Therefore, by Brouwer's fixed-point theorem, there exist forward-looking equilibrium that satisfy: $R_{nt+1} \geq (1 - \theta_{t+1})R_{nt}$ and $L_{it+1} \geq (1 - \theta_{t+1})L_{it}$.

C.4 Steady State Equilibrium

If the steady state equilibrium exists, it is a stationary steady state where all model variables are constant over time. We therefore drop time subscripts of variables when describing the steady state. In such a stationary steady state, the conditional probabilities that workers commute to i given residential location n become:

$$\lambda_{i|n}^L = \frac{\lambda_{in}}{\sum_{j \in \mathcal{C}} \lambda_{jn}} = \frac{\mathcal{A}_{in} L_i^{\alpha\varkappa}}{\sum_{i' \in \mathcal{C}} \mathcal{A}_{i'n} L_{i'}^{\alpha\varkappa}}$$

where we let $\varkappa \equiv \rho/\sigma$ and $\mathcal{A}_{in} \equiv (a_i/\kappa_{in})^{\rho/\sigma}$ summarizes the time-invariant fundamental productivity consistent with the steady-state. Analogously the conditional probabilities that workers live in n given workplace i become:

$$\lambda_{n|i}^R = \frac{\lambda_{in}}{\sum_{n' \in \mathcal{C}} \lambda_{in'}} = \frac{\mathcal{B}_{in} R_n^{\beta\varkappa}}{\sum_{n' \in \mathcal{C}} \mathcal{B}_{in'} R_{n'}^{\beta\varkappa}}$$

where $\mathcal{B}_{in} \equiv (b_n/\kappa_{in})^{\rho/\sigma}$. In sum, the steady state equilibrium is characterized by variables $\{R_n, L_i, \Phi_i, Y_n\}$ solving the system of equations:

$$R_n^{1-\tilde{\beta}\varkappa} = \sum_{i \in \mathcal{C}} \mathcal{B}_{in} \Phi_i^{-1} L_i, \quad \Phi_i = \sum_{n \in \mathcal{C}} \mathcal{B}_{in} R_n^{\beta\varkappa}, \quad L_i^{1-\tilde{\alpha}\varkappa} = \sum_{n \in \mathcal{C}} \mathcal{A}_{in} Y_n^{-1} R_n, \quad Y_n = \sum_{i \in \mathcal{C}} \mathcal{A}_{in} L_i^{\alpha\varkappa}$$

To exploit the result of [Allen, Arkolakis, and Li \(2020\)](#), we define the following matrices \mathbf{C} and \mathbf{D} that summarize the parameters from the left and right-hand sides of the system of equations, respectively:

$$\mathbf{C} = \begin{bmatrix} 1 - \beta\varkappa & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 - \alpha\varkappa & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \mathbf{D} = \begin{bmatrix} 0 & -1 & 1 & 0 \\ \beta\varkappa & 0 & 0 & 0 \\ 1 & 0 & 0 & -1 \\ 0 & 0 & \alpha\varkappa & 0 \end{bmatrix}$$

Matrix \mathbf{C} is a diagonal matrix and invertible when $\alpha \neq 1/\varkappa$ and $\beta \neq 1/\varkappa$, and steady state equilibrium exists when these conditions hold. Then, we define matrix $\Gamma = |\mathbf{DC}^{-1}|$. Using the results in [Allen, Arkolakis, and Li \(2020\)](#), the system of equations has a unique up-to-scale solution

if all eigenvalues of the matrix Γ are no larger than one. In our case the sufficient conditions for a unique up-to-scale solution are:

$$\frac{|\beta\varkappa| + 1}{|1 - \beta\varkappa|} \leq 1, \quad \frac{|\alpha\varkappa| + 1}{|1 - \alpha\varkappa|} \leq 1$$

These conditions hold if and only if $\beta \leq 0$ and $\alpha \leq 0$. The agglomeration forces in productivity (α) and amenities (β) must be negative so that the congestion force dominates the agglomeration force for both workplaces and residential places to ensure a unique up-to-scale solution. The total population in the city pins down the level of the solution, and we obtain a unique stationary steady state.

C.5 Microfoundations of Agglomeration Forces in Amenities

We show that the specification of preferences and residential amenities (B_{nt}) is derived from a simple microfoundation, which is close to the literature on quantitative urban models.

Preference Conditional on a residential place and workplace, an individual decides their consumption pattern. Individuals consume nontradable local services and housing in their residences. The indirect utility of an individual that lives in n and works in i in period t is:

$$u_{int} = \frac{w_{it}}{(P_{nt})^\mu (Q_{nt})^{1-\mu}} \frac{\tilde{B}_{nt}}{\kappa_{int}} \quad (\text{C.12})$$

where w_{it} is the wage in i ; P_{nt} is the price index of local services in n ; Q_{nt} is the housing price in n ; \tilde{B}_{nt} is unobserved fundamental amenities; and κ_{int} is commuting costs from n to i . μ is the share of expenditure devoted to local services, and $1 - \mu$ is the share of expenditure devoted to housing. The price index of local services is a CES function of the prices and number of varieties supplied, taking the form:

$$P_{nt} = \left[\sum_{s \in \mathcal{I}_{nt}} \left(\frac{p_{snt}}{\varphi_{snt}} \right)^{1-\psi} \right]^{1/(1-\psi)}, \quad \psi > 1, \quad (\text{C.13})$$

where ψ is the constant elasticity of substitution between varieties; we assume that varieties are substitutes ($\psi > 1$); \mathcal{I}_{nt} is the set of varieties available in n ; p_{snt} is the price of each variety; and φ_{snt} captures the quality of variety as reflected in consumer taste.

Housing Market Clearing In each block there are homogenous developers who supply housing by combining land and homogenous tradable goods. We adopt a similar setup for developers in [Sturm, Takeda, and Venables \(2023\)](#). The housing market clearing condition is given by:

$$\frac{(1 - \mu)\bar{y}_{nt}R_{nt}}{Q_{nt}} = \left(\frac{Q_{nt}}{\eta\Lambda_{nt}} \right)^{1/(\eta-1)} S_n,$$

where \bar{y}_n is the average income of individuals living in n ; Q_{nt} is housing prices; S_n is the total amount of land; and Λ_{nt} is the exogenous productivity of developers that captures heterogeneity in construction costs across locations. η controls the housing supply elasticity and we posit $\eta > 1$. The left-hand side is the demand for housing and the right-hand side is the supply of housing. Therefore, housing prices in equilibrium are:

$$Q_{nt} = (\eta \Lambda_{nt})^{1/\eta} \left[\frac{(1 - \mu) \bar{y}_{nt} R_{nt}}{S_n} \right]^{(\eta-1)/\eta} \quad (\text{C.14})$$

Local Services The CES demand system implies expenditures on a single variety in n are

$$e_{snt} = \left(\frac{p_{snt}/\varphi_{snt}}{P_{nt}} \right)^{1-\psi} \mu \bar{y}_{nt} R_{nt} \quad (\text{C.15})$$

In each block firms in the local service sector produce a variety using homogenous goods and maximize profit given (C.15). Production incurs a fixed cost of f units of homogeneous goods. Then, the price of each variety is given by: $p_{nst} = \psi/(\psi - 1)$ and firms make zero profits if they sell output level $\bar{z} = (\psi - 1)f$. Then the CES price index (C.13) can be written as:

$$P_{nt} = \frac{\psi}{\psi - 1} \frac{1}{\tilde{\varphi}_{nt}}, \quad \tilde{\varphi}_{nt} = \left[\sum_{s \in \mathcal{I}_{nt}} (\varphi_{snt})^{\psi-1} \right]^{1/(\psi-1)}, \quad (\text{C.16})$$

The market clearing condition for local services is:

$$\left(\frac{\psi}{\psi - 1} \right)^{-\psi} (\varphi_{snt})^{\psi-1} (P_{nt})^{\psi-1} \mu \bar{y}_{nt} R_{nt} = (\psi - 1)f, \quad (\text{C.17})$$

where the left-hand side is the demand for variety s , and the right-hand side is its supply. We substitute the price index and apply the definition of $\tilde{\varphi}_{nt}$ to (C.16) into (C.17) to derive the number of varieties:

$$N_{nt}^* = |\mathcal{I}_{nt}| = \frac{\mu \bar{y}_{nt} R_{nt}}{\psi f} \quad (\text{C.18})$$

We suppose that consumer tastes (φ_{snt}) in n depends on average income in n (\bar{y}_{nt}) and idiosyncratic unobserved taste shocks (φ_{snt}^*):

$$\varphi_{snt} = \varphi_{snt}^* (\bar{y}_{nt})^\vartheta. \quad (\text{C.19})$$

Taste adjusted price (p_{snt}/φ_{snt}) is supposed to be decreasing in average income ($\vartheta > 0$), which is consistent with the better quality of consumption amenities in high-income areas (e.g., Diamond 2016). The generalized mean of order- r of unobserved consumer taste shocks is normalized: $\left[\frac{1}{N_{nt}^*} \sum_{s \in \mathcal{I}_{nt}} (\varphi_{snt}^*)^r \right]^{1/r} = 1$. When we substitute (C.19) into (C.16) together with (C.18), we obtain:

$$P_{nt} = \frac{\psi}{\psi - 1} (N_{nt}^*)^{1/(1-\psi)} (\bar{y}_{nt})^\vartheta = \delta (\bar{y}_{nt})^{1/(1-\psi)+\vartheta} (R_{nt})^{1/(1-\psi)}, \quad (\text{C.20})$$

where we let δ refer a constant parameter.

Amenities Suppose $\frac{\eta-1}{\eta}(1-\mu) = \mu \left(\frac{1}{\psi-1} - \vartheta \right)$ for parameters. Using (C.14) for housing prices and (C.20) for the price index, indirect utility (C.12) can be written as:

$$u_{int} = \frac{w_{it}\tilde{B}_{nt}}{(\delta)^\mu(1-\mu)^{\frac{(\eta-1)(1-\mu)}{\eta}} (\eta\Lambda_{nt})^{\frac{1-\mu}{\eta}} \kappa_{int}(R_{nt})^{-\frac{\mu}{\psi-1} + \frac{\eta-1}{\eta}(1-\mu)} (S_n)^{-\frac{\eta-1}{\eta}(1-\mu)}}. \quad (\text{C.21})$$

We can manipulate (C.21) to derive the preference (5) and write amenities (B_{nt}) as a function of population density (R_{nt}/S_n) as given in (6) in the main text. When we set the elasticity of population density in amenities (β) such that $\beta = \mu\vartheta$, our specification of amenities (6) is consistent with this microfoundation.

D Calibration Appendix

D.1 Step # 1: Travel Mode Choice and Gravity Equation for Commuting

Travel Mode Choice (κ_{int}) To estimate the commuting cost, we follow [Tsivanidis \(2022\)](#) by extending the model to incorporate multiple travel modes. Suppose that the bilateral travel cost for an individual using travel mode m $\kappa_{int}^m(\omega)$ is given by $\kappa_{int}^m(\omega) \equiv \exp(c_{int}^m(\omega)) > 0$ with an inverse of mode-specific travel cost:

$$-c_{int}^m(\omega) \equiv -\delta\tau_{int}^m + \gamma^m + s_{int}^m(\omega),$$

where τ_{int}^m is the travel time in minutes between i and n ; δ captures the marginal increase in travel cost when travel time increases by one minute; γ^m is the mode-specific fixed cost; and $s_{int}^m(\omega)$ is an unobserved idiosyncratic shock to the commuting cost by the mode m between i and n . Workers choose transit mode m to minimize the commuting cost (i.e, maximize $-c_{int+1}^m$) conditional on their location choice.

We assume that $s_{int}^m(\omega)$ follows a Gumbel distribution with two nests: the nest of public modes $\mathcal{B}_{\text{pub}} \equiv \{\text{Walk, Bus, Train}\}$ and the nest of private-vehicle modes $\mathcal{B}_{\text{prv}} \equiv \{\text{Bike, Car}\}$. The former nest does not require owning a private vehicle. Using the well-known log-sum formula ([Train 2009](#)), we can write the expected commuting cost as

$$\bar{c}_{int}^{\text{car}} = -\ln \left[\exp(-\bar{c}_{int}^{\text{pub}}) + \exp(-\bar{c}_{int}^{\text{prv}}) \right], \quad \bar{c}_{int}^k \equiv -\nu_k \ln \left[\sum_{m \in \mathcal{B}_k} e^{-(\delta\tau_{int}^m - \gamma^m)/\nu_k} \right],$$

where ν_k is the dissimilarity parameter of nest $k \in [\text{pub, prv}]$.

We use the 1987 travel survey of Hiroshima to estimate $(\delta, \gamma^m, \nu_{\text{pub}}, \nu_{\text{prv}})$ in this nested logit model by the maximum likelihood estimator. We obtain $\delta = 0.019$ with standard error 0.002. We also estimate that $\nu_{\text{pub}} = 0.129$ with standard error 0.014 and $\nu_{\text{prv}} = 0.117$ with standard error 0.013, implying strong substitution within each nest since both estimates are far from 1.

Then, we have $\mathbb{E}(\ln \kappa_{int}^m) = \bar{c}_{int}$, which we use as the log bilateral travel cost ($\ln \kappa_{int}$) in our main calibration. We suppose that with probability p_{car} , a worker can choose a car as a commuting mode. Otherwise, a car is unavailable so that the private nest is modified as $\mathcal{B}_{\text{prv}, \text{nocar}} \equiv \{\text{Bike}\}$. We set the probability p_{car} based on the car ownership rate in Japan: 10 percent in 1950; 20 percent in 1955; 30 percent in 1960; 40 percent in 1965; 50 percent in 1970; and 70 percent in 1975.²⁵ Then, the expected commuting cost is $\bar{c}_{int} = p_{car}\bar{c}_{int+1}^{\text{car}} + (1 - p_{car})\bar{c}_{int+1}^{\text{nocar}}$, where $\bar{c}_{int+1}^{\text{nocar}}$ is defined in the same way as $\bar{c}_{int+1}^{\text{car}}$, except that the summation in $\bar{c}_{int+1}^{\text{prv}}$ is over $\mathcal{B}_{\text{prv}, \text{nocar}}$ because a car is unavailable.

Gravity of Commuting (ρ/σ) In a steady state, the log of number of commuters from n to i becomes:

$$\ln L_{in} = \frac{\rho}{\sigma} (\ln B_n + \ln w_i - \ln \bar{\kappa}_{in}) + \ln \bar{M}, \quad (\text{D.1})$$

where

$$\begin{aligned} \ln \bar{M} &\equiv \ln \left[M \left(\sum_{i' \in \mathcal{C}} \sum_{n' \in \mathcal{C}} \bar{u}_{i'n'}^{\rho/\sigma} \right)^{-1} \right], \\ -\ln \bar{\kappa}_{in} &\equiv \mathbb{E} \left[\max_m -\ln \kappa_{in}^{m,\omega} \right] = \mathbb{E} \left[\max_m -c_{in}^{m,\omega} \right] = -\bar{c}_{in} \end{aligned}$$

This corresponds to the gravity equation (14) in the main text. In estimating this gravity equation, we further suppose that there is an additional additive error term, which includes measurement errors.

Table D.1: Gravity estimates for commuting

	(1)	(2)	(3)	(4)	(5)	(6)
	ln commuting flow		ln(commuting flow+1)		Commuting flow	
Average commuting cost (\bar{c}_{in})	-4.082 ^a (0.156)	-3.976 ^a (0.170)	-5.758 ^a (0.179)	-3.931 ^a (0.169)	-8.019 ^a (0.195)	-7.031 ^a (0.215)
Estimation	OLS		OLS		PPML	
Number of observations	2,473	1,635	4,356	1,635	4,290	1,635
More than 20 commuters		Yes		Yes		Yes
R-squared/ Pseudo R-squared	0.543	0.522	0.551	0.521	0.764	0.729

Note: We report estimates of (14) by OLS in Columns (1) and (2). In Columns (3) and (4), we use OLS but add 1 to commuting flows to avoid dropping observations with zero commuting flows. We use the PPML in Columns (5) and (6). We use the average commuting costs that we computed in mode choice and include origin and destination fixed effects. Note that Column (5) has slightly fewer observations than Column (3) because of computational issues in PPML (Correia, Guimarães, and Zylkin 2020). Standard errors in parentheses. ^a indicates significance at the 1 percent level.

²⁵Note that we have implicitly assumed $p_{car} = 1$ in estimating the nested logit model using the 1987 travel survey data, given the very high car ownership rate in 1987.

Table D.1 presents the results of the estimation of the gravity equation for commuting. Columns (1) and (2) provide OLS results. In Columns (3) and (4) we use OLS but we add 1 to the commuting flow (L_{in}) so that we do not lose observations with zero commuting flows. We use the PPML for Columns (5) and (6). In each case, we also report results when dropping bilateral pairs of less than 20 commuters to assess the robustness to sampling noise. Our preferred specification is Column (5), which possesses the theoretically desirable properties of the PPML (Santos Silva and Tenreyro 2006), and we set $\rho/\sigma = 8$ in our calibration.

D.2 Step # 2: Inversion of Option Values of Productivity and Amenities

Our focus in this step is to back out the continuation value of amenities (15) and productivity (16). The probability of location choices (C.8) becomes: $\lambda_{int} = \lambda_{ot} \exp(\tilde{V}_{int})^{\rho/\sigma}$. Then, (C.9) and (C.10) can be expressed by:

$$\begin{aligned} R_{nt} - (1 - \theta_t)R_{nt-1} &= \lambda_{ot}\theta_t \left[\sum_{i \in \mathcal{C}} \exp(\tilde{V}_{int})^{\rho/\sigma} \right] M, \\ L_{it} - (1 - \theta_t)L_{it-1} &= \lambda_{ot}\theta_t \left[\sum_{n \in \mathcal{C}} \exp(\tilde{V}_{int})^{\rho/\sigma} \right] M \end{aligned} \quad (\text{D.2})$$

for all locations (i, n) in a city and periods $t = 1, \dots, T$. We also use the following notations

$$K_{int} \equiv \kappa_{int}^{-\rho/\sigma} \left[\prod_{\tau=t+1}^T \kappa_{int}^{-\prod_{s=\tau+1}^T \rho(1-\theta_s)} \right]^{\rho/\sigma}, \quad v_t \equiv u_{ot}^{-\rho/\sigma} \left[\prod_{\tau=t+1}^T u_{ot}^{-\prod_{s=\tau+1}^T \rho(1-\theta_s)} \right]^{\rho/\sigma} \quad (\text{D.3})$$

for commuting costs and outside option values. Then, (D.2) becomes:

$$R_{nt} - (1 - \theta_t)R_{nt-1} = \lambda_{ot}\theta_t v_t M \Xi_{nt}^{\rho/\sigma} \sum_{i \in \mathcal{C}} K_{int} \Omega_{it}^{\rho/\sigma}, \quad (\text{D.4})$$

$$L_{it} - (1 - \theta_t)L_{it-1} = \lambda_{ot}\theta_t v_t M \Omega_{it}^{\rho/\sigma} \sum_{n \in \mathcal{C}} K_{int} \Xi_{nt}^{\rho/\sigma}. \quad (\text{D.5})$$

for periods $t = 1, 2, \dots, T$. Substituting (D.5) into (D.4) yields the system of equations (17) in the main text. Solving the system conditional on observations of population and employment $\{R_{nt}, L_{it}\}$ and parameter $\{\theta_t\}$, we obtain $\{\Xi_{nt}, \Omega_{it}\}$. Given $\rho/\sigma > 0$, this system of equations is solved for unique solutions $\{\Xi_{nt}, \Omega_{it}\}$ up to scale if $L_{it} - (1 - \theta_t)L_{it-1} \geq 0$ and $R_{nt} - (1 - \theta_t)R_{nt-1} \geq 0$ hold. This step does not require the parameter values of agglomeration.

D.3 Step # 3: Estimation of Agglomeration Parameters (α, β)

Step 2 derives $\{\Xi_{nt}, \Omega_{it}\}$ consistent with observed data to be an equilibrium. By construction, in the last period T

$$\Xi_{nT} = b_{nT} \left(\frac{R_{nT}}{S_n} \right)^\beta. \quad (\text{D.6})$$

Given the observed population (R_{nT}), block size (S_n) and parameters (α, β) , we can invert this for fundamental amenities $\{b_{nT}\}$ in period T . In period $T - 1$ we have:

$$\Xi_{nT-1} = b_{nT-1} \left(\frac{R_{nT-1}}{S_n} \right)^\beta (\Xi_{nT})^{\rho(1-\theta_T)}. \quad (\text{D.7})$$

Given population density in period $T - 1$, parameter ρ , migration friction θ_T and option value $\{\Xi_{nT}\}$, we can invert this for the fundamental amenities in the previous period. We continue this process and obtain the sequence of fundamental amenities: $\{b_{nt}\}_{t=1,\dots,T}$. For productivity, we can decompose $\{\Omega_{it}\}_{t=1,2,\dots,T}$ to obtain the sequence of fundamental productivity $\{a_{it}\}_{t=1,\dots,T}$ in an analogous way.

We suppose that fundamental amenities and productivity $\{a_{it}, b_{nt}\}_{t=1,\dots,T}$ consist of location fixed components, time fixed components and variant terms:

$$\ln a_{it} = \ln a_i^F + \ln a_t^* + \ln a_{it}^{\text{Var}}, \quad \ln b_{nt} = \ln b_n^F + \ln b_t^* + \ln b_{nt}^{\text{Var}} \quad (\text{D.8})$$

where $\{a_i^F, b_n^F\}$ are location-fixed productivity and amenities; $\{a_t^*, b_t^*\}$ are the trends of productivity and amenities common for all blocks; and $\{a_{it}^{\text{Var}}, b_{nt}^{\text{Var}}\}$ are the idiosyncratic parts of fundamental productivity and amenities. The location fixed productivity and amenities capture the first nature advantages of locations. Averaging out the trend yields:

$$\ln \left(\frac{a_{it}}{\tilde{a}_t} \right) = \ln \left(\frac{a_i^F}{\tilde{a}_t^F} \right) + \ln \left(\frac{a_{it}^{\text{Var}}}{\tilde{a}_t^{\text{Var}}} \right), \quad \ln \left(\frac{b_{nt}}{\tilde{b}_t} \right) = \ln \left(\frac{b_n^F}{\tilde{b}_t^F} \right) + \ln \left(\frac{b_{nt}^{\text{Var}}}{\tilde{b}_t^{\text{Var}}} \right),$$

where we use the geometric mean of variables (e.g., $\tilde{a}_t \equiv \frac{1}{N} \sum_{i \in \mathcal{C}} \ln a_{it}$). Then, we take the difference between periods and suppose the following moment conditions:

$$\mathbb{E}[\Delta \ln(a_{it}/\tilde{a}_t) \times \mathbb{1}_i(k)] = 0, \quad \mathbb{E}[\Delta \ln(b_{nt}/\tilde{b}_t) \times \mathbb{1}_n(k)] = 0, \quad (\text{D.9})$$

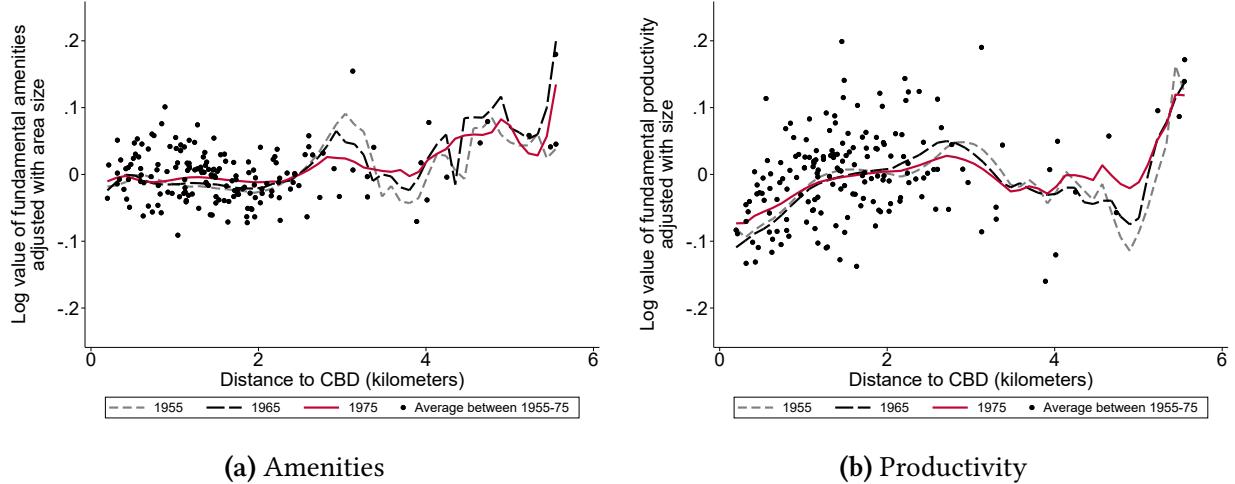
where $\mathbb{1}_i(k)$ is an indicator such that location i is in grid k , which we define based on the distance from the CBD in our main estimation. We use the moment conditions (D.9) to estimate the set of parameters of agglomeration forces (α, β) .

D.4 Calibrated Amenities and Productivity

In Figure D.1 we show the polynomial fitted lines for the log of fundamental productivity (a_{it}) and amenities (b_{nt}) net block size effects for 1955, 1965 and 1975. We also show their averages between 1955 and 1975. We adjust for block size since fundamental amenities and productivity tend to be mechanically undervalued for smaller blocks. Intuitively, other things being equal, a smaller block is likely to have higher population and employment density given the idiosyncratic preferences, irrespective of the block size. Thus, location-specific productivity and amenities may

be undervalued in smaller blocks to offset such a small-block advantage. To adjust for this, we regress our estimate of the log of location-specific productivity and amenities on the log of block size, and we plot the residuals from the regressions.²⁶ We find that both productivity and amenities are not systematically related to distance from the CBD. In particular, fundamental amenities and productivity in the central area of the city are not high relative to the outskirts.

Figure D.1: Fundamental productivity and amenities (Accounting for block size heterogeneity)



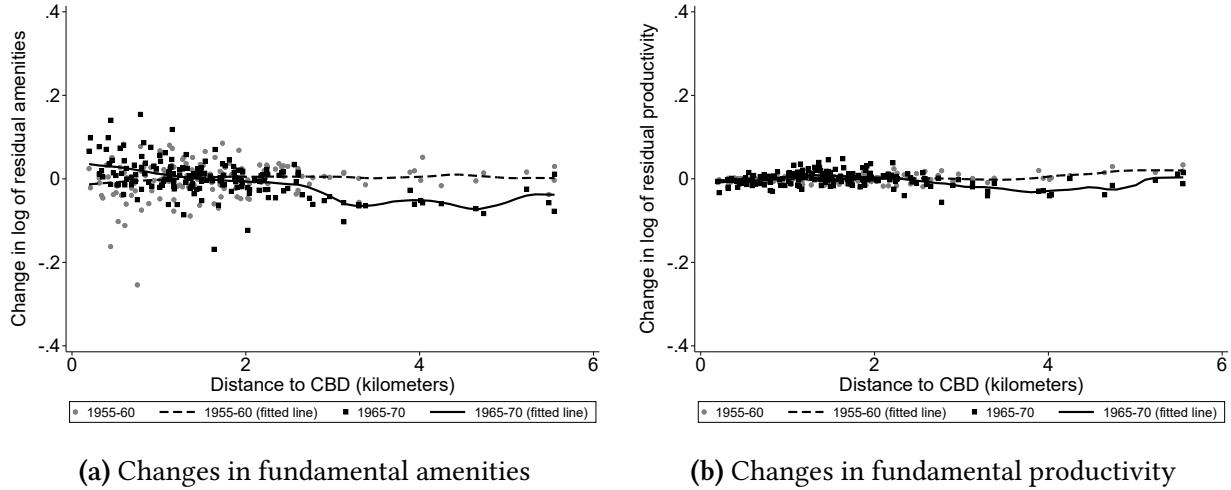
Note: These figures display fundamental productivity (a_{it}) and amenities (b_{nt}) in our calibration after netting out block size effects. The vertical axis shows the residuals of the linear regression of the log of fundamentals on the log of block size. We report local polynomial fitted lines for 1955, 1965 and 1975. In addition, we plot the average of the residuals over the period 1955–1975. Each dot represents a block. The horizontal axis is the distance from the CBD. Panel (a) shows the residuals in amenities, and Panel (b) shows those in productivity.

Next, we examine the moment conditions used for our estimation. In Figure D.2 we visualize the changes in residuals of fundamental amenities $\Delta \ln(b_{nt}/\tilde{b}_t)$ and productivity $\Delta \ln(a_{it}/\tilde{a}_t)$ for 1955–1960 and 1965–1970. We plot each against the distance from the CBD and show polynomial fitted lines. The changes in residuals of amenities exhibit little variation across the city for both periods. This confirms that the idiosyncratic part of the fundamental location advantages in amenities and productivity is less important in explaining the pattern of changes in population and employment. In particular, the flat pattern of changes in amenities during 1955–1960 shows that the idiosyncratic factors in the structural residuals in amenities do not primarily explain the population changes. During 1965–1970, we observe some increase in the residuals close to the CBD but declining in the periphery. This is consistent with the suburbanization that proceeded during these periods in many Japanese cities. For residuals of productivity, their variation is relatively small within the city for both periods. This implies that idiosyncratic shocks in fundamental productivity do not account for the variation in the city employment distribution. Overall, these

²⁶See Train (2009), Chapter 3, for the theoretical justification of using the log of size in the adjustment.

results for the idiosyncratic part of fundamental productivity and amenities support our identification assumption.

Figure D.2: Changes in fundamental amenities and productivity for different periods



Note: These figures show changes in the residuals of fundamental amenities $\Delta \ln(b_{nt}/\tilde{b}_t)$ in Panel (a) and productivity $\Delta \ln(a_{it}/\tilde{a}_t)$ in Panel (b) for 1955–1960 and 1965–1970. Each dot (square) represents a block for 1955–1960 (1965–1970), and we show local polynomial fitted lines: a dashed (solid) line for 1955–1960 (1965–1970). The horizontal axis is the distance from the CBD.

Untargeted Moment Conditions for 1950–1955 In our estimation, we use changes in fundamental amenities and productivity every five years from 1955 to 1975. It is also possible to compute fundamental amenities and productivity for 1950 given the estimated agglomeration parameters (α, β). For those fundamentals, we confirm that changes in the structural residuals in fundamental amenities and productivity do not show significant changes between 1950 and 1955. Letting $b_{n,50}$ and $a_{i,50}$ be estimated fundamental amenities and productivity in 1950, we compute

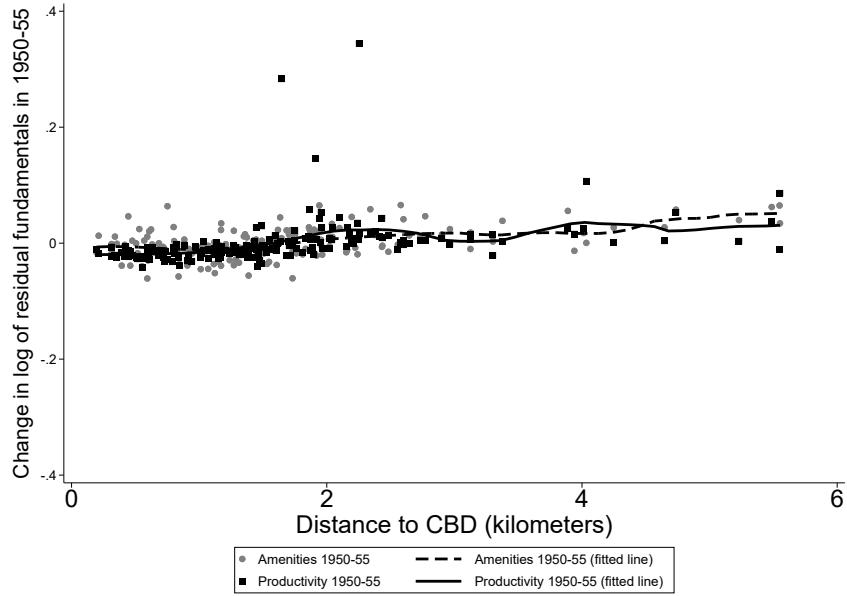
$$\Delta \ln \left(\frac{b_{n,55}}{\tilde{b}_{55}} \right) = \ln \left(\frac{b_{n,55}}{\tilde{b}_{55}} \right) - \ln \left(\frac{b_{n,50}}{\tilde{b}_{50}} \right), \quad \Delta \ln \left(\frac{a_{i,55}}{\tilde{a}_{55}} \right) = \ln \left(\frac{a_{i,55}}{\tilde{a}_{55}} \right) - \ln \left(\frac{a_{i,50}}{\tilde{a}_{50}} \right),$$

where \tilde{b}_{50} and \tilde{a}_{50} represent the geometric means of fundamental amenities and productivity, respectively, in 1950. These can be used to construct analogous moments as per equation (20) for 1950–1955, and this can be used to test the validity of our moment conditions for 1955–1975 as the 1950–1955 moments are not used for our GMM estimation.

In Figure D.3 we visualize these changes relative to the distance from the CBD. The component of the structural residual of amenities exhibits little change between 1950 and 1955, and this suggests that spatial variation in amenity changes was not driven by the structural residuals in this early period. For structural residuals in productivity, while we find a few outliers showing relatively large increases, overall there is minimal variation across the city. This result is consis-

tent with our identifying assumption that changes in the amenities and productivity of each block are uncorrelated with the distance from the CBD.

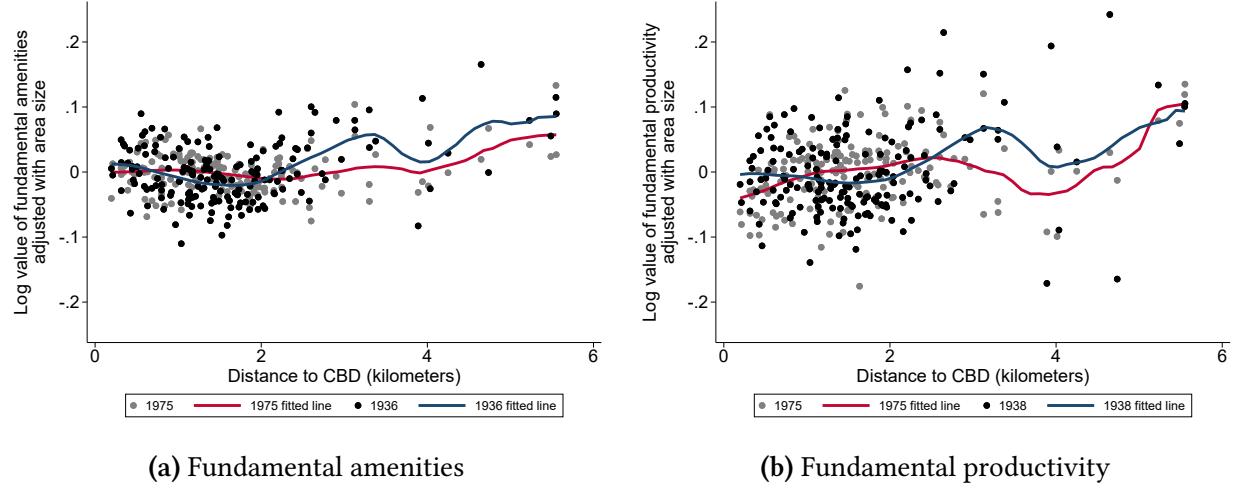
Figure D.3: Changes in fundamental amenities and productivity for 1950–1955



Note: This shows changes in the residuals of fundamental amenities $\Delta \ln(b_{n,55} / \tilde{b}_{55})$ and productivity $\Delta \ln(a_{i,55} / \tilde{a}_{55})$ for 1950–1955. Each dot is an amenity residual for a block, and the dashed line is a local polynomial fitted line for amenities. The squares and solid line are for productivity. The horizontal axis is the distance from the CBD.

Calibrated Fundamentals for the 1930s We validate the pattern of calibrated fundamentals using the pre-war population distribution. We use the population distribution in 1936 and employment distribution in 1938. We suppose that the pre-war population and employment distributions are in a steady state and use the equilibrium conditions to invert the overall productivity and amenities in each block for the 1930s. The transport costs are set to the same level as in 1950, as the transport network in a city did not change much between pre-war and post-war. Given the overall productivity and amenities, we compute the fundamental productivity ($a_{i,30s}$) and amenities ($b_{n,30s}$) using the estimated agglomeration parameters. If the pattern of fundamentals in the 1930s exhibits a similar pattern to the later period, it shows that fundamentals were not directly affected by the atomic bombing. For comparison with the steady state, we contrast fundamentals in the 1930s and 1975. In Figure D.4 we visualize the fundamentals for the 1930s and 1975 after adjusting for block size as in Figure D.1. We find that the overall pattern of fundamental productivity and amenities is similar between the 1930s and 1975, which confirms that these location characteristics were not affected by the atomic bombing.

Figure D.4: Fundamental amenities and productivity in the 1930s and 1975



Note: These figures display fundamental productivity and amenities in our calibration after netting out the block size. The vertical axis shows the residuals of the linear regression of the log of fundamentals on the log of block size. We plot each with local polynomial fitted lines for two different periods: the 1930s and 1975. Each dot represents a block. The horizontal axis is the distance from the CBD.

D.5 Robustness of Agglomeration Parameter Estimates

Moment Conditions In the baseline, we (i) define five grid cells according to the distance from the CBD and (ii) exploit the population and employment data from 1955 to 1975. We now conduct robustness checks for these specifications.

Table D.2: Robustness: GMM estimates for agglomeration parameters

	(1) Productivity	(2) Amenities	(3) Productivity	(4) Amenities
Elasticity of employment density (α)	0.190 ^a (0.0002)		0.178 ^a (0.0001)	
Elasticity of population density (β)		0.192 ^a (0.0009)		0.165 ^a (0.0004)
Sample of blocks	All blocks in the city		All blocks in the city	
Sample of periods	Every 5 years from 1955 to 1975		Every 5 years from 1955 to 1975	
Instruments	10 grids for CBD distance	5 grids for pop. density in 1936		

Note: This table reports generalized method of moments (GMM) estimates for spillovers in productivity (α) and amenities (β). We conduct three robustness checks for our estimation. We use all 174 blocks in the city. In Columns (1) and (2) we define 10 grid cells based on distance to CBD and use them as instruments. In Columns (3) and (4) we define 5 grid cells based on population density in 1936 for instruments. ^a indicates significance at the 1 percent level.

In Table D.2 we report the two-step GMM estimates for three robustness checks. First, in Columns (1) and (2), we define ten grid cells instead of five grid cells to examine the sensitivity of our estimates to the grouping of blocks. Second, in Columns (3) and (4), we define five grid

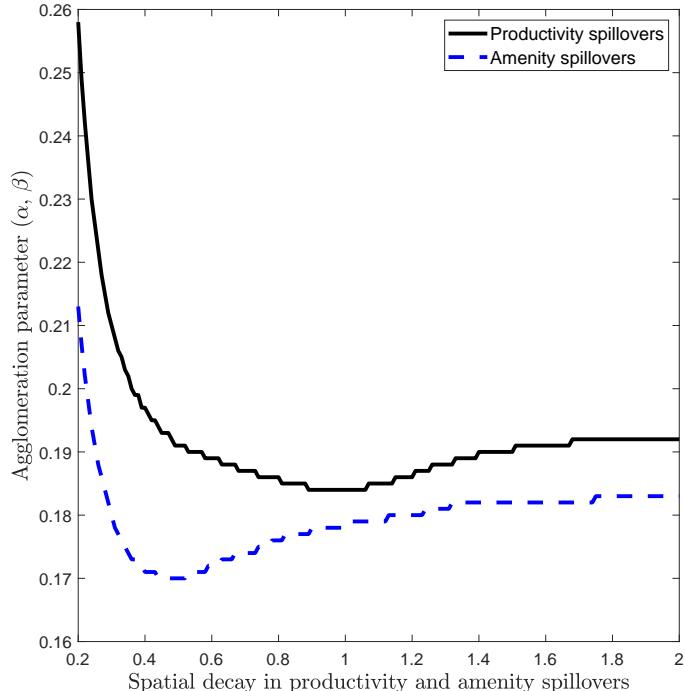
cells according to the population density in 1936. This allows flexibility in defining the moment conditions without an arbitrary definition of the CBD.

Spatial Spillovers in Productivity and Amenities Suppose that productivity and amenities have a spatial spread of spillovers. We consider functional forms similar to Ahlfeldt et al. (2015):

$$A_{it} = a_{it} \left[\sum_{i' \in C} e^{-\delta \tau_{ii'}} \left(\frac{L_{i't}}{S_{i'}} \right) \right]^\alpha, \quad B_{nt} = b_{nt} \left[\sum_{n' \in C} e^{-\delta \tau_{nn'}} \left(\frac{R_{n't}}{S_{n'}} \right) \right]^\beta, \quad (\text{D.10})$$

where δ governs the degree of spatial decay of spillovers; τ_{in} is travel time (walking time) between blocks; and (α, β) are agglomeration parameters. In Figure D.5 we show the estimated values of (α, β) given different values of spatial decay (δ). The horizontal axis shows values of spatial decay, and the vertical axis shows the estimated values of the agglomeration parameters. The solid (dashed) line shows the estimated values of agglomeration forces in productivity (amenities), respectively.

Figure D.5: Spatial spillovers and estimation of agglomeration forces



Note: The figure illustrates the estimated agglomeration parameters (α, β) given different values of spatial decay (δ) under the specification (D.10). The solid (dashed) line shows the estimated agglomeration force in productivity (amenities) given a particular value of spatial decay on the horizontal axis. We consider 181 different values of the spatial decay parameter from 0.2 to 2.0 with an interval of 0.01.

Lagged Agglomeration Forces Following Allen and Donaldson (2022), we suppose that productivity and amenities depend on past employment and population density:

$$A_{it} = a_{it} \left(\frac{L_{it}}{S_i} \right)^{\alpha_1} \left(\frac{L_{it-1}}{S_i} \right)^{\alpha_2}, \quad B_{nt} = b_{nt} \left(\frac{R_{nt}}{S_n} \right)^{\beta_1} \left(\frac{R_{nt-1}}{S_n} \right)^{\beta_2}, \quad (\text{D.11})$$

where parameters (α_2, β_2) control the spillovers from the lagged density. Given inverted option values in Step 2 in our calibration, we can compute fundamental productivity and amenities by the relationship (D.11) in the same way as in Step 3. We use similar moment conditions to estimate parameters (α_1, α_2) for agglomeration in productivity and (β_1, β_2) for agglomeration in amenities jointly. In Table D.3 we report the results. As in our baseline results in Table 2 in the main text, Columns (1) and (2) use all blocks in the city, while Columns (3) and (4) use blocks within 3 kilometers of the CBD. Overall, we find relatively small lagged effects on productivity and amenities. The contemporaneous effects are close to the baseline results.

Table D.3: Robustness: GMM estimates for agglomeration parameters with lagged effects

	(1) Productivity	(2) Amenities	(3) Productivity	(4) Amenities
Elasticity of employment density (α_1)	0.228 ^a (0.0007)		0.232 ^a (0.0002)	
Elasticity of past employment density (α_2)	-0.064 ^a (0.0005)		-0.064 ^a (0.0003)	
Elasticity of population density (β_1)		0.175 ^a (0.0011)		0.198 ^a (0.0037)
Elasticity of past population density (β_2)		0.015 ^a (0.0010)		0.001 ^a (0.0040)
Sample of blocks	All blocks in the city		Blocks within 3 km to CBD	
Sample of periods	Every 5 years from 1955 to 1975		Every 5 years from 1955 to 1975	
Instruments	5 grids for CBD distance		5 grids for CBD distance	

Note: This table reports two-step GMM estimates using data for five periods (1955, 60, 65, 70 and 75). We include lagged spillover effects in productivity and amenities, controlled by two parameters (α_2, β_2) . We use the same instruments as in the baseline. The standard errors are in parentheses. In Columns (1) and (2), we use all 174 blocks in the city and in Columns (3) and (4), we use the 158 blocks within 3 kilometers of the CBD. ^a indicates significance at the 1 percent level.

D.6 Simulating Population and Employment Density for 1945–1950

Having estimated model parameters (α, β) by exploiting the population and employment data from 1950 to 1975, we evaluate how well the model explains the population and employment changes in the recovery period 1945–1950. We compare the observed 1950 distributions of popu-

lation and employment to the simulated ones when we abstract the structural errors. We compute:

$$\begin{aligned} R_{n,50} &= (1 - \theta_{50})R_{n,45} + \sum_{i \in \mathcal{C}} \frac{K_{in,50}(\widetilde{\Xi}_{n,50})^{\rho/\sigma}}{\sum_{n' \in \mathcal{C}} K_{in',50}(\widetilde{\Xi}_{n',50})^{\rho/\sigma}} (L_{i,50} - (1 - \theta_{50})L_{i,45}), \\ L_{i,50} &= (1 - \theta_{50})L_{i,45} + \sum_{n \in \mathcal{C}} \frac{K_{in,50}(\widetilde{\Omega}_{i,50})^{\rho/\sigma}}{\sum_{i' \in \mathcal{C}} K_{i'n,50}(\widetilde{\Omega}_{i',50})^{\rho/\sigma}} (R_{n,50} - (1 - \theta_{50})R_{n,45}), \end{aligned} \quad (\text{D.12})$$

where we use

$$\widetilde{\Xi}_{n,50} \equiv \tilde{b}_n \left(\frac{R_{n,50}}{S_n} \right)^\beta \Xi_{n,55}^{\rho(1-\theta_{55})}, \quad \widetilde{\Omega}_{i,50} \equiv \tilde{a}_i \left(\frac{L_{i,50}}{S_i} \right)^\alpha \Omega_{i,55}^{\rho(1-\theta_{55})} \quad (\text{D.13})$$

on the right-hand side. These are constructed in the same way as equations (15) and (16), except that (a_{it}, b_{nt}) are replaced by the average amenities and productivity over 1955-75 $(\tilde{a}_i, \tilde{b}_n)$, which are our estimates of the block-specific amenities and productivity in (D.8). Since (a_{it}, b_{nt}) include structural errors in amenities (b_{it}^{Var}) and productivity (a_{it}^{Var}), using them exactly rationalizes the observed 1950 distributions of population and employment as the equilibrium outcome. Relative to this benchmark, we assess how well the endogenous forces of our model can explain the 1950 distribution by using $(\tilde{a}_i, \tilde{b}_n)$, which omits the idiosyncratic structural errors.²⁷ Note that using $\Xi_{n,55}$ and $\Omega_{i,55}$ as option values for 1955 implies that when making migration decisions for 1950, people are assumed to correctly anticipate what happens from 1955 and onward.²⁸ This assumption is in line with the perfect foresight assumption in our calibration.

Since the structural errors in our model make our model perfectly match the observed population and employment distributions, we can compare the importance of endogenous forces in the model and structural errors in predicting the recovery by comparing the observed population and employment distributions and their predictions from equations (D.12) and (D.13). We discuss the results in Subsection 5.5 in the main text.

No Agglomeration In Subsection 6.1 we can similarly obtain the model prediction when there are no agglomeration forces by setting $\alpha = \beta = 0$ in equation (D.13) and eliminating the endogenous components in the future option value terms $(\Xi_{n,55}, \Omega_{n,55})$. While the model could still predict recovery if the recovery is driven by fundamental location advantages of the destroyed city center, the model could not predict the recovery if it is driven by agglomeration forces. In

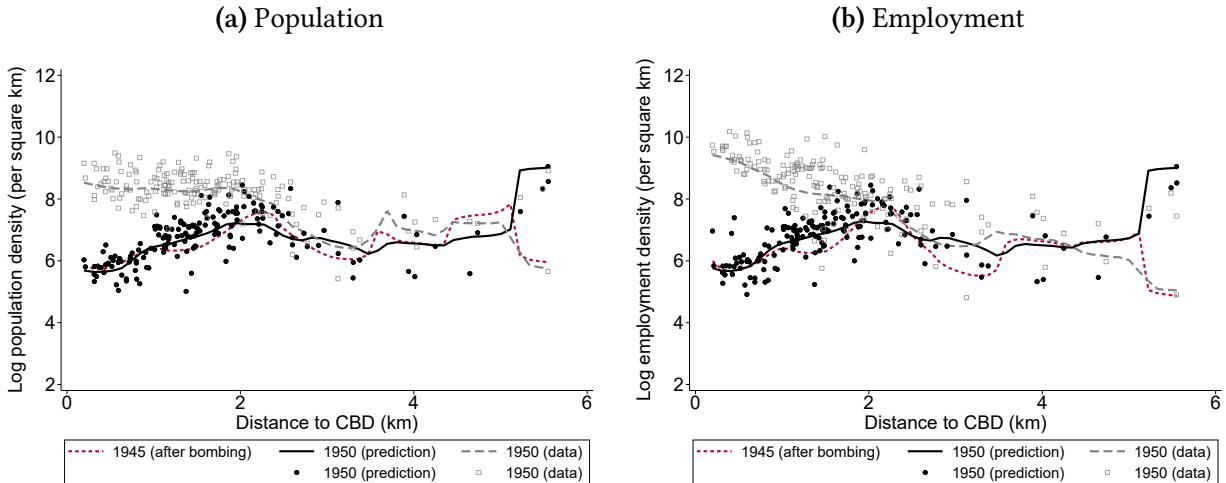
²⁷The year-fixed amenities and productivity $(\bar{a}_t^*, \bar{b}_t^*)$ in (D.8) are also excluded from (D.13), but this does not affect the model prediction because they appear both in the denominator and the numerator of (D.12).

²⁸While using $(\tilde{a}_i, \tilde{b}_n)$ instead of (a_{it}, b_{nt}) implies that the model no longer predicts the observed population and employment distributions $(R_{n,50}, L_{i,50})$, we still assume in this analysis that people expect the observed population and employment $(R_{n,50}, L_{i,50})$ would realize. This is because we aim to assess how much the endogenous forces of our model contribute to predicting the observed population and employment distribution in 1950 without structural errors, relative to our main perfect-foresight model that incorporates structural errors and predicts the observed 1950 population and employment distribution.

this sense, the comparison of model predictions with and without agglomeration forces indicates their importance in accounting for the recovery of central Hiroshima.

Locational Attachment of Landowners As we discussed in Section 7, surviving landowners may have returned home after the war due to locational attachment. This may result in more population in the city center, as in the pre-war population distribution, even without strong agglomeration forces. To assess this possibility, we consider a counterfactual in which we assume that (i) landowners in 1936 (pre-war) were 20 percent of the population; (ii) landowners were distributed within the city proportionally to the population distribution in 1936; and (iii) landowners who survived the atomic bombing returned to their homes and worked in their home location in 1950. Note that the 20 percent landownership rate assumed in (i) may overstate the importance of landowners, given the 10% landownership rate suggested by Kato (1988). We use the survival rate of people from *Hiroshima shisei youran* published in 1947, which documents the survival rate of people according to their distance from the center, in April 1946. With these assumptions, we compute a counterfactual equilibrium when there are no agglomeration forces.

Figure D.6: Population and employment distributions when landowners return



Note: Each figure plots log population density (Panel a) and employment density (Panel b) with local polynomial regressions of each on distance from the CBD. We run three separate regressions: one for the observed 1945 population and employment densities (small dashed line), one for the observed 1950 population and employment densities (long dashed line), and one for the counterfactual (solid line). Each dot represents a block, with different colors for the predicted density and the observed density.

Figure D.6 shows results for the population and employment distributions in 1950. Compared to Figure 6 in the main text, we can see that both population and employment density are high close to the city center. Yet, they are significantly lower than observed. This suggests that it is difficult to explain the recovery of the central area solely based on landownership and its direct effects. See related discussions in Section 7.

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