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1 Introduction

China has experienced rapid urbanization in the past four decades. According to official statistics, the share of population that live in urbanized areas increased from below 20% in 1981 to around 64% in 2021. The contiguously built area increased by more than eight times during the same period. Cities of all sizes have substantially expanded their urban boundaries by annexing nearby agricultural land, forming large areas that are interconnected via urban economic activities such as commuting, shopping, and entertainment.

Despite the rapid transformation from an agrarian economy to an urban economy, to this day, there is no official definition of a city in China that matches its economic function. There are administrative definitions of cities, but they often contain substantial proportions of rural areas and sometimes even overlap with one another. As we describe in more detail in Section 2, the official definition of a city in China is often a misnomer and can easily cause confusion. Importantly, there is no existing definition of Chinese cities that mimics the concept of a local labor market—such as the metropolitan statistical areas (MSA) in the United States—and can be widely used in economic analyses.

Defining cities as local labor markets relies heavily on commuting flows. A local labor market is typically defined as connected areas that include where people live and where they work. There are no official statistics on commuting flows in China that are (i) available at fine geographical levels and (ii) cover the entire country.

This paper presents the first delineation of China's metropolitan areas (MAs) that are based on commuting flows. To this end, we use a novel source of data on commuting flows that are derived from frequent location information captured by smartphones. Specifically, we obtain access to the complete commuting flow matrix between any pair of townships (China is divided into about 40,000 townships) from one of China's leading companies that provide location services on mobile devices. The company not only runs a mobile digital map application that has millions of active users, but also is the main provider of location plugins for other mobile applications. The company uses the frequent location information sent by these applications to calculate each device's usual daytime and nighttime locations, which it refers to as the work and home locations, respectively. These locations are then aggregated to generate commuting flows at the township pair level.

We have remote access to the commuting matrix that reflects the commuting patterns as of November 2017. Per the company's own calculation, the commuting data cover almost the entirety of China's workforce, thanks to the high smartphone penetration rate in China and the ubiquitous presence of the company's location services on mobile devices. We verify the quality of the commuting data by checking it against official statistics on population and employment. We also check commuting flows in selected areas where the population survey of 2015—the first nationwide survey that includes questions on commuting but nevertheless is small in sample size—has a sufficient number of observations with commuting information.

We first document basic patterns of commuting in China. Our first observation is that commuting remains rather short in terms of both time and distance. The 2015 population survey shows that the median one-way commute takes 15 minutes. Barely 2% of the workers have commutes more than one hour. The modes of transportation are mostly rudimental, with about 80% of commuters walking or using two-wheelers such as bicycles, electric scooters, and motorcycles.

These patterns are echoed in the smartphone-based commuting flow data. The median township has 61% of its workers commute within its boundaries. The median within-county commuting flow is 88%. Only districts—the county-level units that comprise the urban core of a municipality or a prefectural-level city—have substantial commuting flows to or from nearby districts.

Administrative boundaries impose substantial barriers to commuting. Gravity regressions show that at the national level, crossing the border of a prefectural-level city is equivalent to a 55 log point increase in distance in terms of hampering commuting flows; crossing a provincial border is equivalent to a 104 log point increase in distance. This is in stark contrast to commuting flows in the United States: Not only do commuting volumes decline more slowly with distance, but also crossing a state border in the U.S. reduces commuting flow in a magnitude that is equivalent to a mere 8 log point increase in distance.

To delineate metropolitan areas, we adopt the iterative clustering algorithm proposed by Duranton (2015). The algorithm merges a geographic unit to another if the share of commuters from the former to the latter surpasses a predetermined threshold. Commuting flows are updated as units are merged, and the process repeats iteratively until no more units can be merged.

The algorithm gives us a set of township clusters. However, few statistics are available at the township level. In order for our delineations to be relevant statistically, we aggregate township clusters at the county level. Specifically, a county is assigned to a cluster if more than half of its population is in the cluster. Finally, we impose minimum population and density restrictions as well as a requirement for contiguity and call the qualifying clusters China's metropolitan areas (MAs).

We experiment with different commuting share thresholds. We compare sets of MAs generated by various thresholds with other definitions of Chinese cities. Prefectures are poor proxies for commuting-based MAs. We show that a city definition that corresponds to the administrative boundary, the one defined as contiguous urban districts and standalone county-level cities, can be largely justified by the commuting-based MAs with a threshold of 10%. We use this version as our baseline delineation of China's MAs.

Our preferred delineation suggests that China has about 500 MAs. Together, they account for 15% of the nation's area and 55% of its population. The largest MA is Shanghai, which has 24.2 million residents. Beijing is the close second with 24 million residents. There are eight MAs with a population of more than 10 million and another 11 with a population between 5 and 10 million.

The 50 largest MAs account for about 23% of the country's population and about 4% of its area.

We then investigate properties of the system of China's MAs. Compared with other definitions, commuting-based MAs has the best fit of Zipf's law. There are substantial size premiums: larger MAs have higher shares of skilled workers, higher wages and firm productivity; they have higher shares of migrants as well as higher housing prices.

China's MAs are relatively small. We construct commuting-based MAs in the United States, Brazil, and Mexico using the same algorithm and the commuting share threshold. Compared with MAs in those countries, the largest MAs in China account for not only a smaller share of the nationwide population, but also a smaller share of area.

We investigate what may have contributed to small MAs in China. We first notice that China's MAs are hierarchical: the size of an MA is highly correlated with its administrative rank. As administrative ranks are largely stable, a city that has great growth potential but have a low administrative rank may find itself constrained to grow and expand. Second, it is difficult to live in one administrative unit while work in another. According to our result, it is rare for an MA to cover multiple prefectures. Only one MA crosses a provincial border. Third, Chinese cities used to feature a high transporation cost due to the poor highway network, the low car ownership, and bus-dominated transit services. We show that recent urban expansions have been strongly correlated with the improvement in rail transit services.

China's rapid economic growth and urbanization has drawn wide-range interests in the study of Chinese cities. Yet the literature has be limited by the lack of proper definitions of the subject of study. Most papers have used prefectural-level cities (e.g., Bosker et al., 2012; Chauvin et al., 2017; Baum-Snow et al., 2020; Fan & Zou, 2021). For example, Baum-Snow et al. (2020) estimate the effect of China's highways on prefecture-level economic activities such as population and GDP. Also using prefectural-level cities, Chauvin et al. (2017) find that Zipf's law does not hold for Chinese cities. A recent study by Dingel et al. (2019) defines China's MAs using satellite nightlight imagery and show that Zipf's law does hold for Chinese cities. This paper is the first to define China's MAs that are based on commuting flows, which is closer to the economic definition of cities. We show that prefectural-level cities are poor proxies for commuting-based cities. We also find substantial differences between MAs based on commuting flows and those based on nightlight. There are large areas that appear connected according to nightlight, yet commuting in between is actually limited.

Recently, there is a renewed interest in the definition of cities, especially in developing countries where proper official definitions are often unavailable and data are limited. Economists and geographers have devised various ways to do so. As noted by Duranton (2021), there is not a single best way to define a city. An approach can serve one purpose well while lack in others. One method is to delineate urban areas using certain building density criteria (Arribas-Bel et al., 2019; De Bellefon et al., 2019). For example, De Bellefon et al. (2019) compare a map of actual buildings to maps of counterfactual random redistributions of the same buildings, and define areas with significant excess building density as urban. Another method is to define metropolitan areas as a set of contiguous spatial units that contain economic activity. A unit is identified as having economic activity either if it contains built-up landcover classified from daytime satellite images (Baragwanath et al., 2019), or if its nighttime light intensity exceeds a given threshold (Dingel et al., 2019). This paper follows the definitions of MAs that are largely based on commuting flows. Similar approaches have been used in the U.S. to define the Core-Bases Statistical Areas (CBSAs) (Office of Management and Budget, 2010) and commuting zones (Tolbert & Sizer, 1996), and to delineate MAs in Colombia (Duranton, 2015) and Japan (Adachi et al., 2020).

The prevalence of cellphone location data presents new opportunities for economists who are interested in studying the spatial dimension of economic activity and human interactions. Recent studies have exploited cellphone location data to study urban consumption (Miyauchi et al., 2021) and racial segregation of economic activity (Athey et al., 2021). Compared with these studies, delineating cities using commuting flows are much less demanding on the frequency of location data. It is also worth noting that cellphone location data usually lack in demographic characteristics and social economic status. Traditional surveys maintain an advantage in those dimensions. An increasing number of countries, including several developing countries such as Mexico, Brazil and China, are incorporating questions regarding commuting and mobility in their recent nationwide population surveys.

The rest of the paper is organized as follows. Section 2 summarizes China's administrative divisions and the official definitions of cities. Section 3 introduces the data and describes basic patterns of commuting in China. Section 4 describes the algorithm and the delineation of commuting-based MAs. Section 5 describes the characteristics of China's MAs. Section 6 concludes.

2 Background

2.1 Administrative Divisions of China

It is helpful to illustrate how China is divided administratively because i) our data are grouped in units of administrative divisions and ii) delineations of MAs are only useful if they can be matched with official statistics, which are usually provided at various administrative levels. Table 1 shows a simplified version of administrative divisions of mainland China. There are four levels of local governments: provincial, prefectural, county, and township.[1] The provincial level units include 4 municipalities (*zhixiashi*), 22 provinces (*sheng*), and 5 autonomous regions (*zizhiqu*). There

[1]Some will refer villages (in rural areas) and communities (in urban areas) as the 5th level of government. Villages and communities are officially part of the "basic level autonomy." Their governing bodies, villagers committees and residential committees, are self-governing organizations and not part of the government, although in reality, higher-level governments have substantial authority over the organization and functions of these committees. Nevertheless, village and community leaders are not in the formal ranks of government officials. Official statistics rarely reach the level of villages and communities.

are no second level units under municipalities. Provinces and autonomous regions are divided into 333 prefectural-level units, including 293 prefectural-level cities (*dijishi*) and 40 prefectures (*diqu*, *zizhizhou*, *meng*). Municipalities, prefectures, and prefectural-level cities are further divided into 2,851 county-level administrations, including 954 districts (*shixiaqu*), 366 county-level cities (*xianjishi*), and 1,531 counties (*xian*, *qi*, etc.). County-level units are further divided into around 40,000 township level administrations, including 8,122 subdistricts (*jiedao*), 21,927 towns (*zhen*), and 9,815 townships (*xiang*).

The Ministry of Civil Affairs is the government agency that oversees the classification of administrative units. It re-evaluates the classification periodically. The population size and the degree of urbanization largely vary between different types of units at the same administrative level. For example, compared with prefectures, prefectural-level cities are more populous and usually contain an urban core. Over the past few decades, as population grew and urbanization proceeded, most prefectural-level divisions have been relabeled from prefectures to prefectural-level cities. At the county-level, districts are contiguous units that form the urban core of a municipality or a prefectural-level city (prefectures in general do not contain districts), while county-level cities are on average more populous and urban than counties. At the township level, subdistricts are more likely to be found in urban settings, while townships are largely rural. However, the classifications are not absolute, nor are there clearcut population or density thresholds for various classifications. Districts are in general more urban, but they also contain towns and townships; counties are less urban, yet they typically have an urban core that consists of one or more subdistricts. Despite their different levels of urbanization, all three types of county-level administrations contain a mix of subdistricts, towns, and townships.

Table 1: Administrative Divisions of Mainland China

<table>
<tr><th>provincial level</th><th>prefectural level</th><th>county-level</th><th>township level</th></tr>
<tr><td>municipality</td><td></td><td>district
county</td><td rowspan="5">subdistrict
town
township</td></tr>
<tr><td rowspan="2">province</td><td>prefectural city</td><td>district
county-level city
county</td></tr>
<tr><td>prefecture</td><td>county-level city
county</td></tr>
<tr><td rowspan="2">autonomous region</td><td>prefectural city</td><td>district
county-level city
county</td></tr>
<tr><td>prefecture</td><td>county-level city
county</td></tr>
</table>

2.2 The Anarchy of Chinese Cities

The term "city" is constantly misused in China's context. A source of the misconception is the confusing definition of "*shi*," the Chinese word for city, which corresponds to administrative units at various levels and are only loosely correlated with the economic meaning of a city: an economically connected area with dense population and an urbanized economy. There are in total 663 *shi* in China. They can be classified into three categories: municipalities (*zhixia-shi*), prefectural-level cities (*diji-shi*), and county-level cities (*xianji-shi*). They respectively correspond to provincial, prefectural, and county level administrative units. There are rural areas within a *shi*, and the collection of *shi* do not exhaust all urban areas in China. Counties that are not classified as *shi* typically contain an urban core as well. One particularly unappealing feature of using *shi* to define Chinese cities is that they could overlap with one another. Prefectural-level cities could contain one or more county-level cities.

Many official statistics are available at the provincial and prefectural levels. Partly for this reason, it is conventional in the literature to treat municipalities and prefectural-level cities as local economies. Yet, there are several problems with this definition. First, although they are called "cities," they are not equivalent to urban areas since they contain vast rural areas. In fact, because there remain only a handful of non-city prefectures, municipalities and prefectural-level cities account for the vast majority of mainland China, which has an official urbanization rate of only 64% in 2020.[2] Second, it is questionable how much economic activity is interconnected within a prefectural-level city, to the extent that it can be treated as an integrated city. Similarly, it is possible that economic connections extend beyond administrative boundaries.

A more sensible definition of cities based on existing official classifications includes collections of contiguous districts, which make up core urban centers of municipalities and prefectural-level cities. Few studies follow this definition.[3] Several remaining issues are with this definition. For example, it leaves out county-level cities, some of which are populous and fairly urbanized. It is also unclear how to treat a county-level city that is contiguous to the districts. Should it be included as part of the urban core, or treated as a stand-alone city? If there are two neighboring county-level cities, what determines whether they should be counted as one city or separated cities? To answer these questions, it is necessary to have some consistent measures of connectivity both within and

[2]The official definition of urban residents include those who live in urban residential communities, and that of rural residents refer to those who live in villages. Villages and urban residential communities are much finer geographic units whose statistics are typically not available.

[3]A few exceptions include Au & Henderson (2006), Desmet & Rossi-Hansberg (2013), Baum-Snow et al. (2017), and Lin (2017).

across administrative boundaries, on which official statistics provide few clues.[4]

3 Data

3.1 Data Sources

We have access to commuting flow data between all pairs of townships in November 2017.[5] The data are collected by a leading provider of digital map and online navigation services in China. The company collects mobile devices' location information from its popular digital map application on mobile devices and from other applications that it provides location services to. From each device's location data, the company calculates its typical daytime location and typical nighttime location in the past three months, which it refers to as the "workplace" and "home," respectively.

Given the wide coverage of the mobile applications and the frequency of the location records, the data present a good approximation of actual commuting flows in China. The company's mobile application has about 600 million active users in mainland China. It is also the leading provider of location services used in other popular mobile applications. So its presence in mobile devices is ubiquitous. China also has a high smartphone penetration rate. The smartphone-to-population ratio was about 63% in 2020.[6] The rate is likely still higher among worker.

A typical device generates about 30 location records per day, more than enough to determine the typical daytime and nighttime locations over a period of three months. In addition, the median township in China covers about 70 km^2. The precision of smartphone GPS location data is much higher than that.

It is worth noting that the data track devices, not people. The data miss workers who do not have a smartphone, or users who do not allow their smartphones to track locations. The data may include some non-workers who possess a smartphone and have daily routines in whereabouts, such as students who commute between home and school, and retirees who have regular itineraries. The company uses other information from the device to infer the demographics of the user; it generates its own estimation of population and employment at the township and county

[4]For the simplicity of presentation, in the remainder of the paper, we refer all provincial-level administrations (municipalities, provinces, and autonomous regions) as "provinces," all prefectural-level administrations (prefectural-level cities and prefectures) as "prefectures," all county-level administrations (districts, county-level cities, and counties) as "counties," and all township-level administrations (subdistricts, towns, and townships) as "townships."

[5]We access the data remotely by sending codes to an in-house engineer. We also have access to commuting flows between all pairs of townships in November 2019 as well as flows between pairs of county-level administrations in both years. For the main analyses, we use the 2017 data because the latest supportive statistics we have are from 2017 or earlier. We cross-check the quality of the data in different years and in different levels of aggregations. Our main results and conclusions do not change if we use the data from 2019 or at the county level.

[6]https://newzoo.com/insights/rankings/top-countries-by-smartphone-penetration-and-users/. Last visited on December 2, 2021. The monthly report of July 2017 by the Ministry of Industry and Information Technology (MIIT) indicates a higher ratio at about 86%, with 1.2 billion mobile Internet users (https://www.miit-icdc.org/info/1010/3003.htm, in Chinese, last visited in March, 2022).

levels.[7] As we show below, counts of population and workers from commuting flow data match well with official statistics.

The commuting flow data based on smartphone locations are novel since there are no data on commuting in China at the national level. A few large cities, such as Beijing and Shanghai, implement household travel surveys periodically. But there is no such survey at the national level. Even at the city level, such surveys are typically limited in size. For example, the 2015 household travel survey in Beijing, one of the largest surveys of this kind in China and covering more than 50,000 households, is a one-in-200 sample and surveys residents in only 698 out of 2,109 geographic units (transportation analysis zones) that divide up Beijing. The traditional surveys are usually residence-based and likely under-represent migrant workers, who according to some estimates account for more than 30% of the residents in China's largest cities. The population survey of 2015 is the first nationally representative survey to include questions on commuting. But its sample size is too small to calculate credible commuting flows at fine geographic levels. The cross-prefecture commuting flows are also not well documented in this survey as the workplace, if outside the prefecture of residence, is not recorded. We use the population survey and other statistics to cross-check the quality of smartphone location data.

3.2 Data Verification

We check the quality of the commuting flow data by comparing them with nationwide population surveys and official statistics along several important dimensions. Because official statistics at the township level are scarce, we aggregate our data at the county level.

For official statistics, we use county-level population from the 2017 statistical yearbooks. Panel A of Figure 1 shows that the two population measures, in log terms, are highly correlated and similar to each other (tightly distributed along the 45 degree line).

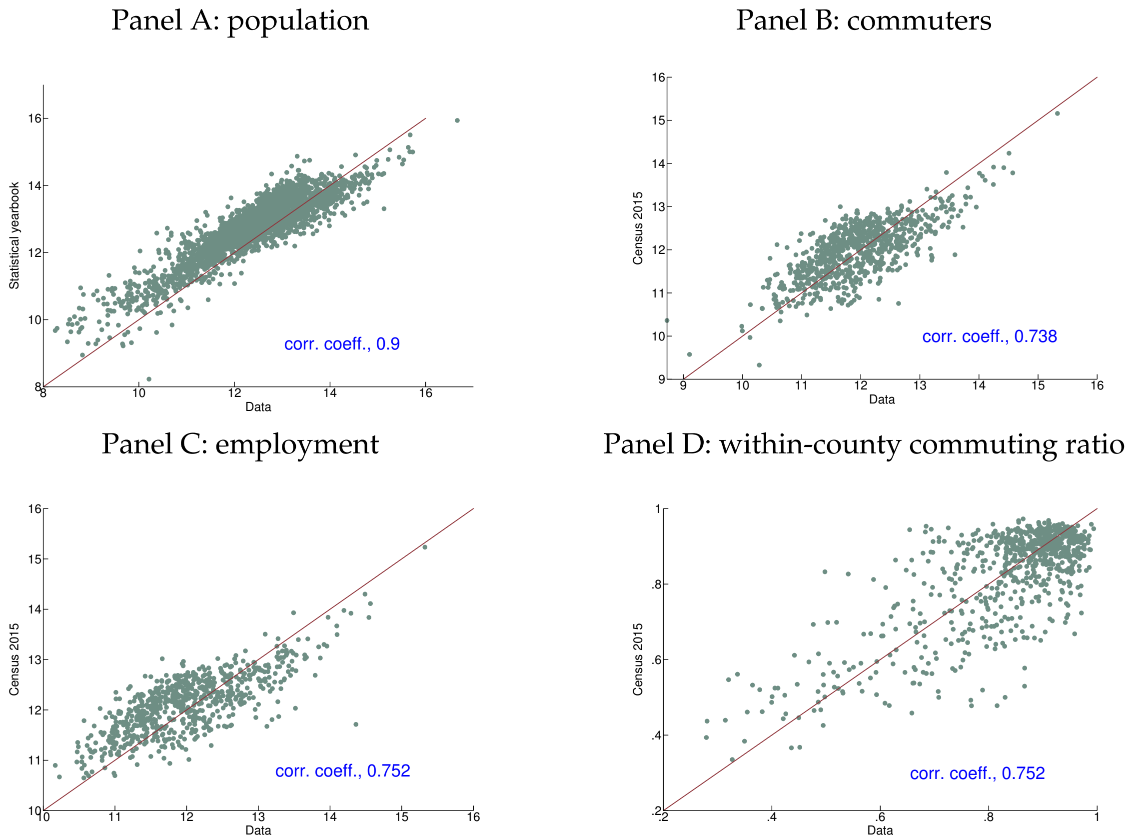
We use the individual level sample of the 2015 population survey to construct statistics related to commuting. The population survey is a one-percent representative sample of the national population. The sample available to us is smaller with more than one million observations. The survey includes a set of questions on commuting, including commuting time, mode of transportation, and the townships of residence and workplace. The census follows a residence-based stratified sampling procedure and does not cover all counties. To reduce the measurement error in the comparisons, we restrict the sample of county-level units to those with at least 500 observations. They largely corresponds to counties with more than half a million population. There are 197 such units in the sample.

For each unit we define three commuting-related measures that have counterparts in our commuting flow data. The first measure is the number of commuters by residence, defined in the census data as employed workers who report a positive time of commuting. The second measure is the number of workers by workplace. Most employment statistics in China are residence-

[7] We have access to the imputed employment (sum of commuters by workplace) and population at the township and county levels, but not data from individual devices. We also do not have the distribution of imputed demographics.

based, and reflect how many workers *live* in each place. Although the population survey is also residence-based, information on where the worker works allows us to recover how many people *work* in each county.[8] The third measure is the share of workers who commute within the same county. Panels B, C, and D of Figure 1 plot the log numbers of commuters, log employment, and within-county commuting ratios, respectively, from the population survey and the commuting flow data. The two versions of the same measurement line up closely along the 45 degree line. The correlation coefficients are high in Panel A, while relatively lower in Panels B to D as there are only less than 200 counties for comparison.

Figure 1: Commuting Flow Data Quality Check



Note: Each dot represents a county. The x-axis represents county characteristics constructed from the commuting flow data; the y-axis represents the counterpart from official statistics. Official statistics for Panel A are from the 2017 Statistical Yearbook; those for Panels B, C and D are from the 2015 population survey. Panel A plots log county population. Panel B plots the log number of commuters by residence. Panel C plots the log number of employment by workplace. Panel D plots the share of commuters who commute within the county. Panels B and D restrict the sample to counties with more than 500 observations, while Panel C restrict the sample to counties with more than 250 worker observations.

[8] For this statistic, we use all the data in the population survey. We then restrict workplace counties to those with more than 250 worker observations. This is consistent with the 500-observation restriction we make to counties by residence because the employment-to-population is roughly 0.5.

3.3 Basic Patterns of Commuting Flows

A typical commute in China is short in distance and time. The 2015 population survey shows that the median one-way commuting time among all workers is 15 minutes. 8% of workers report commutes that cost more than 30 minutes, and barely 2% have commutes that take more than an hour. The modes of transportation are mostly rudimental. 41% walk to work; 36% use two-wheel vehicles such as bicycles, electric scooters, and motorcycles; 8% use automobiles, and 10% ride public transit.[9] Commutes that cross administrative boundaries are rare. 29% of workers commute outside the township of residence, and only 12% commute outside the county of residence.

These numbers align with the commuting flows based on the smartphone location data. Figure 2 Panel A shows the distribution of the share of commutes that are bounded within a township. The median township has 61% of its workers commute within its boundaries. In about two-thirds of townships, more than half of the workers live and work in the same township. These numbers suggest that the vast majority of Chinese townships are self-contained labor markets. Panel B shows that cross-county commuting is even less common. The median within-county commuting ratio is 88%, the 25th percentile is at 72%, and the 75th percentile at 91%.[10]

Compared with those in the United States, China has drastically different commuting patterns. The U.S. is among the most mobile countries and its sprawling cities render long commutes. The average one-way commute in the U.S. was 27.6 minutes in 2019, much higher than that in China.[11] We also compare the distribution of within-county commuting ratio between these two countries. Chinese and U.S. counties are rather comparable geographically. Both countries have about the same land area and are divided into about 3,000 county-level units. Commuting across county borders is much more common in the United States, as is visibly evident from the much flatter distribution in Figure 2 Panel B. The median within-county commuting ratio is 66% in the U.S., the 25th percentile is at 52%, and the 75th percentile at 80%.

[9]Non-agricultural workers, who account for 68% of the workforce in 2015, have slightly longer commuters. Median one-way commuting time among non-agricultural workers is also 15 minutes. 11% have commutes that cost more than 30 minutes and 3% cost more than 60 minutes. 31% walk, 38% use two-wheelers, 11% use automobiles, and 15% take public transportation. There is an "others" category in the modes of transportation, which accounts for about 5% of the commuters.

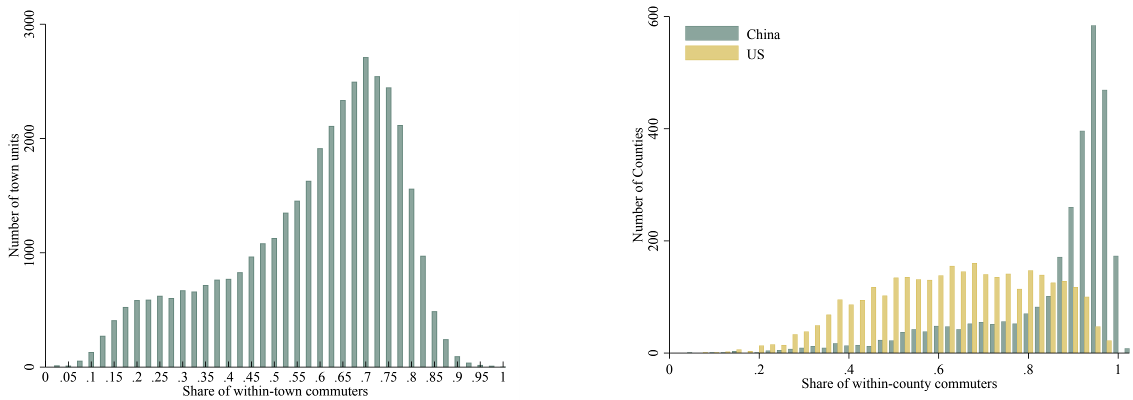
[10]Figure A.1 shows the distribution of within-unit commuting for counties and districts, respectively. The ratio of within-unit commuting is much lower in districts.

[11]http://www.census.gov/newsroom/press-releases/2021/one-way-travel-time-to-work-rises.html. Last visited in January, 2022.

Figure 2: Within-unit Commuting Ratio

Panel A: Townships

Panel B: Counties



Note: Graphs show the number of townships and counties by the share of within-unit commuters. For China, the data are from smartphone location data in November 2017. For the U.S., data are from the 2011-2015 5-Year Commuting Flows constructed by the U.S. Census Bureau using data from the American Community Surveys.

To better describe how distance and administrative boundaries affect commuting flows, and how they differ in China compared with the U.S., we run the following gravity regression:

$$\ln Comm_{od} = \lambda_o + \lambda_d + \rho \ln Dist_{od} + \mathbf{D}_{od} \cdot \rho + \varepsilon_{od}. \quad (1)$$

$Comm_{ij}$ is the number of commuters between the place of residence o (origin) and the place of work d (destination). λ_o and λ_d are origin and destination fixed effects, respectively. $Dist_{od}$ is the linear distance between the centroids of the origin and the destination. $\mathbf{D}_{od}$ is a set of binary variables indicating whether o and d belongs to the same administrative unit, be it a county, a prefecture or a province (or a state).

We run equation 1 on Chinese and U.S. counties. Table 2 reports the results. The first two columns show that distance imposes a substantial barrier to commuting. The elasticity of the commuting flow between pairs of Chinese counties with regard to distance is around -2.3. Conditional on distance, administrative boundaries impose further restrictions to commuting. Everything else equal, if two counties are in different prefectures, the commuting flow in between will be lower by a magnitude that is equivalent to a 55 log point increase in distance. Crossing a provincial boundary is equivalent to an additional 49 log point increase in distance. In total, if two counties are in different provinces, the commuting flow in between would be 236 log point lower than if they are in the same prefecture.

This is in stark contrast to the commuting patterns among U.S. counties, shown in Columns 3 and 4. The distance elasticity is only about half of that in China (-1.178 vs. -2.274), which may reflect better transportation infrastructure (e.g., denser road network) and higher car ownership. What is more striking is that crossing state boundaries imposes little additional barrier to commuting. Commuting flows decline by a merely 10 log points at the state border, which is equivalent to about a 8 log point increase in distance.

We also run the gravity regression on the 334 townships in Beijing, which has one of China's most connected urban areas. The last two columns of Table 2 show that distance still imposes a substantial barrier within Beijing, although somewhat smaller than the nationwide pattern at the county level. What is more surprising is that district borders impose substantial barriers to commuting even within Beijing, considering that urban planning, design of road network and public transit are all highly coordinated at the municipality level. Beijing's 16 districts typically have much weaker power to act on their own than prefectures in a province or counties in a prefecture. This suggests that large barriers imposed by administrative boundaries go beyond reasons with regard to geography and transportation.

The overall limited commuting, the large distance elasticity, and the substantial border effects all suggest that China's local labor markets are confined by administrative boundaries. Metropolitan areas that encompass many towns, counties are probably hard to find. In the following section, we delineate China's MAs using a clustering algorithm.

Table 2: Gravity Model of Commuting Flows

	Dependent variable: log number of commuters					
	counties in China		counties in the U.S.		townships in Beijing	
Variables	(1)	(2)	(3)	(4)	(5)	(6)
log distance	-2.490	-2.274	-1.194	-1.178	-1.727	-1.449
	(0.005)	(0.005)	(0.006)	(0.006)	(0.025)	(0.031)
= 1 if same prefecture		1.247				
		(0.009)				
= 1 if same province/state		1.110		0.097		
		(0.006)		(0.023)		
= 1 if same district						1.022
						(0.068)

Note: Commuting flows between townships and counties in China are from smartphone location data in November, 2017. County-level commuting flows in the United States are from the 2011-2015 5-Year Commuting Flows constructed by the U.S. Census Bureau using data from the American Community Surveys. The sample includes origin and destination pair with positive number of commuters. Origin and destination fixed effects are included in all columns. Robust standard errors are in parentheses.

4 Delineation of China's Metropolitan Areas

4.1 Algorithm

We follow the iterative aggregation algorithm proposed by Duranton (2015). The algorithm groups pairs of spatial units based on the commuting flow between them. In essence, unit A is aggregated to unit B if the share of workers who reside in A and work in B exceeds a pre-determined threshold. After each round of aggregation, commuting flows among the aggregated set of spatial units are updated, and a new round of aggregation proceeds according to the same criteria. This process is repeated until no further units can be aggregated.

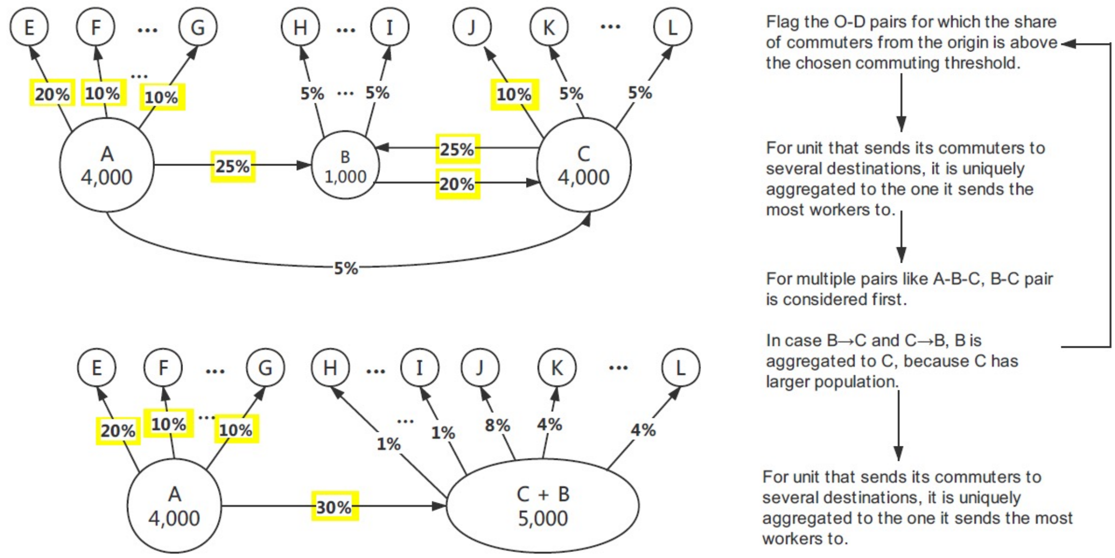
Figure 3 illustrates the algorithm. The top graph shows the initial commuting flows. The direction of the arrow points from the unit of residence towards the unit of workplace. The number in the circle indicates the number of workers who reside in the unit, and the number next to each arrow indicates the size of the commuting flow. For example, the graph indicates that 20% of workers who reside in B work in C. Suppose the threshold of commuting flow is chosen at 10%, the top graph highlights flows that are above this threshold.

The algorithm sets the following rules to ensure that in each round a spatial unit is involved in at most one aggregation. First, if a unit sends its commuters to several destinations, it is uniquely aggregated to the one to which it sends the most workers. In this example, A is aggregated to B as 25% of the commuters who reside in A work in B, though the commuting shares from A to E, F, G also exceed 10%. Second, the unit with a smaller population is aggregated to the larger one in case there are two-way aggregations. In this example, the algorithm proceeds with B being aggregated to C, although C is supposed to be aggregated to B in the same round. Third, if there is a chain of aggregations in the same round, the last aggregation "link" is chosen to be executed. As illustrated in Figure 3, if in the same round A is aggregated to B and B to C, the algorithm first aggregates B to C. Also, in each round, the aggregation of pairs of spatial units is executed sequentially when more than one origin unit is merged to the same destination unit.

The spatial units and commuting flows are updated after each round. The bottom graph of Figure 3 shows that now 30% of workers who reside in A work in the aggregation of B and C. The next round would involve further aggregating A into $B + C$.

Notice that 10% of workers who reside in C work in J. However, once B and C are aggregated, the combined unit only sends 8% of its workers to J, so $B + C$ will not be further merged with J. On the other hand, consider an alternative scenario where A sends 5% of its workers to B and another 5% to C. In the initial round, A will not be slated to merge with either B or C. But once B and C are merged, A sends 10% of its workers to the agglomerate, which is above the threshold. These examples illustrate the underlying mechanism of the algorithm: large employment centers are first grouped together; while the agglomerate becomes even larger employment centers, it further groups nearby units.

Figure 3: Illustration of Clustering Algorithm



The algorithm is similar to the hierarchical clustering algorithm that is used in defining commuting zones in the United States (Tolbert & Sizer, 1996). Other definitions of cities or local markets use a mix of commuting flows, population size, and population density criteria. In the U.S., core-based statistical areas (CBSAs) consist of larger metropolitan statistical areas and smaller micropolitan statistical areas. A CBSA is centered around an urban core of a sufficiently large size. An outlying county is aggregated into a CBSA if either of the following criteria is met: (i) at least 25% of the workers living in the outlying county work in the CBSA core; or (ii) at least 25% of the employment in the county is accounted for by workers who reside in the CBSA core. The second criterion captures the "reverse commuting" of those who live in the core city while work in the outskirts. Dingel et al. (2019) applies the iterative clustering algorithm with a threshold of 25% to the U.S. counties. The resulting metropolitan areas are highly similar to CBSAs.

4.2 Criteria and Baseline Results

We apply the algorithm with various thresholds to the 2017 township-level commuting flows and get sets of township clusters. Because statistics at the township level are rare, we further aggregate the clusters at the county level. A county is assigned to a cluster if more than 50% of its population are in townships that fall into the initial delineation of the cluster. The algorithm gives us something akin to commuting zones—clusters of counties that are connected via commuting flows. We impose contiguity restrictions so noncontiguous clusters will be taken as separate commuting clusters.[12] We further apply restrictions on population size and density to obtain clusters that we call metropolitan areas (MAs). We restrict the county clusters to those that have a combined population of at least 500,000 and a population density that is more than 100 persons per km^2. 100 per km^2 is about the 25th percentile of the county population density, and 500,000 is about the average county population. Those restrictions are of course arbitrary. Few clusters have a population density below the cutoff. Since we define MAs as aggregations of counties, it is natural to restrict an MA to be larger than a typical single county.[13]

This approach has several advantages. First, township-level commuting flows allow us to delineate MAs at a fine geographical level. Because cross-border commuting shares are low, had we used the county-level commuting flows, the vast majority of counties would not be part of any cluster. Yet many such stand-alone counties are large in size, often with a population exceeding one million. It is not clear whether to classify those large stand-alone counties as MAs. Defining clusters at the township level allows us to identify single-county MAs that have an interconnected urban core with more than half of the county's population. Second, aggregating clusters at the county level allows existing statistics to be matched to MAs.

One remaining critical decision to make is on the threshold of the commuting flows. Naturally, a higher threshold leads to smaller MAs. The relationship between the number of MAs and the threshold is less clear. A lower threshold makes it less restrictive to form an MA, thus increasing the number of MAs. But as the threshold is further lowered, a larger proportion of the population will be concentrated in a smaller number of MAs, and the total number of MAs likely start to decline.

There is also no theoretical guidance on what is the "right" threshold. The choice ultimately depends on the local setting and the geographic level one is working with.[14] The definition of CBSAs in the United States is most closely approximated by a threshold of 25% (Dingel et al., 2019). Duranton (2015) use 10% as the preferred threshold for MAs in Colombia. Dingel et al. (2019) use 10% as the preferred threshold for MAs in Brazil. The delineation of the U.S. CBSAs is based on counties, which have an average population of 100,000 and an average area of about 3,000 km^2. The delineations in Colombia and Brazil are based on municipalities. An average municipality in Colombia has a population of 45,000 and an area of 1,000 km^2. An average municipality in Brazil has a population of about 40,000 and an area of 1,500 km^2. The average Chinese township has a population of 38,000, but is much smaller by area, covering an area of 260 km^2.[15]

[12]The contiguity restriction has negligible effects on the set of commuting clusters. Only two clusters contain noncontiguous parts under the 10% commuter-share threshold in 2017.

[13]A 2014 standard by China's State Council classifies cities by residential population in urban areas: greater than 10 million (megacity), 5 to 10 million (extra-large), 1 to 5 million (large), half a million to one million (medium), and below half a million (small). Please refer to the "Notice of the State Council on Adjusting the Standards for Categorizing City Sizes" (http://www.gov.cn/zhengce/content/2014-11/20/content_9225.htm, in Chinese. Last visited in March, 2022).

[14]Naturally, it is more demanding for a larger geographic unit to cross a given commuting flow threshold.

[15]In all these cases, the median is smaller than the mean, in both area and population.

We experiment with varying thresholds ranging between 2% and 30%. Table 3 reports the summaries of MAs according to various thresholds. As the threshold increases, the number of large MAs declines. The number of MAs that have a population of more than 10 million is 19 when the threshold is 2%, 15 at 5%, 8 at 10% and zero if the threshold is higher than 20%. The total number of MAs (after applying restrictions on overall population and population density) first increases with the threshold and then declines.

The last two rows report the MAs' aggregate shares in the nationwide population and area. When the threshold is 2%, the 193 MAs account for 65% of the population and 27% of the area. At 10%, the 537 MAs account for 55% of the population and 15% of the area. At 25%, the 335 MSAs account for 18% of the population and 7% of the area.

The next three columns report the distributions of MAs according to different versions of administrative definitions. Column 8 treats a municipality (a provincial-level administrative unit) or a prefectural-level city as an MA. The 256 units that meet the population size and density bars account for 34% of the country's area and 89% of its population. They account for the majority of China's population and is thus unlikely to be a good definition of metropolitan areas. Column 9 uses the contiguous urban districts, which form the urban core of a municipality or a prefectural-level city, as the definition of an MA. 252 such MAs cover about 8% of the country's area and 39% its population. While they represent China's most dense areas, they miss possible urban clusters in counties and county-level cities as well as counties that have been closely connected to the urban core. Column 10 reports a revised version that further includes 229 county-level cities (subject to meeting population and density criteria). The inclusion of county-level cities does not change the tally of the largest MAs. About 60 county-level cities have more than one million residents, while most of them have a population between 500,000 and one million. According to this definition, there are 481 MAs in China, which collectively account for 54% of the population and 12% of the area.

Finally, Column 11 reports MAs delineated based on nightlight. We use the 2017 VIIRS satellite nightlight data and follow a similar strategy as in Dingel et al. (2019).[16] The nightlight imagery suggests a few large clusters of urban areas in China, including 9 megalopolises. The total 738 MAs it identifies account for 21% of China's area and 75% of its population. According to this defintion, the top two MAs roughly cover the entire Yangtze River Delta and the Pearl River Delta, with a population of 91.6 million and 55.0 million, respectively. Similarly, Dingel et al. (2019) identify the Pearl River Delta as the largest metropolitan area in the world using the 2010 nightlight data, which is formed through the process that "several original centers that over time merge across boundaries" (World Bank, 2015). However, we find although the nightlight seems to be connected

[16] Dingel et al. (2019) use the DMSP satellite imagery from 2010. The sources of satellite nightlight data have changed between 2010 and 2017. We use the converted 2017 VIIRS data that are consistent with the DMSP data (Li et al., 2020) and choose 30 as the nightlight intensity threshold—the preferred choice by Dingel et al. (2019).

in these regions, patterns from commuting flows clearly identify multiple clusters.

Table 3: Metropolitan Areas under Various Definitions

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	commuting flow							administrative			nightlight
MA pop.	commuter share cutoff (%)							muni.	urban	(9) +	brightness
(million)	2	5	10	15	20	25	30	+ pref.	distr.	cnty-cities	cutoff=30
⩾ 10	19	15	8	3	0	0	0	14	7	7	9
5 - 10	13	14	11	4	0	0	0	78	11	11	11
1 - 5	61	120	170	172	103	43	14	157	144	203	226
0.5 - 1	100	206	348	414	404	292	189	7	90	260	492
total	193	355	537	593	507	335	203	256	252	481	738
% of pop.	65	58	55	47	31	18	11	89	39	54	75
% of area	27	19	15	12	10	7	4	34	8	12	21

Note: The table shows the distribution of MAs according to various definitions. Columns 1 through 7 report MAs defined by commuting flows with various thresholds. Columns 8 through 10 show three administrative definitions of MAs. Column 11 shows MAs defined by nightlight brightness as in Dingel et al. (2019). Clusters with more than 500,000 residents are reported. MAs are also restricted to those with a density over 100 persons per km^2.

The administrative definition that we believe best fits the economic definition of a city is the one presented in Column 10. The commuting flow based approach with a threshold of 10% generates the size distribution of MAs that is the closest to this definition. Both definitions indicate that there are around 500 MAs in China, which collectively account for 12%-15% of the area and 54%-55% of the population. That population ratio is also close to the official urbanization rate, which is reported to be 64% in 2020 according to the population census conducted in that year.

We further compare commuting flow based MAs with other definitions by calculating the correlation coefficients between different definitions in log population and log area. Specifically, for each MA according to the commuting flow definition with a certain threshold, we match it with the corresponding MA in the alternative definition. MAs in different definitions do not perfectly match one-on-one. To match MAs to different administrative definitions, we first rank MAs within each administrative unit under that definition by population, and match the largest MA to that administrative unit. If an MA covers multiple administrative units, it is assigned to the unit that contains the largest share of the MA's population. Commuting-based MAs and nightlight-based MAs are matched according to the center county-level unit in each definition.

Figure 4 reports the correlation coefficients. Overall, correlation coefficients for log population between different definitions are high, typically above 0.6 except for the MAs defined as urban districts.[17] The correlation coefficient is typically the highest when the threshold for the commut-

[17] A high correlation coefficient means that larger MAs in one definition is also typically larger in another definition. It does not mean that the MAs have similar population sizes. Table 3 provides additional evidence on the size distribu-

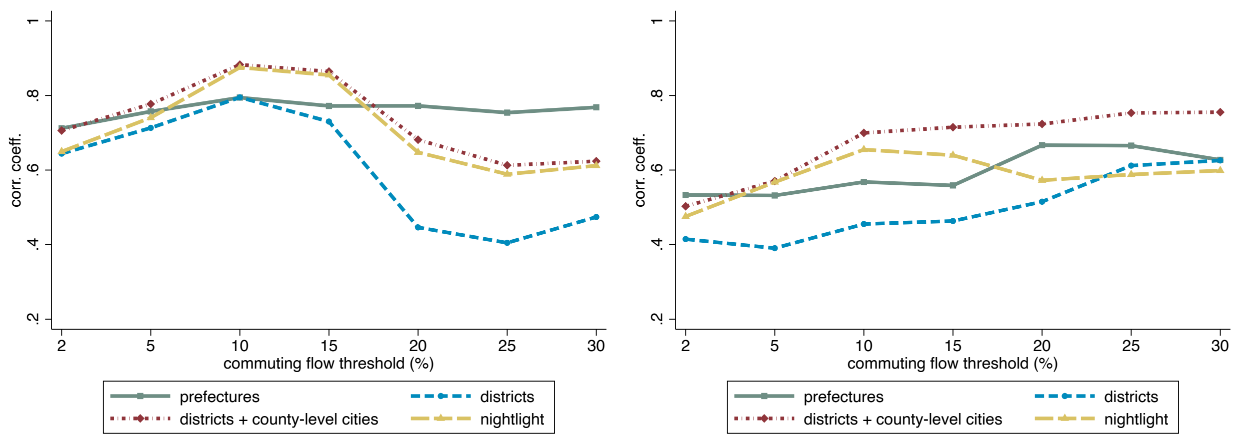
ing flow is chosen at 10%. Commuting-based MAs with 10% cutoff are most similar to MAs that include urban districts and county-level cities. The correlation coefficient for that pair is almost 0.9. In other words, if one intends to use one of the official definitions, the one includes county-level cities and contiguous districts in municipalities and prefectural-level cities not only makes the most intuitive sense, but also can be largely justified by a commuting-based definition with the 10% threshold.

Panel B shows the correlation coefficients for log area. These correlation coefficients, between 0.4 and 0.8, are generally lower than those for log population.

Figure 4: Correlations across Various MA Definitions

Panel A: population

Panel B: area



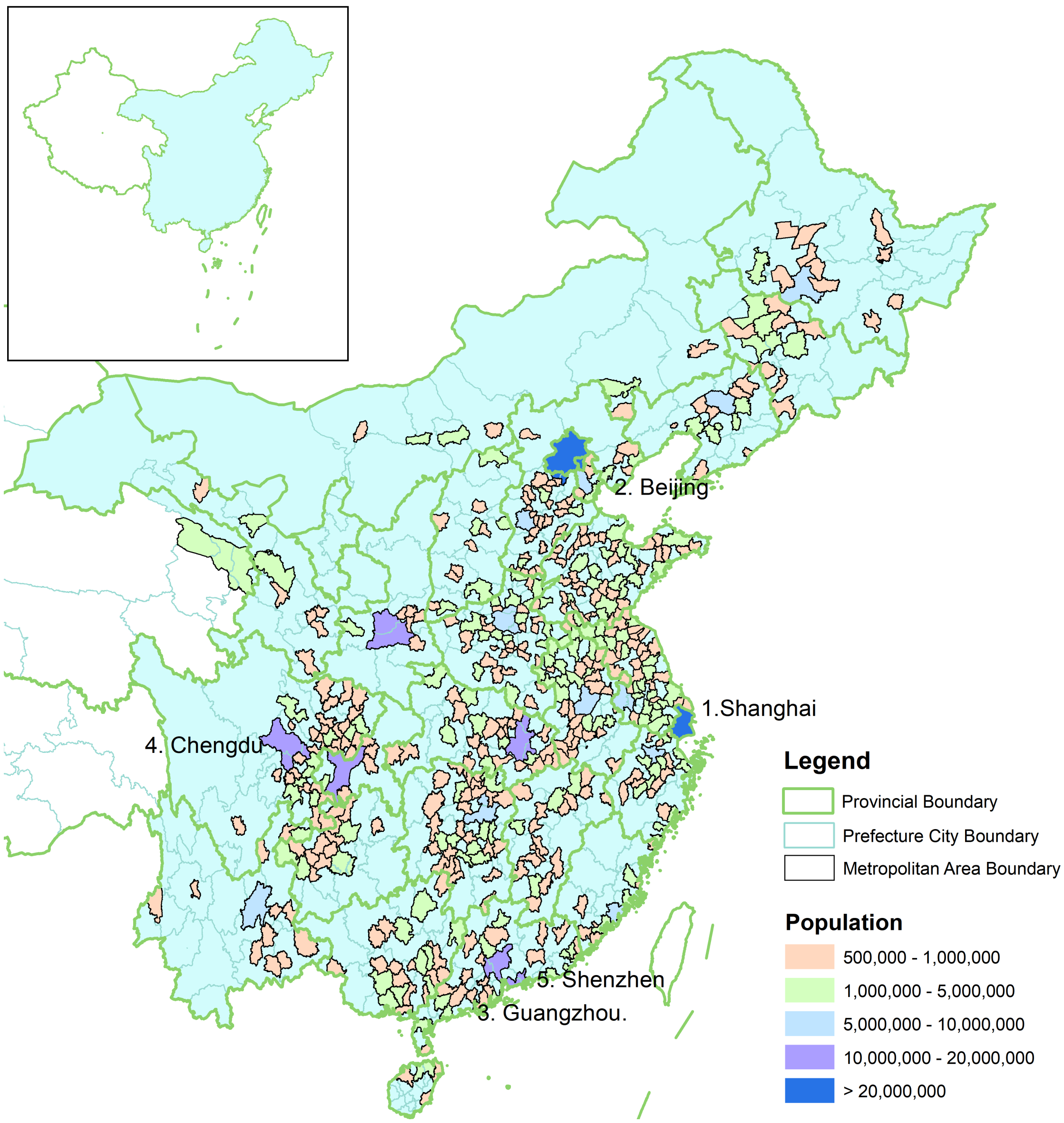
Note: The graphs show the correlation coefficients between MAs based on commuting flows (with various thresholds) and other definitions: municipalities plus prefectural-level cities, contiguous urban districts, contiguous urban districts plus county-level cities, and MAs based on continuous nightlight. Panel A shows correlation coefficients for log population, and Panel B shows those for log area. Here we do not impose the population and density restrictions.

Figure 5 shows the distribution of commuting-based MAs with the threshold at 10% on a map. The map hightlights Central and Eastern China as there are only two MAs in Western China with the 10% threshold. The green lines and the blue lines are the provincial and the prefectural-level city boundaries, respectively. MAs are color-coded according to their population sizes. The largest MAs are Shanghai, Beijing, Guangzhou, Chengdu, and Shenzhen, each with more than 10 million residents. Shanghai and Beijing each has more than 20 million residents. China's northern plains (including Hebei, Beijing, Tianjin, and Shandong), the Yangtz River Delta (including Shanghai, Jiangsu, Zhejiang, and Anhui), the Pearl River Delta (Guangdong), the central south (Henan, Hubei, and Hunan), and the Sichuan Basin (between Chengdu and Chongqing) are heavily urban-

tion of MAs according to different definitions. Appendix Figures A.2 and A.3 show scatter plots of commuting-based MAs of various thresholds against the corresponding MAs by other definitions. Those graphs confirm that cities defined as urban districts plus county-level cities are most consistent with commuting based MAs with the 10% threshold.

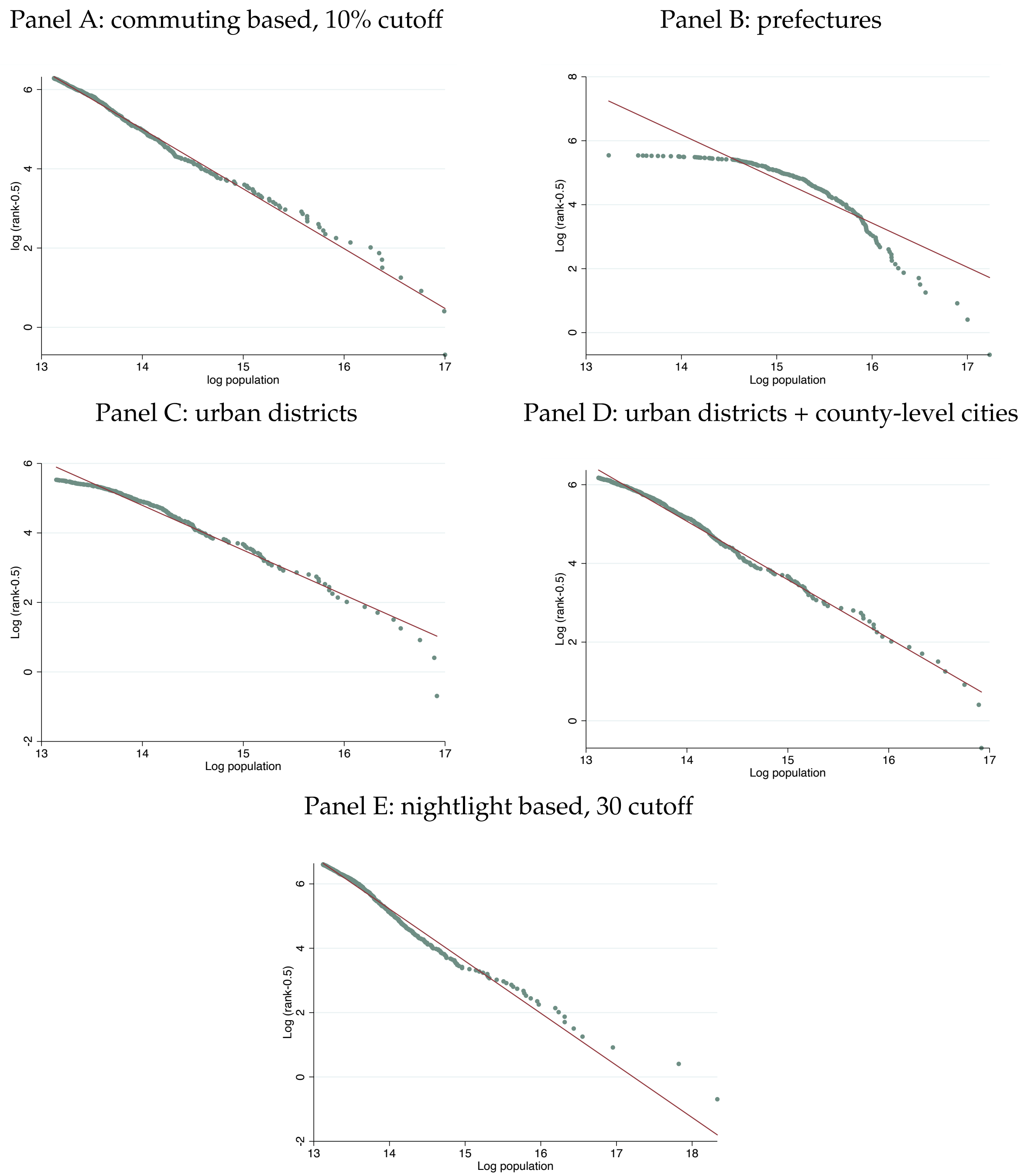
ized. Most MAs lie within prefectural boundaries and are much smaller than their corresponding prefectural-level cities. Few cross a provincial boundary. Appendix Table A.1 lists the 10 largest MAs according to this definition. The MAs on the list are also conventionally perceived as the largest cities in China.

Figure 5: County-Level Delineations of Metropolitan Areas in mainland China: 10% Commuter-Share Threshold, 2017



Note: The map shows metropolitan areas in Central and Eastern China according to our preferred definition. Only two MAs in Western China are not shown here. In this definition, MAs are obtained by intersecting township-based commuting clusters under the 10% commuter-share threshold with county units and then applying contiguity requirements as well as population and density restrictions. The 2017 population data are from the statistical yearbooks.

Figure 6: Zipf's Law according to Various MA Definitions



Note: The graphs show the log linear relationship between population rank and population size according to different definitions of MAs. In Panel A, the slope is -1.508 (the standard error is 0.006), and the $R-$squared of the fit is 0.992. In Panel B, the slope is -1.381 (the standard error is 0.043), and the $R-$squared of the fit is 0.800. In Panel C, the slope is -1.289 (the standard error is 0.014), and the $R-$squared of the fit is 0.970. In Panel D, the slope is -1.486 (the standard error is 0.007), and the $R-$squared of the fit is 0.988. In Panel E, the slope is -1.620 (the standard error is 0.008), and the $R-$squared of the fit is 0.982. The same size and population density restrictions are applied to all MA definitions.

5 Characteristics of China's Metropolitan Areas

5.1 Zipf's Law

A prevailing pattern of the city size distribution is the log-linear relationship between population and the population rank, often referred to as Zipf's law (Gabaix & Ioannides, 2004). Figure 6 Panel A shows that our preferred definition of MAs exhibit a near perfect linear relationship between log population and log population rank. The linear relationship explains over 99% of the variation. Panel B shows that municipalities plus prefectural-level cities present a poor fit of the log-linear relationship. Panel C shows that defining cities as contiguous urban districts results is a decent approximation of Zipf's law. Panel D shows that the log-linear relationship holds if county-level cities are included in the list of cities. Panel E shows that the log-linear relationship holds for nightlight-based MAs using the 2017 data, which is consistent with the finding in Dingel et al. (2019) who use the 2010 satellite nightlight.

Appendix Figure A.4 shows the relationship between log population size and log population rank using commuting-based MAs of alternative thresholds. Setting the threshold at 15% or 20% yields systems of MAs that largely fit the Zipf's law, though not as well as setting the threshold at 10%. Thresholds that are either too small or too large lead to poorer approximations of the log linear relationship.

5.2 City Size Premium

Large metropolitan areas are places where skill concentrates (Costa & Kahn, 2000; Moretti, 2004; Bacolod et al., 2009; Davis & Dingel, 2020) and where wage, productivity and housing prices are higher (Au & Henderson, 2006; Baum-Snow & Pavan, 2013; Davis & Dingel, 2019; Eckert et al., 2020). We estimate city-size premiums in skill and occupation composition, share of migrants, housing price, wage, and productivity (total factor productivity) using various definitions of MAs. We regress each measure against log MA population according to a given definition.

We first check the relationship between city size and the share of college graduates. We construct the share of population with a college degree (at least 15 years of education) at the MA level using the 2015 population survey. The first row of Table 4 reports that the size premium in skill is substantial. According to the commuting-based definition with our preferred threshold, doubling the size of the city is associated with a 7.2 percentage point (p.p.) increase in the skill share. The nationwide sample average of the 2015 population survey is merely 12.34%. The city size premium in skill is the highest according to this commuting-based definition of MAs. Other definitions, including those based on prefectures and urban districts, yield smaller size premiums.

Higher skill shares in larger cities reflect more jobs in high-skill occupations in these cities. To show that, we build the crosswalk between occupations in the 2015 population survey and the International Standard Classification of Occupations (ISCO-88). High-skill jobs, defined as those in managerial, professional, technical and associated professional occupations (ISCO 1, 2 and 3), account for 6.59% of all the jobs. The second row of Table 4 indicates that the magnitude of city-size skill premiums in occupation composition is the highest using the commuting-based MA definition. Doubling the MAs' population size is associated with a 2.8 p.p. increase in the ratio of high-skill jobs.

Larger MAs also attract more migrants. Using the 2015 population survey, we calculate the share of migrants in each MA, where migrants are defined as those whose *hukou* registrations are outside the MA of residence. The nationwide sample average is 25.43%. The third row of of Table 4 shows that doubling the population size of commuting-based MAs is associated with a 11.1 p.p. increase in the share of migrants. The premium is 9.1 p.p. when MAs are defined as urban districts and 3.0 p.p. when they are defined as prefectures.

Large cities typically feature high housing prices. We scraped second-hand housing prices at the neighborhood level in 2017 from a home sale listing website (soufun.com). We regress log housing prices on a set of housing characteristics including the building age and floor-to-area ratio as well as a set of MA fixed effects. The value of those fixed effects indicates the housing price of the MA after adjusting for differences in housing quality. The size-premium of the housing price varies across different definitions of MAs. As the size of the city doubles, the housing price increases by around 26 to 41 percent.

We also check the relationship between the city size and worker's wage and firm productivity. There is no recent publicly-available nationwide dataset in China that contains wage information that could allow us to calculate residual wage at the MA level. We instead use the population survey in 2005, which asks respondent's monthly income. Similarly, we regress log wage on a set of personal characteristics such as age, gender, *hukou* status, industry and occupation as well as MA fixed effects. The fixed effects estimates refer to the MA-level wage after adjusting for differences in industry, job, and individual characteristics. The fifth row of Table 4 reports that doubling the size of the MA is associated with a 6.3% increase in monthly income according to the commuting-based definition, and a 13.4% increase if MAs are defined as urban districts.

We calculate firm TFP using the 2006 Survey of Chinese Manufacturing Firms following Levinsohn & Petrin (2003). We regress log firm TFP on a set of industry fixed effects as well as MA fixed effects, and then regress the MA fixed effects estimates on log MA population. The last row of Table 4 shows that the average firm productivity is about 7.6% higher in a city that is twice the size, according to our preferred commuting-based definition.

Table 4: City-size Premium

	Mean	CB	NB	UD	UD+CC	PR
share of college graduate	12.34%	0.072	0.057	0.050	0.059	0.023
	(0.329)	(0.005)	(0.004)	(0.006)	(0.006)	(0.006)
# obs	1,354,988	341	473	239	368	256
share of workers in high-skill occ.	6.59%	0.028	0.020	0.015	0.020	0.005
	(0.248)	(0.002)	(0.002)	(0.0023)	(0.002)	(0.003)
# obs	1,354,988	341	473	239	368	256
share of migrants	25.43%	0.111	0.086	0.091	0.100	0.030
	(0.345)	(0.010)	(0.008)	(0.011)	(0.011)	(0.014)
# obs	1,354,988	341	473	239	368	256
log housing price	18,099 RMB[#]	0.283	0.261	0.413	0.313	0.336
	(20003.19)	(0.038)	(0.028)	(0.044)	(0.037)	(0.064)
# obs	154,705	189	208	135	219	139
log wage	992.6 RMB[#]	0.063	0.074	0.134	0.100	0.077
	(1,023.8)	(0.018)	(0.013)	(0.016)	(0.017)	(0.019)
# obs	598,864	231	275	204	290	249
log TFP	5.626	0.076	0.062	0.073	0.046	0.094
	(1.074)	(0.028)	(0.027)	(0.026)	(0.026)	(0.030)
# obs	286,810	525	721	251	478	256

Note: Each cell in Column "Mean" reports the nationwide sample average of the variables and the associated standard error. [#] The mean of housing price or monthly wage is shown in absolute values to be informative. Each cell in Columns "CB" to "PR" reports the estimated coefficient associated with log population and the associated robust standard error, where the outcome variable is indicated in the first column. These five columns correspond to five different ways of defining MAs: CB stands for commuting-flow based MAs; NB stands for nightlight based MAs; UD stands for urban districts in a municipality or a prefectural-level city; UD+CC includes also county-level cities in addiont to urban districts; PR stands for municipalities plus prefectural-level cities. Data for the outcome variables come from the following sources. Share of college graduates, share of workers in high-skill occupations, and share of migrants are from the 2015 population survey. The share of college graduates is calcuated as the share of population who receive at least 15 years of education. The share of workers in high-skill occupations are the ratio of those in managerial, technical and associated professional occupations. Migrants are defined as those whose *hukou* registrations are outside the MA of residence. Log housing price at the neighborhood level in 2017 is scraped from soufun.com, adjusting for housing characteristics. Log monthly wage is from the 2005 population survey, adjusting for industry, job, and individual characteristics. Log TFP is calculated as the average Solow residual of 2-digit industries using the firm-level data from the 2006 Survey of Manufacturing Firms.

5.3 Are Chinese MAs too Small?

China imposes various restrictions to prevent cities, especially its largest metropolises, from getting too large. The most salient among such restrictions is the *hukou* policy in prefectural-level cities, which restricts job opportunities and denies many social benefits to migrant workers and their families. As can be seen in Figure 5, most commuting-based MAs are much smaller than their corresponding prefectural-level cities and few MAs cross prefectural boundaries.

There have been debates on whether Chinese cities are too small. Based on patterns of real wage distribution against city sizes, Au & Henderson (2006) conclude that Chinese cities are indeed smaller than their optimal sizes. However, they use the administrative definition of cities, which we have shown is an imperfect measure. Their main sample includes only about 200 cities. In addition, the paper is based on data in the late 1990s. Since then, China's large cities experienced substantial growth despite restrictions. The conclusion may have changed as a result.

This line of work is mostly theory-based. Whether cities are too big or too small is relative to the optimal sizes predicted by theory. Instead, we compare the concentration of population in clusters defined by commuting flows in China with similarly constructed clusters in the United States, Mexico, and Brazil.[18] For the United States, commuting flows are at the county level and are from the 2011-2015 American Community Surveys. For Brazil, commuting flows are at the municipality level and are from the 2010 Population Census. For Mexico, commuting flows are at the municipality level and are from the 2015 Population Census. For each country, we apply the clustering algorithm on commuting flows with the threshold set at 10%. For China, we apply the algorithm at the township level (then assigning each county to a cluster) as well as at the county level. Intuitively, it is more demanding to meet the commuting threshold for larger geographic units. Therefore, the county-based clusters are smaller than the township-based. We then rank the clusters by population.

Figure 7 Panel A plots the cumulative shares of the 200 largest clusters in each country's population. Large clusters in the United States account for a substantial share of the nationwide population. The largest metropolitan area in the U.S. — the New York City Area — has a population of about 23 million and accounts for about 7% of the U.S. population. The 15 largest clusters in the U.S. account for 41% of the nation's population. Clusters in China are much smaller. Its largest cluster, a 16-county area around Shanghai, has a population of 24 million, but that only accounts for up to 1.7% of China's population. The 15 largest clusters in China account for only 18% of the nationwide population. Clusters in Mexico and Brazil, measured as their shares in the nationwide population, are relatively smaller than those in the U.S., but still much larger than those in China.

One may point out that China's population is 4.2 times that of the United States, 6.7 times that of Brazil and 10.8 times that of Mexico, so largest cities in China need to be correspondingly larger to account for the same share of its national population. For example, for Shanghai to account for the same share of national population as New York City, it needs to have a population of near 100 million. There is probably a limit to the density of a city.

While this argument has a valid point, it is worth noting that China's MAs are relatively small in area as well. Figure 7 Panel B shows that the cumulative density of area is also much higher in the United States and Mexico than that in China. The top 15 clusters in the U.S. account for 8% of the nationwide area, while the top 15 clusters in China account for a mere 2%, though China and

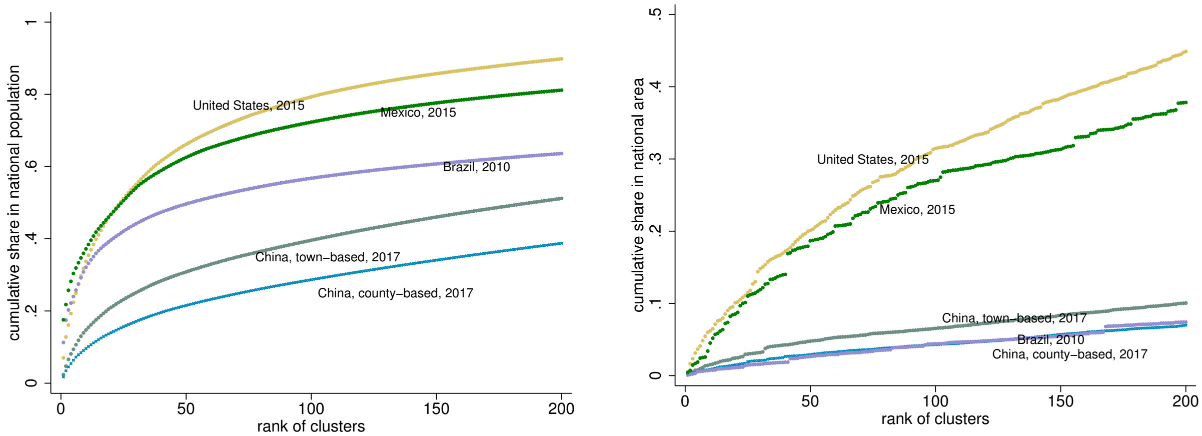
[18]Those countries have publicly available commuting flow data. They are also large countries in both population and area. Brazil and Mexico have similar income levels as China.

the U.S. have a similar land area. Clusters in Brazil, on the other hand, are comparable to those in China in terms of their share in the nationwide land area.[19,20]

Figure 7: The Size Distribution of Commuting-Based Clusters in China and Selected Countries

Panel A: population

Panel B: area



Note: Top 200 commuting-based clusters with the largest population in each country and year as indicated. Clusters are ranked from the largest to the smallest by population. Each line represents the cumulative share of the nation's population (Panel A) or area (Panel B). Clusters are all formed using the same 10% threshold. For China, commuting flows are from smartphone location information in the three months ending in November 2017. Two sets of clusters are formed. The first set is based on commuting flows at the township level, and counties are assigned to the biggest cluster it intersects with. The second set is based on commuting flows at the county level. For the United States, clusters are formed using county-level commuting flows, with data from the 2011-2015 American Community Surveys. For Brazil, clusters are formed using municipality-level commuting flows, with data from the 2010 Population Census. For Mexico, clusters are formed using municipality-level commuting flows, with data from the 2015 Population Census. There are 2,855 counties in China, 3,108 counties in the United States, 5,567 municipalities in Brazil, and 2,443 municipalities in Mexico. All clusters are not subject to population or density restrictions.

5.4 Determinants of City Sizes in China

While there are many reasons why Chinese cities are relatively small for the size of the country, we discuss three determinants of China's city sizes that we discover using the commuting flow data and the clustering algorithm. First, Chinese cities are hierarchical, and the size of the city is highly correlated with its administrative rank. The administrative hierarchy may impose barriers

[19] Appendix Figure A.5 plots the cumulative shares of population (Panel A) and area (Panel B) for all commuting-based clusters. Similar conclusions hold. For example, clusters in the top 20 percentile in the United States account for over 80% of the population and over 40% of the area; while clusters in the top 20 percentile in China account for 40% of the population and about 15% of the area.

[20] Population increasingly concentrates in larger clusters over time. Appendix Figure A.6 Panel A shows that the share of population in the largest clusters in the U.S. increased substantially between 1970 and 2015. There is also an increase in population concentration in the largest clusters in China between 2017 and 2019. The concentration of population in large MAs often accompanies expansion of these MAs in area. In the United States, the share of area accounted for by those large labor markets increased substantially between 1970 and 2015, reflecting the large-scale suburbanization and urban sprawl in the second half of the 20th century. Expansion in area is also observed for China between 2017 and 2019, though at a much smaller scale.

on cities, especially those lower in the administrative hierarchy, to expand and grow. Second, as we have documented in Figure 2 and Table 2, administrative boundaries impose serious barriers for cities to grow. As we elaborate below, it is rare for Chinese MAs to grow across prefectural or provincial boundaries. Third, Chinese cities used to feature a high transporation cost due to poor road network, low car ownership, and bus-dominated transit services. We show that recent urban expansions have been strongly correlated with the improvement in rail transit services.

5.4.1 Administrative Hierarchy

One salient feature of China's MAs is that the size of the MA is highly correlated with its administrative rank. Appendix A.1 reports the 10 largest commuting-based MAs. All of them are municipalities or provincial capitals except for Shenzhen, which itself is a special economic zone. In 25 out of 27 provinces and autonomous regions, the largest MA in the province is the corresponding provincial capital. In 163 out of 229 prefectural-level units that contain at least one MA, the largest MA is the one that consists of the prefecture's core urban districts.

The strong correlation between administrative rank and city size is a prevalent phenomenon throughout China's history and the relationship seems causal. Bai & Jia (2020) study the sizes of Chinese cities over hundreds of years. They find that cities that were designated as provincial capitals became bigger, while those that were deprived of the capital city status subsequently lost population and the size of its economy shrank.[21]

The role of administrative hierarchy implies that lower-ranked cities may get unfavorable policies that are not related to their geography and market advantage. For example, economic conditions have changed substantially in China during the past few decades. An outward economy has made coastal and port cities economically more important, while provincial capitals are mostly inland cities. Thus it is striking that the largest cities in a province remain largely unchanged. For a Chinese city to grow larger, it is often necessary to obtain an "administrative hat," such as being designated as a "special economic zone" or a "coastal port city."

Another feature of Chinese system of MAs that stems from its hierarchical nature is that there are few MAs that are formed exclusively among county-level units that are not urban districts. There are essentially two types of MAs. The first type mostly consists of urban districts. Sometimes a large MA also includes nearby non-district counties. The second type includes stand-alone non-district counties that have an urban core that is large enough and meet the population and density criteria. Out of 537 MAs according to our preferred definition, there is not a single MA that consists of more than one county (or a county-level city) and do not include an urban district. In other words, the only way for a county or a county-level city to be in a multi-county cluster is to be part of the urban core of a prefectural city or a municipality.

This suggests that administrative hierarchy within a city matters for city sizes. As China

[21] Ades & Glaeser (1995) find capital cities in autocratic countries tend to be much larger and more developed than other cities in the country. They hypothesize that political capture and political rent is a potential explanation.

is gradually urbanizing and cities expand, the Ministry of Civil Affairs periodically reclassifies counties and county-level cities that are adjacent to an urban core into districts, both as a result and a cause of urbanization. The reclassification is highly correlated with the pattern of how commuting-based MAs expand, which provides another piece of suggestive evidence that administrative decision, or at least administrative approval, plays a large role in city growth in China.

Using the commuting flow matrix from November 2019, we delineate the MAs using the same set of criteria as we did for the 2017 matrix. We assemble a dataset of county-to-district conversions that took place between 2015 and 2019.[22] Comparing MAs in 2017 and those in 2019 we find that being reclassified as a district is highly correlated with being added to a nearby urban cluster between 2017 and 2019. Six out of 30 (20%) counties that were converted to a district between 2015 and 2019 became part of an MA between 2017 and 2019, a much higher probability than counties that did not have a relabeling (less than 10%).

5.4.2 Administrative Boundaries

A related feature of Chinese MAs is that they are largely confined within administrative boundaries. Figure 2 and Table 2 show that administrative boundaries impose severe restrictions to commuting. According to our preferred definition, only 17 out of 537 MAs cross a prefectural border, merely one (Beijing) crosses a provincial border. In contrast, 36 out of the 100 largest commuting-based MAs in the U.S. cross a state border. Of the 10 largest MAs in the U.S., there are seven cross-state MAs.

Local governments in China impose various rules that make it difficult to live in a county while work in another, not to mention commuting across prefectural or provincial borders. Many jobs are only offered to people with local *hukou*, and much of the benefits—such as healthcare coverage and public school access—is tied to where one works, not where one lives. Public transportation networks typically do not extend beyond administrative boundaries. For an MA to expand across county borders, it is often necessary to first convert nearby counties into districts. Only then could those counties be included in the city's urban planning.

5.4.3 Urban Rail Transit

Transportation cost is one of the major determinants of city size as in the canonical urban model. As shown in Table 2, distance imposes a substantial barrier to commuting. The difference in the distance elasticity between China and the U.S. may be explained by transportation infrastructure and car ownership. China used to feature poor road network, low car ownership, and bus-dominated transit services, which experienced rapid growth/improvements only in the recent two decades.[23] The modes of transportation are still rudimental in 2015, with automobile and public transit accouting for less than 20% (Section 3.3).

[22] We extend the period back to 2015 because it may take time for the reclassification to have observable effects.

[23] The total length of urban rail transit increased from less than 400 *km* in merely 4 cities in 2001 to more than 8,000 *km* in 51 cities in 2021.

Here we focus on how the improvement in urban rail transit may lead to urban expansion. We assemble a datast of urban rail lines that were put into operation between 2017 and 2019. We find that MAs with new rail lines are more likely to witness an urban growth. Out of 33 MAs with new rail lines, 22 (67%) increase in area by incorporating adjacent county units, much higher than MAs that did not have rail lines being added (27%).

6 Conclusions

Using novel commuting flow data at fine geographical levels, this paper first documents basic commuting patterns in China. Commuting is largely short and administrative boundaries impose severe barriers for commuting. We define China's commuting-based metropolitan areas using a clustering algorithm. One version of China's administrative definition of cities, which includes contiguous urban districts as well as stand-alone county-level cities, can be mostly justified by a commuting-based definition at a low commuting flow threshold. Overall, Chinese MAs are relatively small. Although some parts of the country seem continuously urbanized according to nightlight satellite images, the commuting link within these regions remains modest.

We explore the characteristics of China's commuting-based MAs. First, the size distribution of MAs fits Zipf's law. Second, Chinese MAs exhibit large size premiums along important dimensions, such as the share of college graduates, the ratio of high-skill occupations, average wage, housing price, and the total factor productivity.

The commuting-based MAs defined in this paper offer the first delineation of Chinese cities according to a city's most important economic functions—to provide employment opportunities and to house its residents. The delineation of commuting-based MAs is a useful tool for policymakers. The provision of public goods, such as public transit and public housing, can be greatly improved from the perspective of commuting-based MAs. In a similar spirit, place-based policies need to target MAs instead of administratively defined units.

This paper shows the potential of new sources of big data in generating policy-relevant measures of social economic conditions in a timely, granular, and high-frequency manner. Our definition of commuting-based MAs provides a useful tool for researchers who are interested in questions related to Chinese cities and local labor markets.

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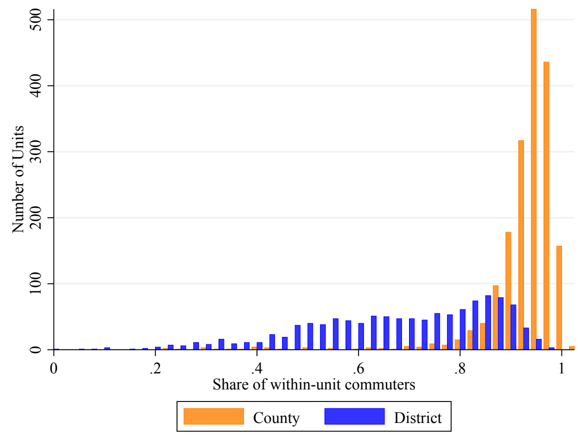
A Additional Figures and Tables (Online Appendix, Not for Publication)

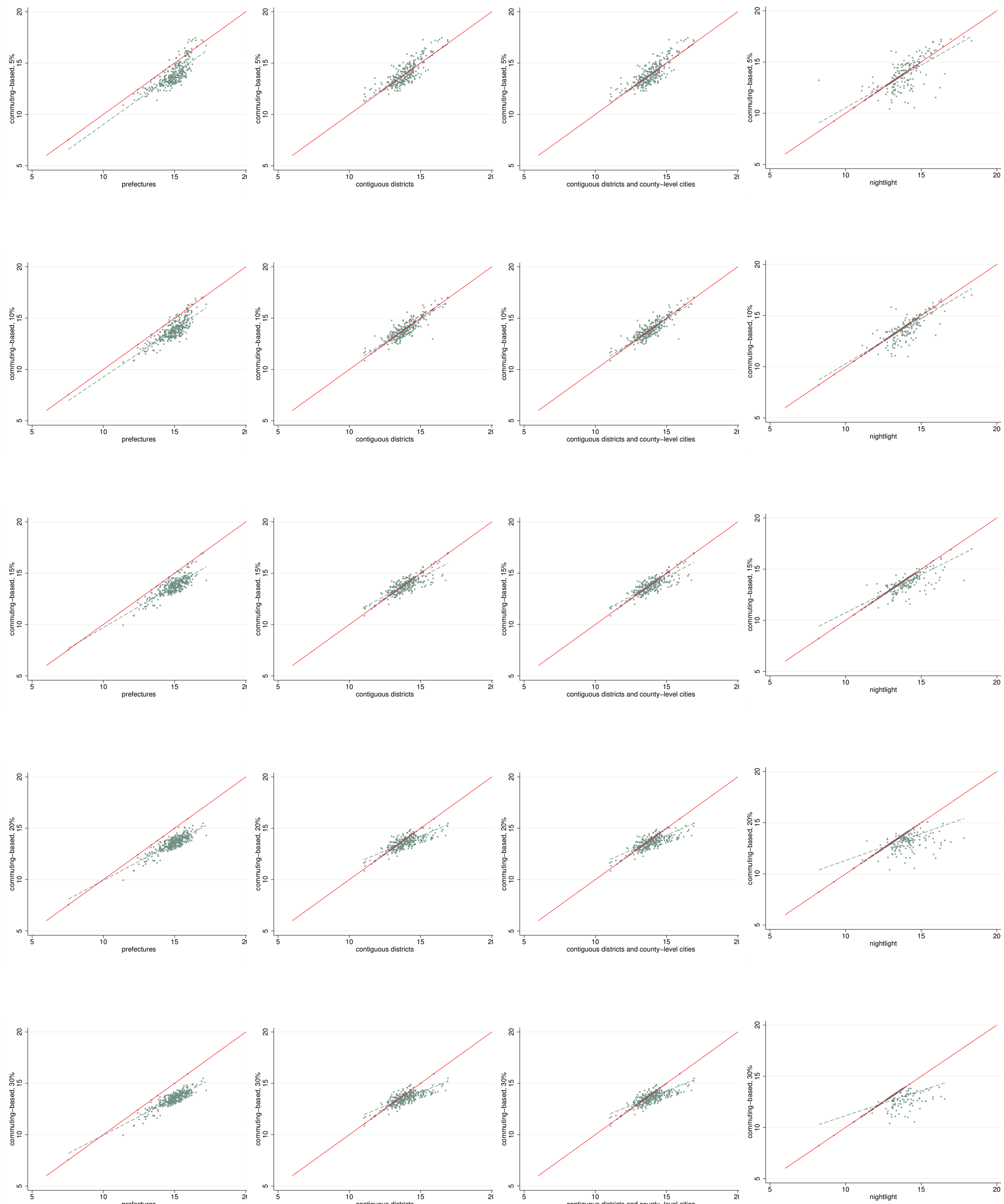
Figure A.1: Within-unit Commuting Ratio: County vs. District



Note: Graphs show the number of counties and districts by the share of within-unit commuters using smartphone location data in November 2017.

Figure A.2: Correlations between Commuting-based MAs and Other Definitions: Population

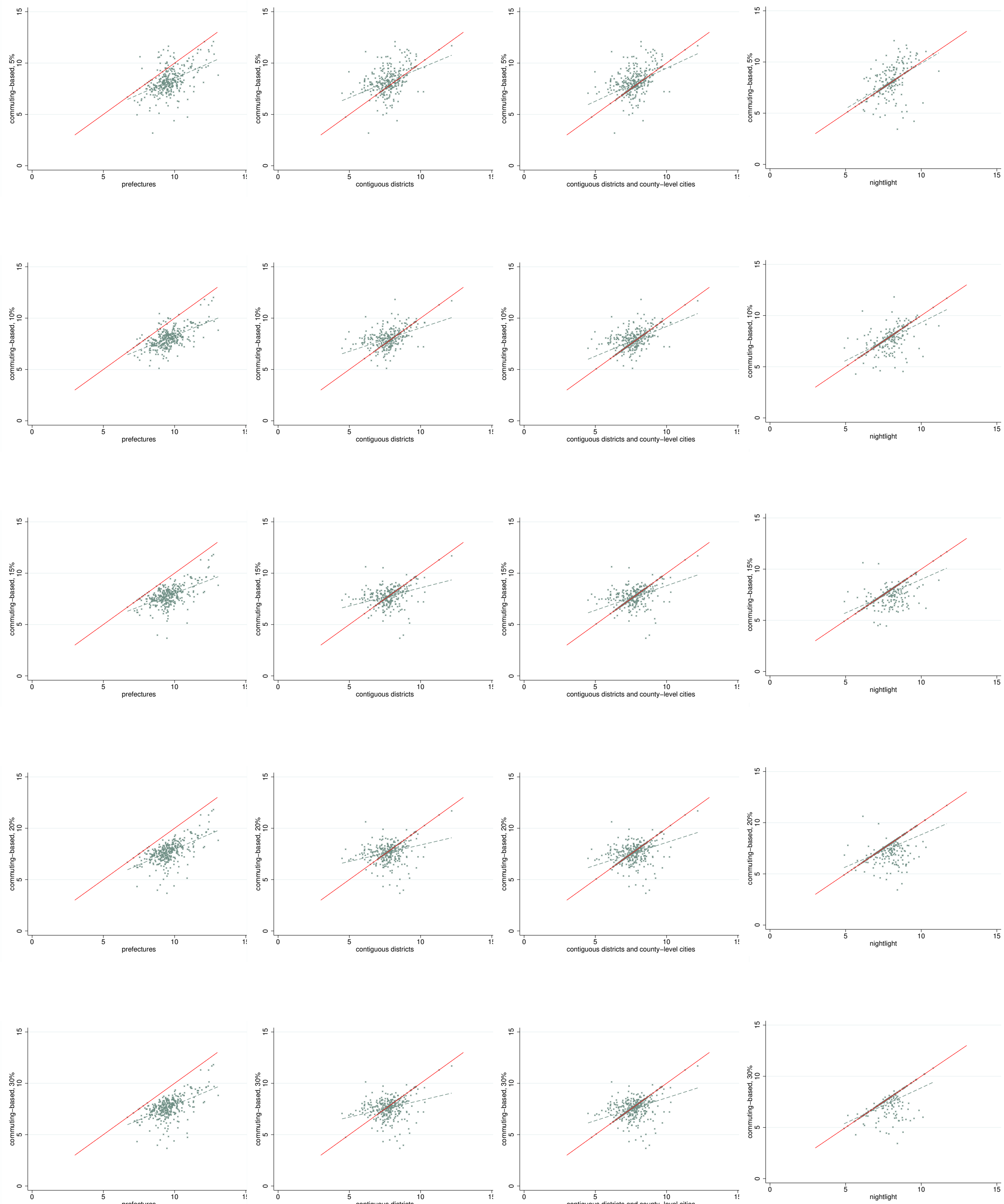
Col A: prefectures Col B: districts Col C: + cnty cities Col D: nightlight



Note: Correlations in log population between commuting-based MAs and those according to other definitions. Each column corresponds to an alternative definition. Each row corresponds to a different threshold for commuting flows. Here we do not impose the population and density restrictions.

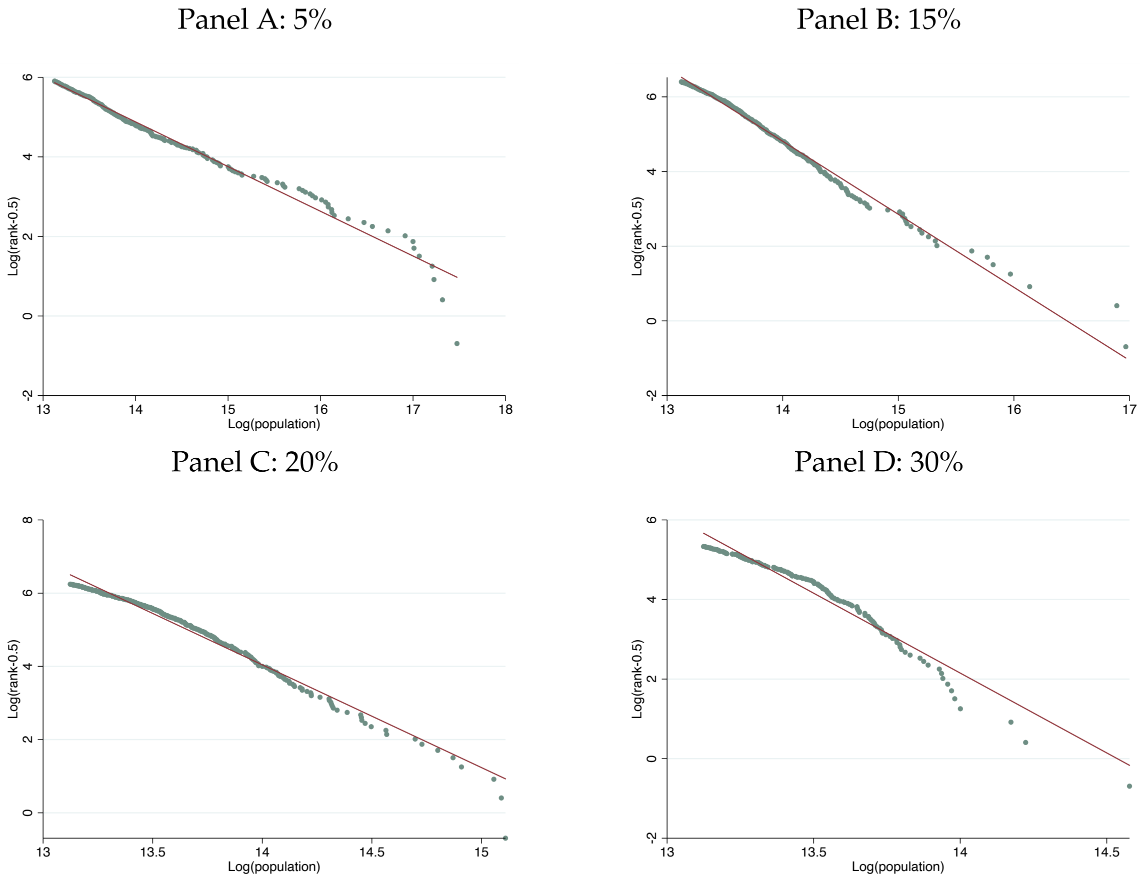
Figure A.3: Correlations between Commuting-based MAs and Other Definitions: Area

Panel A: prefectures   Panel B: districts   Panel C: + cnty cities   Panel D: nightlight



Note: Correlations in log area between commuting-based MAs and those according to other definitions. Each column corresponds to an alternative definition. Each row corresponds to a different threshold for commuting flows. Here we do not impose the population and density restrictions.

Figure A.4: Zipf's Law

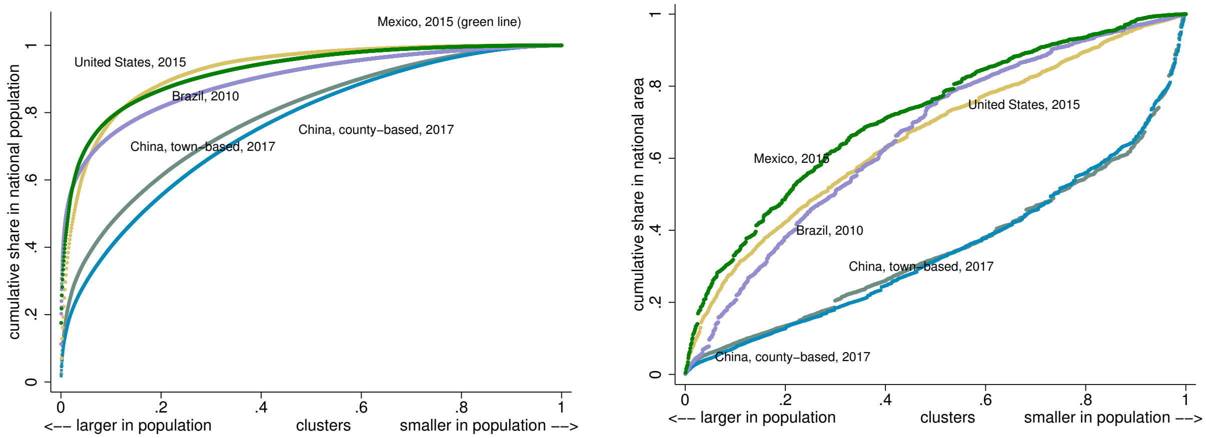


Note: The graphs show the log-linear relationship between MA's population rank and its population size. Each panel corresponds to a different threshold for commuting flow shares. Panels A to D use a threshold of 5%, 15%, 20%, and 30%, respectively.

Figure A.5: The Size Distribution of Commuting-Based Clusters in China and Selected Countries

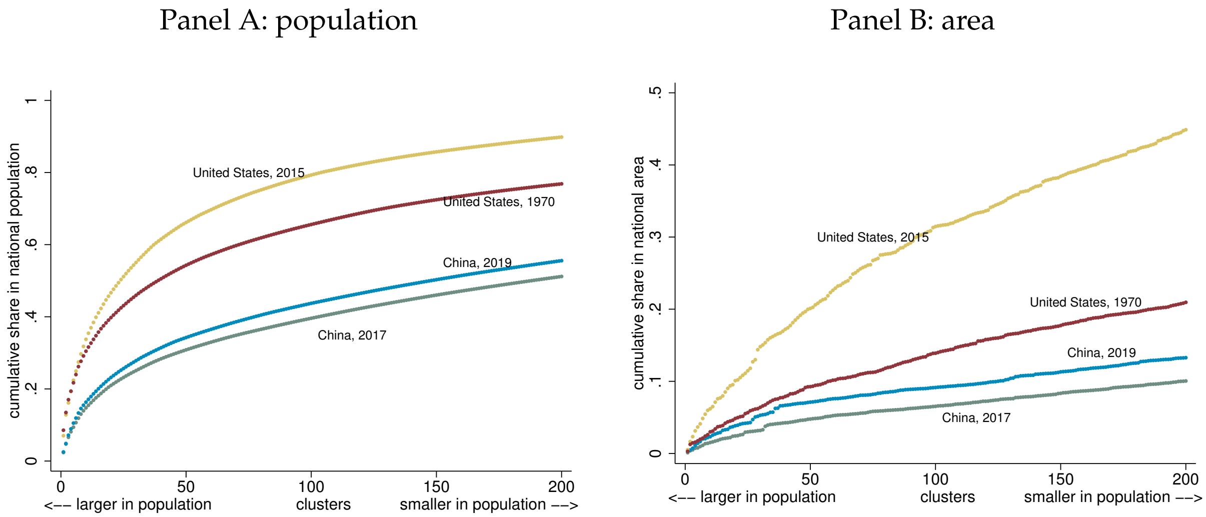
Panel A: population

Panel B: area



Note: All commuting-based clusters in each country and year as indicated. Clusters are ranked from the largest to the smallest by population. The x-axis indicates the percentile of the distribution of cluster population size. Each line represents the cumulative share of the nation's population (Panel A) or area (Panel B). Clusters are all formed using the same 10% threshold. For China, commuting flows are from smartphone location information in the three months ending in November 2017. Two sets of clusters are formed. The first set is based on commuting flows at the township level, and counties are assigned to the biggest cluster it intersects with. The second set is based on commuting flows at the county level. For the United States, clusters are formed using county-level commuting flows, with data from the 2011-2015 American Community Surveys. For Brazil, clusters are formed using municipality-level commuting flows, with data from the 2010 Population Census. For Mexico, clusters are formed using municipality-level commuting flows, with data from the 2015 Population Census. There are 2,855 counties in China, 3,108 counties in the United States, 5,567 municipalities in Brazil, and 2,443 municipalities in Mexico. All clusters are not subject to population and density restrictions.

Figure A.6: The Size Distribution of Commuting-Based Clusters in China and the United States, Seclected Years



Note: The graphs show the top 200 commuting-based clusters with the largest population in each country and year as indicated. Clusters are ranked from the largest to the smallest in population. Each line represents the cumulative share of the nation's population (Panel A) or area (Panel B). Clusters are all formed using the same 10% threshold. For China, township level commuting flows are from smartphone location information in the three months ending in November 2017 and November 2019. Each county is assigned to the biggest cluster it intersects with. Two sets of clusters are formed in 2017 and 2019, respectively. For the United States, clusters are formed using county-level commuting flows, with data from the 2011-2015 American Community Surveys and the 1970 population census. All clusters are not subject to population and density restrictions.

Table A.1: The Top Ten Metropolitan Areas By Population

		By Metropolitan Areas		
Name	Rank	Population (million)	Area (km^2)	No. of Counties
Shanghai	1	24.2	8058.5	16
Beijing	2	24.0	19115.5	21
Guangzhou	3	19.1	9266.7	14
Chengdu	4	15.6	16410.1	20
Shenzhen	5	13.0	3142.1	10
Chongqing	6	12.9	13965.6	13
Wuhan	7	12.6	11955.4	17
Xi'an	8	11.6	16660.2	23
Tianjin	9	9.5	3660.1	11
Zhengzhou	10	8.2	7916.5	12

Note: The table reports the 10 largest MAs by population, according to our preferred commuting-based definition of MAs. The last column reports the number of county-level administrative units in each MA.