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Expansion and growth in Chinese cities, 1978–2010

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Abstract
It has long been recognized that compact versus more sprawling urban forms can have very different environmental impacts. As the Chinese population continues to rapidly urbanize, the size, shape, and configuration of cities in China will undoubtedly change to accommodate expansion of housing, industry, and commerce, causing direct and indirect environmental impacts at multiple scales. It is therefore imperative to understand how urban areas are evolving as socio-economic reforms in China are implemented across different regions. This paper compares trends in 142 Chinese cities (including 17 agglomerations) to understand urban expansion and population growth following reforms, 1978–2010. The results show that cities tripled in size, while doubling in population over the same period. In coastal areas targeted by early policies, urban land increased 4–5 times since 1978, for all city sizes. Large agglomerations are the primary consumers of land in coastal and western regions, each adding an average of 450 km^2 during the study period, while small-medium cities consumed an average 20 km^2. Although populations in these agglomerations increased an average 1.3 million, 2000–2010, cities within 100 km of each agglomeration grew >1.8 million collectively. Proximity to large agglomerations contributed to the growth of small-medium cities, especially in western regions.

Keywords: urbanization, land cover change, remote sensing, Landsat, change detection, urban geography, urban sprawl

1. Introduction

The environmental impacts of urban form have been well studied in recent decades: the size, structure, and growth of cities lead to significant and lasting changes in local precipitation and temperature (Weng 2001, Kaufmann *et al* 2007), expansion of the urban heat island effect (Zhou *et al* 2004), reduced water quality (Shao *et al* 2006), and loss of arable land (Tan *et al* 2005, Seto *et al* 2012). Moreover, many environmental impacts are exacerbated when new growth is expansive and/or fragmented in form (Alberti 2005), such as the low density, dispersed forms of urban expansion common in the US and other developed countries (Ewing *et al* 2002), and emerging in many rapidly developing nations as well (Leichenko and Solecki 2005).

In the US and EU, urban form is generally the outcome of two very different processes: (1) transportation decisions and transport policy, whereby the public sector provides infrastructure for public and private vehicles, and (2) land use decisions, such as those made by the private sector with respect to privately owned land for residential, industrial, and commercial space. The very different nature of these two areas of policy and the lack of coordination between them has limited efforts to regulate urban form, in some cases leading to urban sprawl (Anderson *et al* 1996). In China, these processes have evolved somewhat differently. Land use and transport decisions have been entirely at the hands of the central government, up until reforms were implemented in

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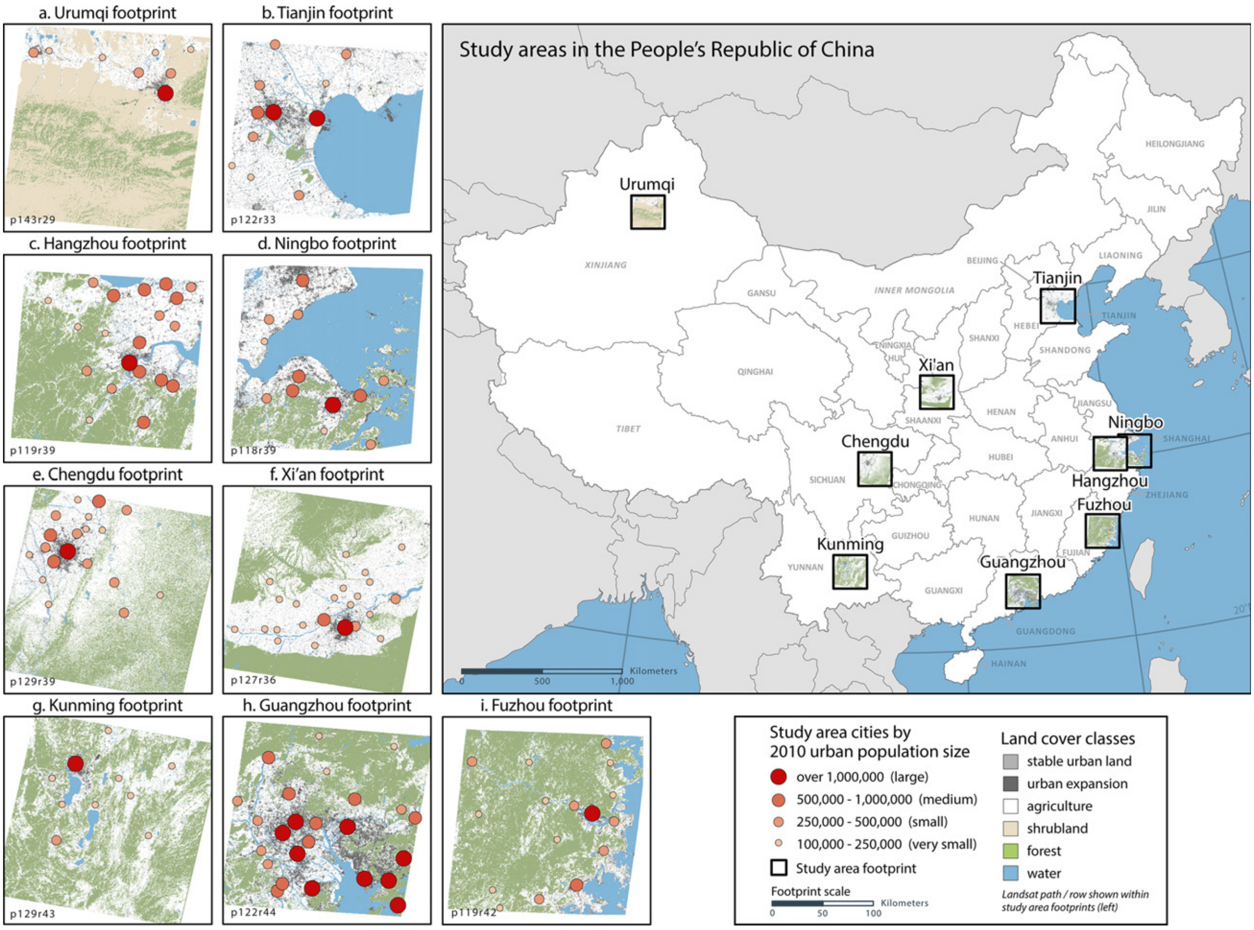

Figure 1. Maps of each study area footprint showing the distribution of the 17 large agglomerations and 125 medium, small, and very small cities assessed in this research.

the late 1970s. At that time, efforts to reduce the dominance of central state planning—including decentralizing decision-making and fiscal powers, permitting a more market-led economy, privatizing urban enterprises and housing, and opening China to foreign direct investment (FDI) (Yeh and Wu 1995, Ma 2004)—led to a western-style split in policy affecting land use, transport decisions, and ultimately, urban form.

The outcome of reforms has been a phenomenal social and economic shift throughout China that includes rapid urbanization, industrialization, and economic growth. The urban landscape in China has been impacted heavily by locational decision-making by domestic and foreign firms, although the latter is still often controlled by development zones – often at the city edge—designated by the government (Cho and Tung 1998). While FDI has long been recognized as an important element for growth (de Mooij and Ederveen 2003), there is increasing evidence that investment from the state in under-performing regions has been a key factor affecting land development (Ke 2010). Transport infrastructure continues to be provided by state or local governments, but is also influenced by the private sector in some locations (Li and Li 2013). In recent years, the emergence of a land use market and the subsequent sale/leasing of land use rights by the government form 30–70% of municipal budgets, and these budgets, in turn, have been used to finance extensive urban development projects (Lin 2007, Lichtenberg and Ding 2009). As a result, cities have expanded at unprecedented rates, with a near doubling of urban land extent between 2000 and 2010 (Schneider *et al* 2014).

Clearly, the growth of Chinese cities has become increasingly complex, with multiple parties affecting land use decisions at multiple levels and scales. To mitigate the effects of rapid growth and provide effective policy alternatives, it is therefore critical to understand the evolving nature of cities, towns, and settlements across China in the post-reform era.

The goal of this letter is threefold. First, we aim to provide a quantitative assessment of the spatial and temporal patterns of growth in a sample of 142 cities in China using remote sensing data spanning 1978–2010 (figure 1). The second goal is to compare rates and patterns of urban expansion in coastal cities, where reforms were implemented in the 1970s–1980s, to those in western cities, which have only recently been targeted as part of China's Western Development Program initiated in the 1990s and formally approved in 2000 (Lai 2002). Finally, the third goal is to connect these trends to population data, since it is the growth and distribution of population that ultimately drive policy in many countries. As the Chinese government plans to move an additional 250 million into cities in the next decade, understanding urban form and its related environmental impacts will become increasingly important to the health, well-being and quality of life for the majority of China's residents.

2. Background and study area selection

Because China's first wave of urbanization has been focused in coastal areas, the majority of work has been dedicated to mapping three mega-agglomerations: (1) Beijing (Zhang *et al* 2002, An *et al* 2007), (2) Shanghai and the Yangtze River Delta (Zhang 2001, Liao *et al* 2008, Yue *et al* 2010), and (3) Guangzhou and the Pearl River Delta (Weng 2001, Seto *et al* 2002). There has been an explosion of publications (>150) during the last decade mapping China's cities, but these investigate one city at a time with little comparative analysis, and >85% focus on coastal regions. A more comprehensive view of urban expansion comes from Wang *et al* (2012), who documented growth in 147 of China's largest cities for 1990–2010 by digitizing urban extents in Landsat imagery. Their results include only a limited core area for each city; any small cities or peri-urban growth that may function as part of the metropolitan area were not included in their analysis.

Three important characteristics were used to define the sample for study: (a) level of economic development; (b) city size; and (c) region in which the city is located. We first stratified on the Landsat footprints ($\sim$185 × 185 km), and filtered the footprints by selecting those with the greatest variability in terms of per capita economic output, number of new firms and city population size (2000–2005). At the same time, we tried to sample as evenly as possible between coastal and western China. The final sample of nine footprints includes 17 agglomerations (defined here as extended urban regions comprising the contiguous built-up area of the core and nearby cities) and 125 cities. Additional tests described in Alix-Garcia *et al* (2013) allowed us to conclude that that these areas are representative of China's cities as a whole.

To determine the effects of growth across a range of city sizes, we use the 2010 urban population (county-level) to stratify the cities into four classes based on UN definitions (UN 2011): (1) large agglomerations, >1 million; (2) medium-sized cities, 500 000–1 million; (3) small cities, 250 000–500 000; and (4) very small cities, 100 000–250 000. Each footprint has one large agglomeration (with the exception of the Guangzhou footprint, which has eight, and Tianjin, which has two), as well as 8–22 medium, small and very small cities.

3. Methods

3.1. Defining urban land

This work defines urban land as places dominated by the built environment. The 'built environment' includes all non-vegetative, human-constructed elements, such as roads, buildings, etc, and 'dominated' implies coverage greater than 50% of a landscape unit, such as a pixel (Schneider 2012). Although vegetation such as parks may be contained within a city, these areas are not considered urban, even though they may function as urban space. Expansion of urban areas refers to wholesale conversion of land within a landscape unit (it is assumed that the entire pixel is converted). In the remote sensing analysis, all areas converted to built surfaces are labeled 'urban expansion' whether they are located near the city, in peri-urban zones, or in rural areas.

3.2. Remote sensing of urban expansion

The maps of urban expansion were obtained through historical analysis of Landsat MSS, TM and ETM+ data for seven time periods (1978–1984, 1984–1990, 1990–1995, 1995–2000, 2000–2003, 2003–2006, 2006–2010). We relied on a supervised multi-date change detection technique that exploited temporal information from dense time stacks of Landsat data (figure 2) (Schneider 2012). This approach resolves the confusion between new urban land and other land cover types by including images from multiple seasons and multiple years. While there may be confusion between bare ground and urban areas during the course of one year, there is often a high probability that nearby fields or open areas will be vegetated during at least one season, and thus be 'separable' from built-up areas that are predominantly non-vegetated year round. Information from multiple years is also beneficial: images that follow the date of urban change actually help 'confirm' that an area has been developed. All Landsat scenes were stacked and used as input to a boosted decision tree classifier (C4.5, Quinlan 1993) to detect stable/changed areas for the five periods spanning 1990–2010. Training site selection for C4.5 was performed in-lab through interpretation of Landsat and Google Earth imagery and through field campaigns to each location. On-site visits (2009–2011) confirmed two key transitions in each region: cropland to urban land, and forest/shrubland to urban land.

The 1990 urban land extent was used to constrain where we mapped change in the 1978–1990 period. Here, we assume that any conversion of land to urban uses is unidirectional; any urban expansion from 1978–1990 will appear as urban land in 1990. The Landsat MSS data were therefore classified as change/no-change using the 1990 urban extent as a mask. The stacked Landsat MSS data for 1978–1990 were used as input to C4.5, and training data were selected through interpretation of the Landsat imagery.

The final maps were calibrated and assessed for accuracy using Google Earth imagery, on-site visits, and photo interpretation of test sites by multiple analysts (Schneider 2012). To quantify the uncertainty in the maps, we estimated multiple measures (see Schneider 2012). The overall accuracies of the maps averaged 90–94% confirming their suitability for this analysis.

An important component of our methodology is how we defined the extent of each city (figure 3). Following convention in urban geography, we extract the built-up area using radial zones: 25 km buffers for large agglomerations, 10 km for

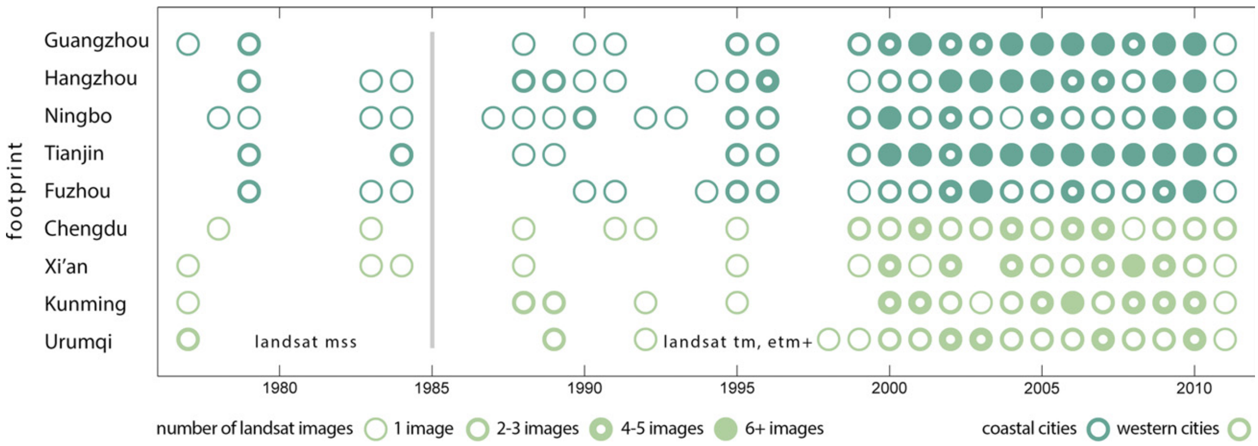

Figure 2. A visualization of the number of Landsat MSS, TM and ETM+ images (35–100 per footprint) used to map urban expansion and land cover change in each scene footprint for seven periods spanning 1978–2010. Note that the Landsat path/row is provided in figure 1.

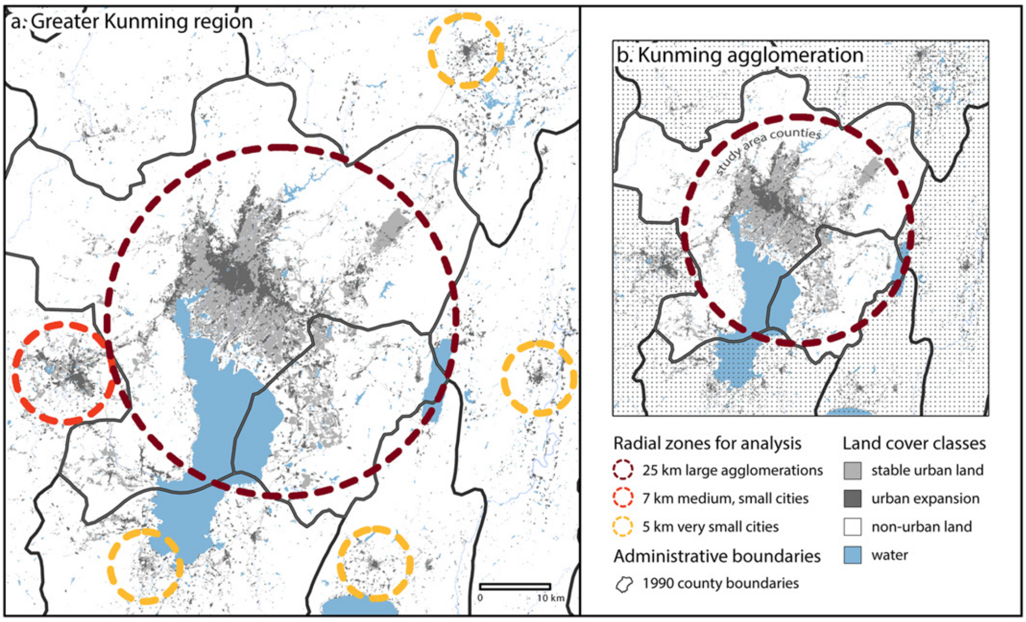

Figure 3. An example of the county boundaries and radial buffer zones used to define the extent of cities and agglomerations in the sample. The city extents are delineated by the 2010 built-up area in the remote sensing-based maps (radial zones are used to extract this area), and the corresponding county-level demographic data are matched to these estimates. The figure shows examples for (a) cities of multiple sizes in the Kunming footprint, and (b) an agglomeration comprised of multiple counties (Kunming).

medium-sized and small cities, and 5 km for very small cities (note that cities were only included if their full built-up extent was visible on the image footprint). This approach allows us to (a) provide estimates that are comparable within a size class by standardizing the study area extent; (b) define cities based on their full built-up extent rather than administrative boundaries; and (c) distinguish the extent of cities where the built-up area of one spreads into another. For a few large agglomerations, some nearby cities are included within the 25 km radial zone. Because these small cities may function as part of the agglomeration but are governed independently, we also include these as separate data points in the medium-small size categories.

3.3. Demographic data and administrative boundaries

Since Chinese census data on urban populations are unreliable prior to 2000 (persons living/working in urban areas with rural *hukou* were still counted as rural) and often unavailable for early dates, we rely on county-level population data (NBS, multiple years) corresponding to the built-up extent of each city. The county is an important administrative level in China; there is evidence that fiscal and administrative

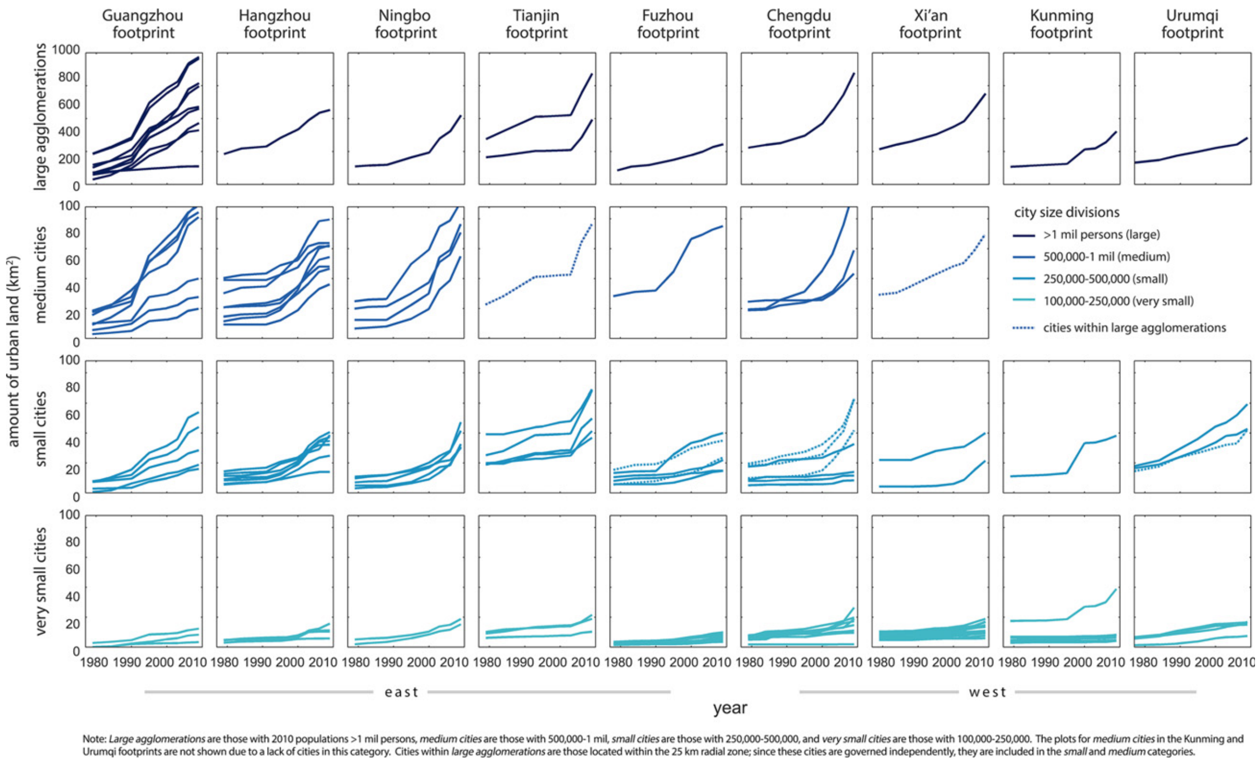

Figure 4. Amounts of urban land and urban expansion from 1978 through 2010 for (top to bottom) large agglomerations, and medium, small, and very small cities in nine footprints across China. Note the change in scale on the *y*-axis for large agglomerations (top row).

decision-making are conducted at the county level (Cheung 2008), and while municipal boundaries vary through time, county boundaries are considered more stable. County-level boundaries were acquired in GIS format for the earliest available year, 1990 (CIESIN 1996). In a few locations, the government redrew boundaries to create new counties; data for these counties were aggregated to the 1990 county. For counties that merged, disaggregated data from later periods were collected to create a final dataset consistent with the 1990 county boundaries.

Because county-level populations are somewhat larger than the city population (rural residents are included in these estimates), we assess population trends 1990–2010 independently from the urban land information. To connect trends in the urban population to urban expansion, we exploit county-level urban population data for 2000 and 2010. We connect the urban population to land use by selecting the counties corresponding to the radial zone for each of the 142 cities (figure 3). In the majority of cases, there was a 1:1 match between the buffer zone and the county. For large agglomerations, data from multiple counties were merged to match the buffer area.

4. Results

To understand how cities are changing across China, we turn first to the expansion of urban land, 1978–2010 (figure 4, appendix figure A.1). The results show that development accelerates in coastal cities after reforms, with high rates of expansion beginning in the late 1980s and early 1990s. Areas targeted with the earliest reforms (Shenzhen, Ningbo) begin to expand rapidly before the others, and small- and medium-sized cities in these regions also begin developing earlier, likely due to the significant spillover effects of the economic growth that occurred in large cities. By comparison, other large coastal agglomerations (e.g. Hangzhou, Fuzhou) and neighboring small cities begin to expand in the late 1990s.

Because reforms were not implemented in the West until after 1991, evidence of urban expansion does not appear until the late 1990s. Chengdu takes off earlier than the others, since it was the first western city to receive a national-level high tech zone to spur growth and expansion. Kunming's jump in urban land follows a building boom for the World Horticultural Expo in 1999, but large amounts of new land in the 2006–2010 period suggest continued rapid growth. A similar upward climb is apparent in Xi'an, while Urumqi experiences a steady rise in urban land; even small and very small cities in the Urumqi footprint follow this trend.

Figure 4 illustrates that differences in both the timing and design of domestic policies are clearly marked on the urban landscape. Early in the post-reform period, the entire coastal region was designated as an open economic zone (Cho and Tung 1998). In effect, this policy evened the playing field, allowing cities of all sizes to grow, compete in the global marketplace, attract FDI, and subsequently, expand rapidly. Major cities (especially Special Economic Zones) still played a critical role in fostering investment, trade, and economic growth, so the central government tried to emulate this model in the west by designating major growth centers in the 1990s (Ke 2010). This, combined with a smaller rural population

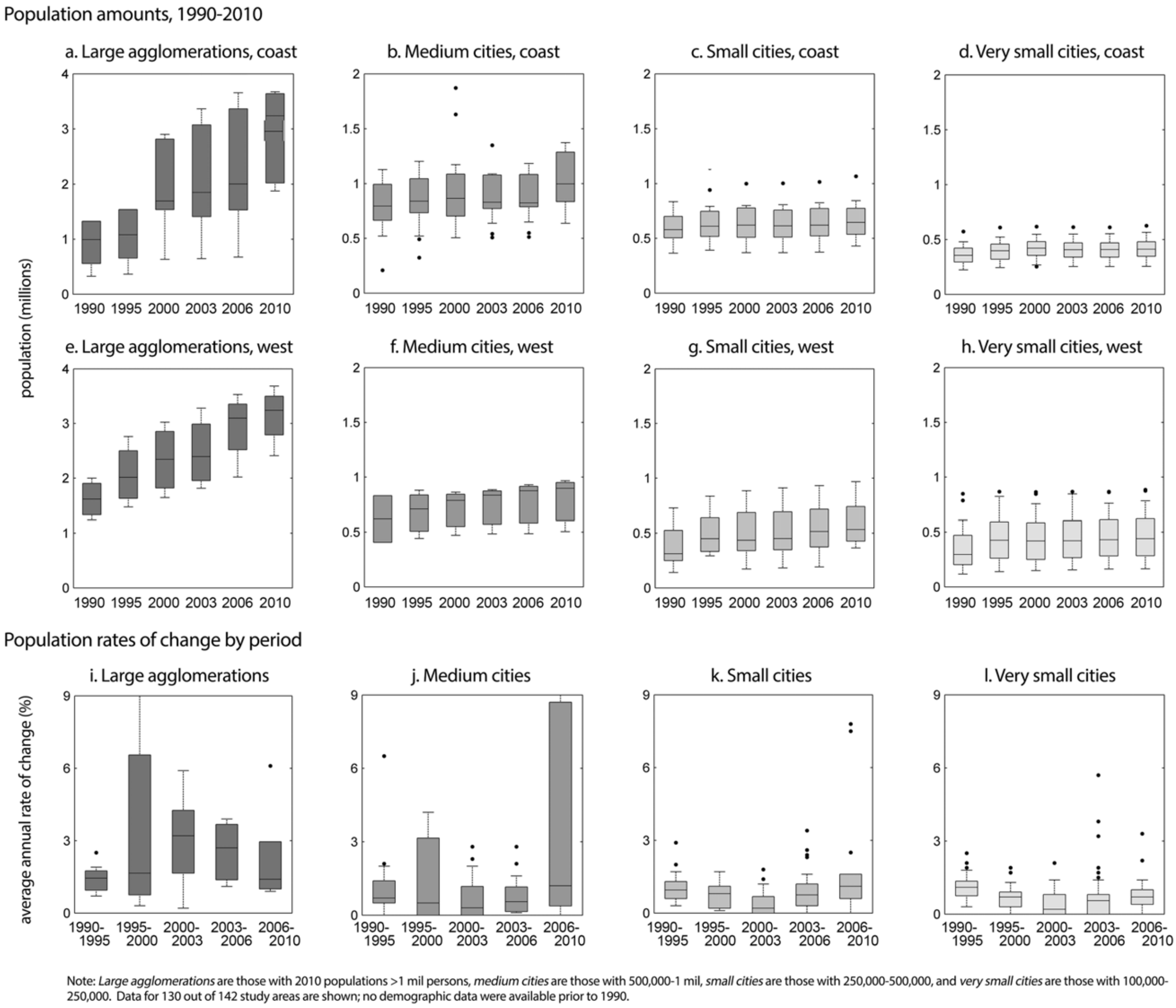

Figure 5. Box plots illustrating the distribution of population and rate of population change across six time points, 1990–2010, derived from county-level population statistics collected for each city (data for 130 out of 142 cities were available for analysis). Note the change in scale on the y-axis for large agglomerations (left column, top two rows). The overall rates of change show very similar trends across regions, and are thus pooled by size class (bottom row).

migrating into urban areas (the west has 27% of China's population on 71% of its land, c2010), means that expansion in Western regions is clustered around large metropolitan cities, with some spillover growth in nearby small and medium cities.

Figure 4 highlights one additional trend: across all regions, cities in nearly all size classes experience a distinct jump in urban land during the 2006–2010 period. This expansion translates to an average annual increase of 3.7 (coast) to 5.0% (west) over the period. These rates of growth are phenomenal when compared with global averages of <2% expansion for mid- to large-sized cities annually (Angel *et al* 2005, Schneider and Woodcock 2008). Medium and small cities, especially, witnessed a jump in expansion, with rates of 4.1% and 6.8% for the coast and west, respectively. This period corresponds to the heightened focus on the west by the central government, so new expansion in the Western region is expected. However, it is surprising to see significant expansion in coastal areas, given the extensive growth that had already occurred. By 2006, coastal cities had already tripled or quadrupled in size, but in the 2006–2010 period, these cities expanded another 4% annually. The six cities in our sample near Shanghai average >16% expansion annually, in fact, highlighting the continued expansion of mega-urban regions.

The expansion of urban land parallels an important shift in population across city sizes (figure 5). Large agglomerations grew significantly, 1990–2010: large coastal cities grew from a median of <1 million to nearly 2 million by 2000, finally reaching a median of 3 million by 2010. Large agglomerations in the west, however, began the period with larger populations, with a median of 1.7 million persons in 1990, reaching 2.2 million by 1995, and 3.2 million by 2010. This trend reflects the fact that several small coastal cities have grown to large metropolitan areas in just a twenty-year time span (e.g. Shenzhen). The trend in the west, meanwhile, confirms that cities chosen for investment/growth were already prominent in the region before new policies took effect.

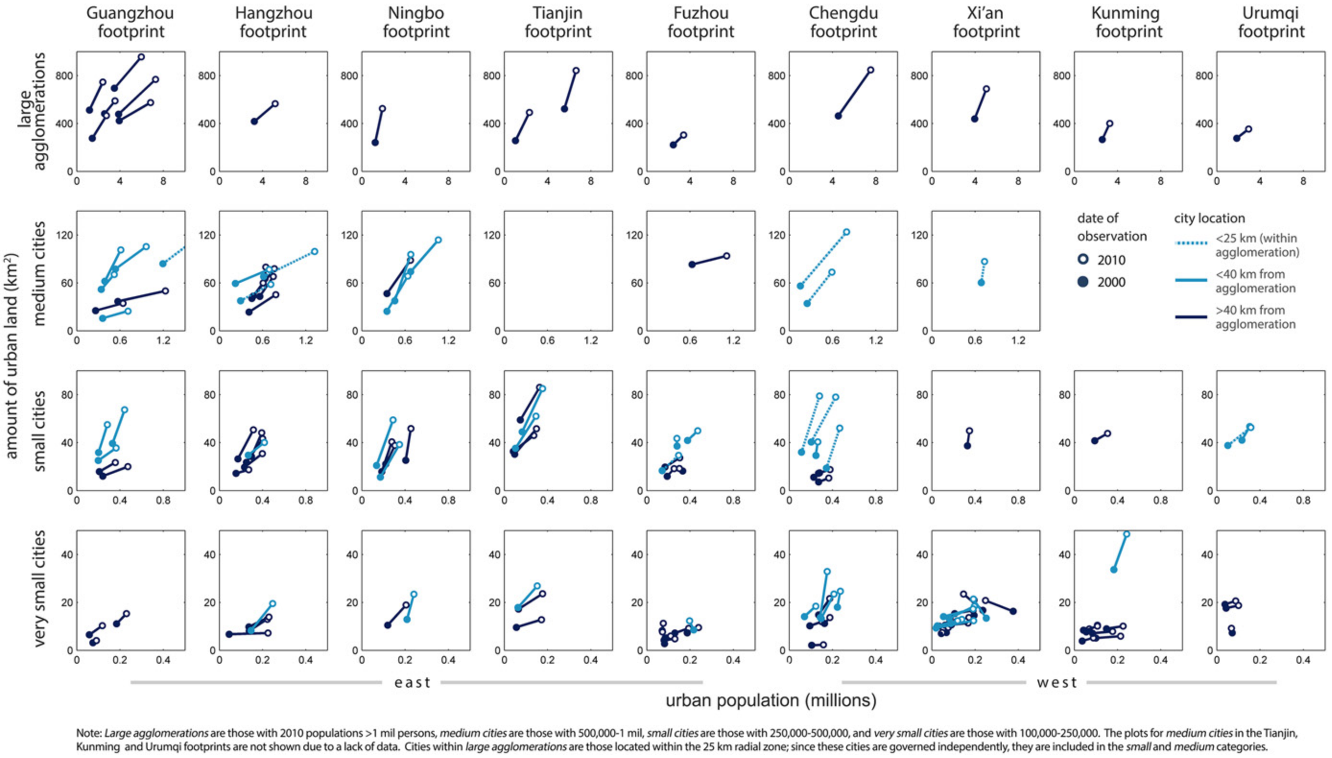

Figure 6. Change in urban population (x-axis) compared to expansion of urban land (y-axis), 2000–2010, for all sample cities. Note the difference in scale across city size classes.

For medium-sized cities (figure 5), population growth appears steady and significantly high across periods; cities increase from a median of 600 000 in 1990, to 1 million by 2010. In the 2006–2010 period, rates of change in medium-sized cities are actually higher than those in large agglomerations, indicating a shift toward medium-sized city growth. While cities under 500 000 (small-very small size classes) do not show significant population growth, there is a small increase across the study period for both regions. Note that urban growth may have been large in small cities, but the trends could be masked in the total county values. In addition, persons that moved to cities prior to 2000 may have been counted as part of the rural population if they moved from rural areas within the same county or from a neighboring county. Finally, there are several outliers in the small city population data: a few locations experienced extremely rapid growth for one or more periods (2–8% annually, compared to an average annual rate of change of 0.7% across all periods). What is unique about these cities is that all are located within 20 km of major agglomerations. Before 2000, these points correspond to significant jumps in population near Guangzhou (Gaoming), while later, all are close to Chengdu (Wenjiang, Longquanyi).

To understand the relationship between urban land and population growth in greater detail, we connect urban population trends to estimates of urban expansion in each city, 2000–2010 (figure 6). Note that it is possible to compare slopes (i.e. rate of change in population with respect to rate of change in urban land) across city sizes, since the scale relationship is held constant. Here, the majority of cities can be characterized by one of two trends: a flat slope, indicating a significant amount of population growth occurring in tandem with urban expansion, or a steep slope, suggesting only small population growth relative to very large amounts of new development. With respect to city size, most large agglomerations exhibit the latter trend; a steep rise in urban land over the ten-year period with more limited population growth. There are a few exceptions: Urumqi has been on the receiving end of a targeted migration policy to move people west, while Hangzhou's population growth may be related to its proximity to the booming Shanghai agglomeration. Fuzhou's growth is constrained by terrain.

The variability in cities under 1 million (figure 6, three bottom rows) is likely the result of several factors. The limiting effects of topography are clear for cities near Fuzhou and Kunming (small, flat trajectories). Another determinant may be distance: all medium-small cities in the west with steep increases in urban land are located close to major agglomerations (<40 km). In the Xi'an footprint, some very small cities have actually dropped in population; nearly all are located >50 km from Xi'an's core.

In coastal footprints, proximity to a large agglomeration appears to have a more limited effect. There are cases where cities both near and far from major agglomerations exhibit steep slopes, and similarly, cases where cities have flatter trend lines. In the Guangzhou footprint, however, the results suggest that proximity to a major urban center may be a factor affecting small city expansion. Given the extensive amount of expansion and proliferation of cities >1 million throughout the

Pearl River Delta region, nearly all cities are now proximate to a large agglomeration. The only cities not affected by the building boom are those in mountainous areas, where terrain has limited accessibility and growth.

5. Discussion and conclusions

This work aims to improve our understanding of China's extraordinary urban transformation. The pace of urban change is staggering: urban populations have more than doubled during the last 30 years, while urban land extent has more than tripled for all city sizes and locations. In coastal areas targeted by early policies, urban land has increased four to five times since 1978, for all city sizes. What factors have contributed to this transformation? It is becoming increasingly clear that several complex, interconnected factors are at work (Ma 2004, Lin 2007). The demographic shift of the population, spurred by policies to increase agricultural productivity and boost consumption, has played a critical role, as did strong, consistent, and targeted state-led industrialization and growth policies. These interventions included not only opening the economy to FDI, but development of economic zones (with considerable incentives, tax breaks for companies) and infrastructure to draw investment (Cho and Tung 1998). In promoting economic growth and land use reform, a fiscal situation has been created at provincial and county levels that has fostered an unhealthy dependence on local revenues of land sales (Lichtenberg and Ding 2009). This has motivated land sales and fostered an extraordinary building boom, largely driven by increased pressures on local governments to attract investment and further boost economic growth (Ke 2010).

This research also provides a more nuanced view of Chinese urban development by taking into account the effects of city size, proximity to major urban centers, and regional differences. In terms of size, large urban centers are the primary consumers of land: large agglomerations have each added an average of 450 km^2 since 1978 (this amount is greater than Kunming's 2010 extent), while neighboring cities have consumed just 20 km^2, on average. If new urban land in medium, small, and very small cities is summed by footprint, the amount is only 190 km^2, or less than half of the land consumption of each of the 17 large agglomerations in the sample. The same is not true for population, however. Urban populations in large agglomerations have increased by an astonishing 1.3 million persons, on average, 2000–2010. By comparison, nearby cities, when summed by footprint, have increased >1.8 million persons over this period (mean increase of 140 000 per city). While China's urbanization is often linked to its more than 160 cities with populations >1 million, the results show that small-medium cities have had far more significant growth in recent periods.

One goal of this work was to compare eastern and western regions, including the possible differential impact of policy interventions on population and land use change. Because of the large number of agglomerations and the interventions put in place in all of these cities by the central government (Cho and Tung 1998), it is nearly impossible to disentangle policy effects from other drivers. What is clear is that the timing of the policies matters, and the focus of the policies has differed across regions, resulting in regional differences in growth trajectories and urban form. With large amounts of expansion in cities of every size, many coastal urban areas are now emerging as polycentric urban regions and extended conurbations. For example, Hangzhou is quickly joining the greater Shanghai area as a mega-agglomeration articulated by multiple large and medium-sized cities. In contrast, a few major urban centers are the foci of economic development and expansion in the west, and proximity to these areas is an important factor for small city growth. Although polycentricity and multi-nodal urban regions have been the goal of recent urban planning in the west, the dominance of the central core urban area—where economic zones were targeted—remains intact. The impacts of these very different urban forms are unfolding currently, as Chinese cities make headlines with unprecedented air pollution, smog, traffic congestion, etc. Understanding the social, environmental, and economic effects of these urban forms is thus an area that requires further investigation.

The ongoing challenges associated with rapid urbanization in China are many. This research has revealed one critical result: the majority of Chinese cities are increasing in population density due to continued migration into urban areas (especially cities <1 million). Cities have expanded, and this trend will likely continue, so a focus on compact urban form may be unrealistic. Rather, the role of urban design (e.g. smaller block sizes, walkable neighborhoods, zoning codes that allow for a plurality and variety of real estate construction) and the provision of adequate services/housing to all segments of the population need to be addressed. Kunming, for example, is moving toward 'smart growth' concepts as a way to embrace urban environmental sustainability and compete for trade and FDI. Finally, the predominance of large agglomerations encompassing multiple cities will require coordinated metropolitan planning that, in nearly all cases, does not currently exist. The only way to effectively plan for growth in these extended urban regions, promote efficient use of resources and provision of services, and mitigate social and environmental consequences equitably will be to reduce the fragmented nature of governance in many areas.

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Appendix

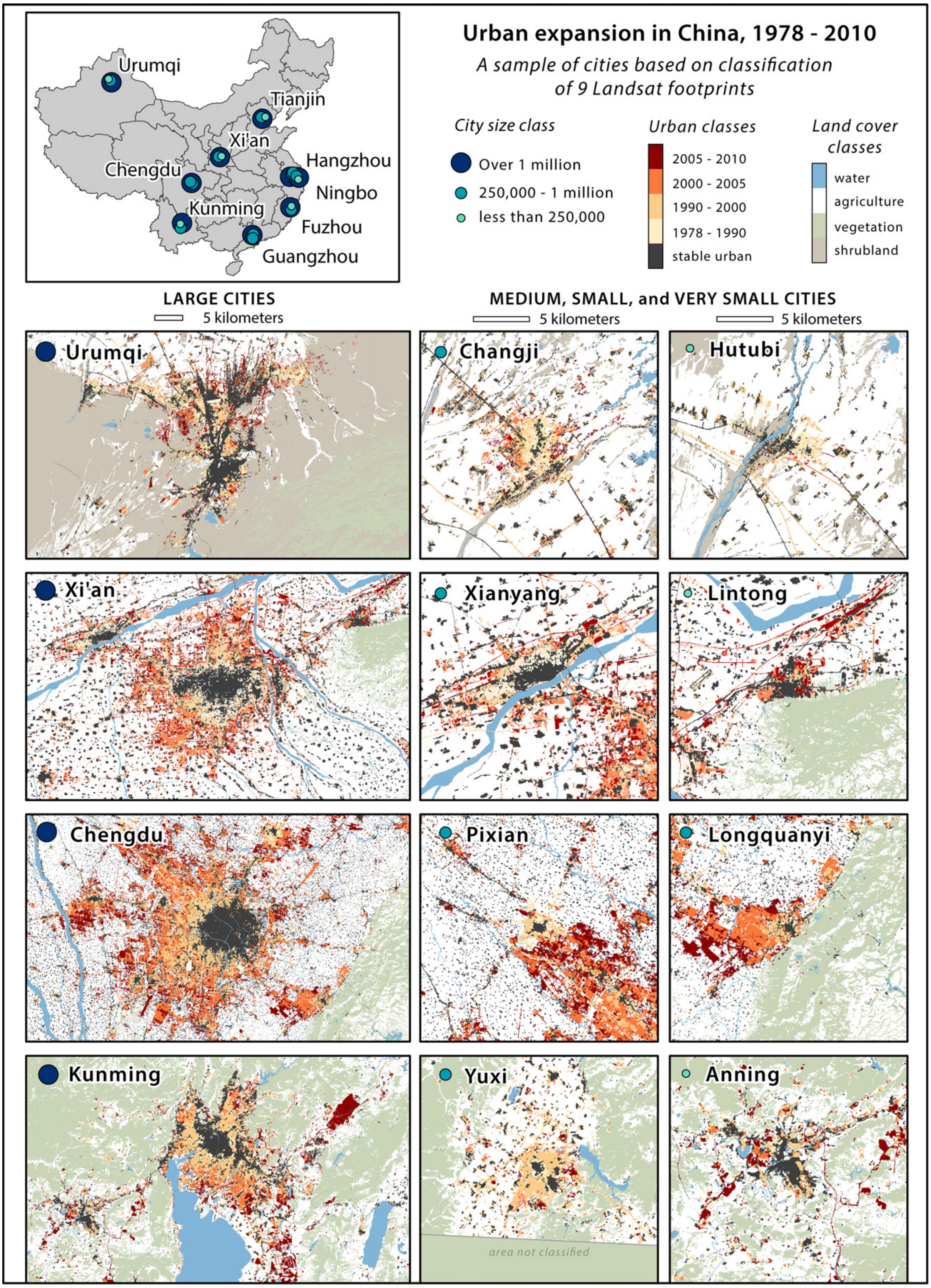

Figure A.1. Local views of the Landsat-based maps developed for nine regions in China.

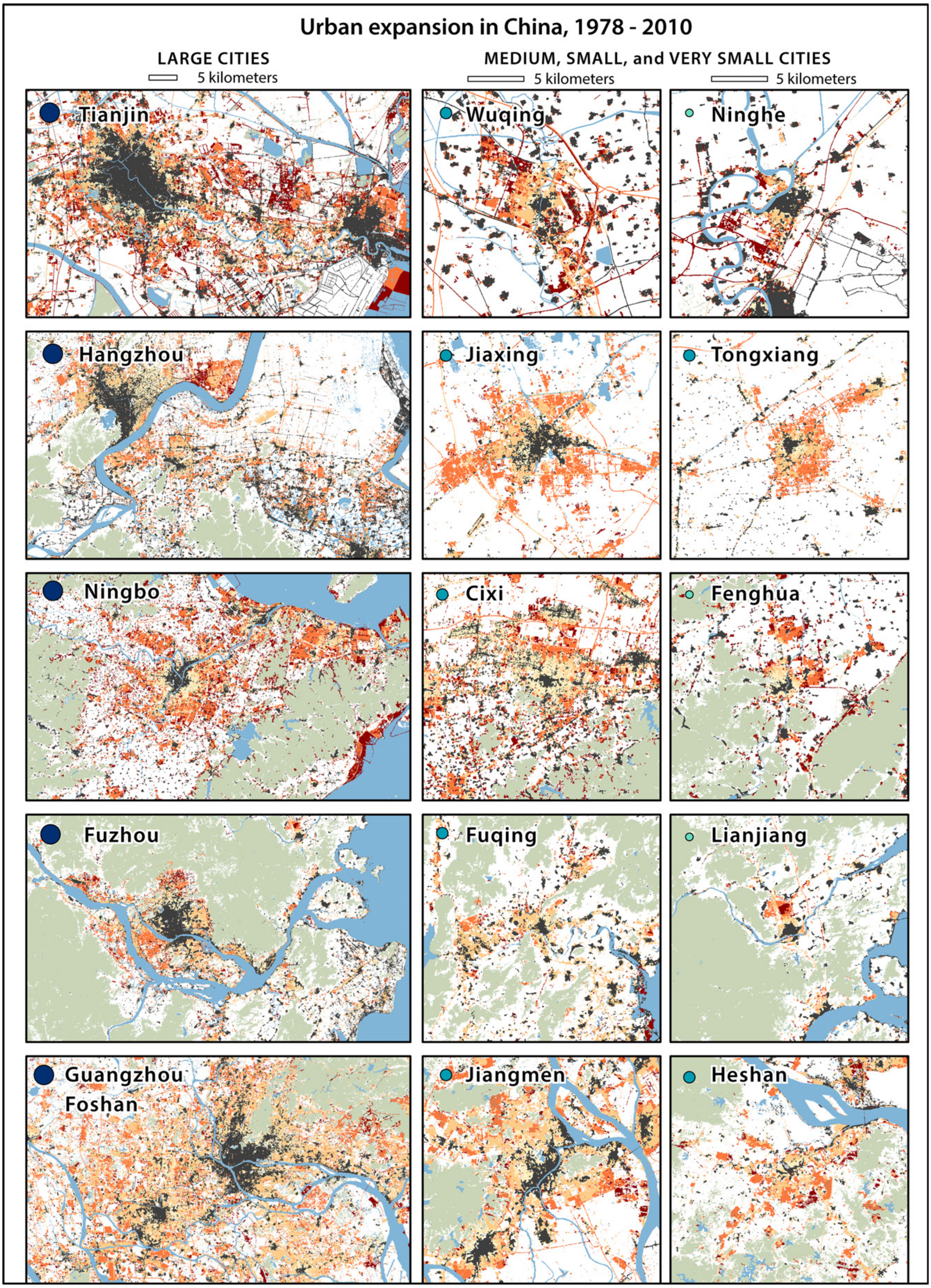

Figure A.1. (Continued.)

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