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Urban land expansion: the role of population and economic growth for 300+ cities

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Global urban populations are projected to increase by 2.5 billion over the next 30 years. Yet, there is limited understanding of how this growth will affect urban land expansion (ULE). Here, we develop a large-scale study to test explicitly the relative importance of urban population and Gross Domestic Product (GDP) growth in affecting ULE for different regions, economic development levels and governance types for 300+ cities. Our results show that population growth, more than GDP, is consistently the dominant determinant of ULE during 1970–2014. However, the effect of GDP growth on ULE increases in importance after 2000. In countries with strong governance, economic growth contributes more to ULE than population growth. We find that urban population growth and ULE are correlated but this relationship varies for countries at different developmental stages. Lastly, this study illustrates that good governance is a necessary condition for economic growth to affect ULE.

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INTRODUCTION

Urbanization is fundamentally a process including both urban population growth and urban land change[1]. However, there is very little understanding about the relationship of urban population growth and urban land expansion. What explains the physical expansion of cities? Does having more people in urban areas lead to the expansion of urban land? Or does economic activity drive urban land use change? With forecasts of global urban population growth of 2.5 billion between 2018 and 2050, there is an urgent need to understand how this massive demographic shift may affect the expansion of urban land areas.

Urban land change affects biogeochemical cycles, regional to global climate, hydrological systems, and biodiversity[2]. Expansive urban growth is strongly linked to higher per capita urban greenhouse gas emissions[3], habitat fragmentation and biodiversity loss[4,5], inefficient use of natural resources[5], and loss of agricultural lands[6,7]. Compact urban growth is positively correlated with improved human health outcomes[8], economic growth[9], energy and resource efficiency[10].

Studies on the determinants of ULE have typically focused on a single city[11,12], cities in a single country[13,14] or cities within a region[15,16]. Only three studies[1,17,18] have examined drivers of urban expansion for cities globally. Each of these studies have focused on either one specific year or one static time period with country-scale GDP data. All these studies (local or global) examine potential determinants of ULE (e.g., slope, arable land, temperature, population etc.) and have shown that ULE is driven by many factors, with demographic or economic growth as the primary drivers[19–21]. These findings support theory from urban economics and urban science that posit population and income as the primary drivers of ULE. For example, urban economics identifies demand for land as a derivative demand that is shifted by exogenous factors such as population and income. A more recent theoretical development—the science of cities—points to scaling laws relating urban population, wealth and land area[22]. Detailed case studies also highlight the effects of local policies and regulations such as zoning and housing policies[23], floor area ratios[24], subsidies for transport infrastructure and foreign direct investment[25] as additional drivers of ULE.

While local or regional studies provide insight into the drivers of urban expansion for a particular place, it is difficult to generalize the results for other places. Moreover, majority of these studies on ULE focus on cities in Europe, North America, and China[26,27]. Herein lies a scale and geographic mismatch between scientific knowledge about urban expansion and contemporary trends of global urbanization: most of the urban population growth in the next three decades will be in developing countries with relatively lower levels of economic development and yet there is limited understanding of ULE processes in these places. The United Nations (UN) estimates that, nearly 70% of the urban population growth will take place in just 20 countries (Supplementary Fig. 1, UN, DESA[28]), with all but one in either developing or least developed countries.

This is important because there is a strong correlation between the level of urbanization and national average income level. In 2018, high-income countries had a level of urbanization of 81% on average, while low-income countries had an urbanization level on average of 32% (UN, DESA[28]). Although the relationship between urbanization and national income is complex, there is strong empirical evidence that as countries urbanize, national incomes also rise.

However, there is much variation in national incomes for countries with similar levels of urbanization. Some of this variation may be attributable to differences in governance and institutions. There is much evidence that effective institutions and governance are preconditions for cities to deliver municipal services and create vibrant, equitable and livable places[29,30]. Rule of Law and effective governance are necessary to create an environment attractive for private capital investments, which are necessary for infrastructure, industry, and innovation[31,32]. Well-governed cities, those with safe roads, clean water, and health services generally have functioning institutions.

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Collectively, the literature points to urban population growth, economic development, governance, and institutions as important factors that shape urban expansion. However, because the majority of the existing literature tends to focus on single case studies, and testing various potential exploratory variables driving ULE, there is very little understanding of how the level of economic development and demographic change affect ULE across different contexts, or in particular regions, countries, or cities. This study fills these knowledge gaps. Our study is different from past studies because we focus only on population and economic growth as the dominant drivers of ULE and examine how geographic region, stage of economic development, and quality of national governance affect the relative importance of these factors. To this end, we explicitly test the relative importance of population growth and GDP growth in shaping ULE across 300 cities and over 45 years in two different time periods (1970–2000 and 2000–2014). We also consider the role of governance, which was not considered in any of the previous studies, as a factor that mediates the effects of economic and population growth on ULE.

The central question we ask is: What matters more for ULE under different geographic, development and institutional contexts: population or GDP growth? Our analysis answers the following questions: (1) What are the city-scale patterns of population growth, economic growth, and ULE across world regions for the period 2000–2014? (2) What drives ULE more: population or economic growth? (3) How does the relative importance of urban population growth and economic growth change across geographic regions, national income levels, and institutional settings?

This analysis is grounded theoretically on the concept of urban scaling and a derivative urban expansion accounting framework (presented in the Supplementary Note 1). Urban scaling refers to the idea that major urban properties, such as urban greenhouse gas emissions and urban area extent, show scaling relationships with urban population[33–35]. We formulate a growth accounting model of urban land expansion, based on urban scaling theory. Growth accounting is a tool developed by economists[36] to breakdown the growth of a variable of interest into several components. Our model breaks down the growth of urban land into two major factors in the theoretical framework: the growth in urban population and the growth of gross metropolitan product.

RESULTS

Trends in ULE, population, and economic growth rates

Our results show large variability in average annual growth rates of ULE with population and GDP per capita at the city scale (Fig. 1). On average, urban land is expanding at much lower rates than population or GDP per capita growth rates for cities with populations greater than one million. The average annual ULE rate in a million-plus city is 1.08%, whereas the average annual growth in population is 1.58% and in GDP per capita is 4.21%.

There is no single dominant trend across regions (Fig. 1). Cities where population growth rate is more than ULE rate are concentrated in Africa, Middle East, India, Central, and South America (hence CS America), and North America (Fig. 1a). In contrast, cities with higher ULE rates than population growth rates are concentrated in China and East and Southeast Asia (hence E & SE Asia) and Europe. The majority of cities in India and Africa show higher population growth rate than ULE. As expected, cities in Europe and North America exhibit the lowest urban land and population growth rates.

We observed clear geographic patterns in the ULE and economic growth rate for selected regions (Fig. 1b). With few exceptions, cities with higher ULE growth rates than GDP per capita are concentrated in Africa. Higher economic than ULE growth rate, however, follows a trend with the highest in cities of China (6–15%) followed by India (2–7%) and E & SE Asia.

In Africa, most cities have a higher population growth rate than economic growth rate with few exceptions in cities of Nigeria, Ethiopia, Mozambique, and South Africa. A few cities in these countries (e.g., Benin city, Ibadan, Kano, Addis Ababa, etc.) have doubled the rates of GDP per capita from 2000 to 2014. Similarly, we found higher economic growth rates than population growth rates in all 81 Chinese cities. However, in the East & SE Asia region, higher GDP per capita rates than population growth rates are observed only in the cities of Indonesia (e.g., Ujung Pandang, Surabaya, Jakarta) and Taiwan (e.g., Taipei, Taichung), cities in Japan and South Korea show less population growth rates from 2000 to 2014. A few cities in the Middle East region—Doha (Qatar), Sharjah (UAE), Dubai (UAE)—have exceptionally high population growth rates.

There are considerable variations in growth rates of GDP per capita, population and ULE within regions (Fig. 1c–e). Regions where we found more variability (i.e., low to high) in GDP per capita growth rates at city scale are E & SE Asia, Africa, and CS America. Cities in Middle East show the maximum variability in population growth rates followed by Africa. Middle East is the only region where population growth rates are much higher than economic or ULE growth rates. Significant variability in ULE rates is exhibited by Africa, India, and China regions. However, ULE rates are much lower than population or GDP per capita growth rates in both India and Africa.

ULE is driven more by population than economic growth

Our regression model shows that the urban population growth rate has more influence in driving ULE than economic growth in both pre-2000 and post-2000 periods (Table 1, Model I). In the pre-2000 period, a unit increase in population growth rate is associated with an increase in annual ULE rate by 16%, whereas a unit increase in GDP per capita growth rate is associated with a 7.3% increase in the ULE rate. Similarly, in the post-2000 period—a unit increase in population growth rate is associated with a 23% increase in the ULE rate, and a unit increase in GDP per capita growth is associated with a 12.4% increase in the ULE rate. Further, our analysis shows that the effect sizes of GDP per capita growth and population growth have increased from pre-2000 to post-2000. For instance, a city's ULE rate has increased from 0.16 to 0.23 with one unit increase in population between pre-2000 to post-2000. These results are robust even after controlling for regions, income groups, and institutional factors (Table 1, Model II–V). The interactions between explanatory variables are statistically insignificant in all models.

Average annual ULE rates in high-income (HI) countries are significantly different from all other income groups when controlled for population and GDP per capita in pre-2000 (Table 1, Model II). However, in post-2000, we found no significant differences in ULE rates of HI and upper middle-income (UMI) countries. Similar trends were observed with the addition of a regional dummy variable. In pre-2000, after controlling for GDP per capita and population, average levels of ULE rate are highest in India as compared to North America—followed by China and Africa (Table 1, Model III). Africa shows highest average ULE rates compared to North America region in the post-2000 period. Average ULE rates in India shows less significant differences from North America compared to pre-2000. In contrast, China shows no significant differences in ULE rates compared to North America in post-2000. Taken together, these trends show increased convergence in ULE rates over time across the world.

The goodness-of-fit measures of our regression models (measured by the R^2 statistic) increased slightly from 0.21 to 0.28 (Table 1, Model I), for the pre-2000 and post-2000 periods, respectively. This increase is consistent across all the models

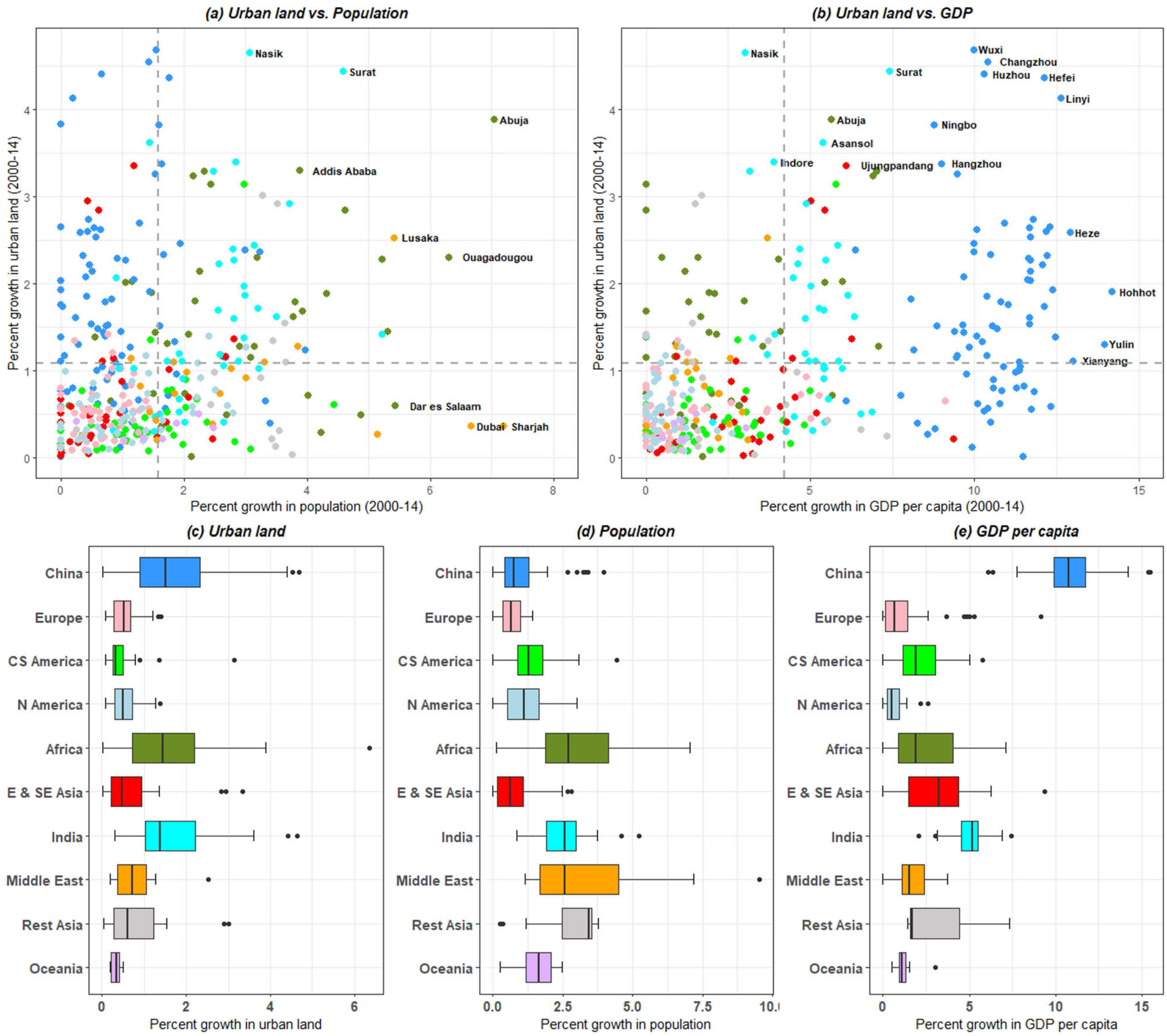

Fig. 1 Percent growth in ULE, population, and GDP for 363 cities (2000–2014). Regional variations in percent growth of **a** ULE with population, **b** ULE with economic growth (vertical dotted line shows mean percent growth in population/GDP per capita and horizontal dotted line shows mean percent growth in urban land), **c** ULE, **d** population, and **e** GDP per capita (Box plots represents 1st and 3rd quartiles, median and outliers). Regional color coding is consistent in scatterplots and boxplots. Percent growth in urban land area have been calculated from Mahtta et al.[37]. Population and GDP per capita growth rates have been calculated from the Oxford Economics 2016 database[48]. Note: The trends for the pre-2000 period are not shown due to the data unavailability of GDP at city-scale.

(Table 1, Model II–V). We expand on the interpretation of the R^2 statistic in the Supplementary Note 2. Even after controlling for regional dummies, GDP per capita and population variables can only explain about 40% of the variation in ULE at the city scale.

ULE in lower to higher-income countries

To examine the varying influence of economic and population growth on ULE, we used averages across income groups and geographic regions. We found an inverted U-shape curve for the relationship between GDP per capita growth rate and ULE (Fig. 2). The contribution of annual growth in GDP per capita towards ULE is the lowest in low-income (LI) countries and is consistent in the cross-section analysis across both time periods. However, the percent contribution of economic growth towards urban expansion increases many-fold for LI and middle-income countries. At the same time, it decreases significantly for the HI countries (Fig. 2a).

The change from pre-2000 to post-2000 contribution of economic growth to ULE occurs across LI to HI regions. In HI regions, the decrease in the relative contribution of economic growth from pre-2000 to post-2000 is concentrated in North America (Fig. 2b). The contribution of GDP per capita to urban growth declined from 38 to 26%, while that of population growth increased from 63 to 74%. In contrast, the contribution of GDP per capita rates increased in the other global regions, from the pre-2000 to post-2000 period. The largest increase in the contribution of GDP per capita rates occurred in China, followed by India, CS America, and Africa. This suggests that in countries undergoing economic development, GDP per capita growth could be an important factor that shapes how urban expansion unfolds. In LI countries, while the GDP per capita growth rate has become an important predictor in the post-2000 period, population growth's relative contribution remained high in urban growth.

Table 1. Regression results with (log) ULE growth (% annual) as a dependent variable at the city scale.

	Pre-2000 (Model I)	Post-2000	Pre-2000 (Model II)	Post-2000	Pre-2000 (Model III)	Post-2000	Pre-2000 (Model IV)	Post-2000	Pre-2000 (Model V)	Post-2000
GDP per capita growth (% annual)	0.073***	0.124***	0.070***	0.113***	0.029	0.107***	0.052***	0.125***	0.047***	0.161***
	(0.017)	(0.012)	(0.019)	(0.016)	(0.036)	(0.027)	(0.019)	(0.016)	(0.019)	(0.016)
Population growth (% annual)	0.161***	0.230***	0.096***	0.158***	0.095***	0.167***	0.154***	0.211***	0.110***	0.214***
	(0.024)	(0.034)	(0.026)	(0.039)	(0.027)	(0.038)	(0.025)	(0.036)	(0.025)	(0.037)
Low income$_{(Ref= High income)}$			0.764***	0.649**						
			(0.278)	(0.280)						
Lower middle income$_{(Ref= High income)}$			0.699***	0.448***						
			(0.132)	(0.148)						
Upper middle income$_{(Ref= High income)}$			0.412***	0.123						
			(0.132)	(0.150)						
Africa$_{(Ref= N America)}$					0.655***	0.547***				
					(0.221)	(0.207)				
China$_{(Ref= N America)}$					0.792***	0.066				
					(0.248)	(0.315)				
CS America$_{(Ref= N America)}$					0.253	−0.464**				
					(0.214)	(0.185)				
Europe$_{(Ref= N America)}$					0.140	0.041				
					(0.190)	(0.176)				
India$_{(Ref=N America)}$					0.898***	0.415*				
					(0.173)	(0.230)				
Others$_{(Ref= N America)}$					0.536***	−0.274				
					(0.192)	(0.173)				
Strong and getting weaker$_{(Ref= Strong and getting stronger)}$							−0.094	−1.305***	−0.534**	0.509***
							(0.165)	(0.096)	(0.421)	(0.167)
Weak and getting stronger $_{(Ref= Strong and getting stronger)}$							0.149	−1.006***	0.421***	−0.319*
							(0.118)	(0.159)	(0.133)	(0.164)
Weak and getting weaker $_{(Ref= Strong and getting stronger)}$							−0.341*	−1.278***	0.402***	0.470***
							(0.185)	(0.158)	(0.135)	(0.146)
Constant	0.491***	−1.260***	0.314***	−1.270***	0.323*	−1.105***	0.574***	−1.169***	0.496***	−1.693***
	(0.106)	(0.090)	(0.106)	(0.091)	(0.188)	(0.136)	(0.121)	(0.189)	(0.116)	(0.162)
R^2	0.205	0.283	0.292	0.308	0.304	0.359	0.226	0.374	0.284	0.307
F Statistic	31.552*** (df = 2; 244)	71.018*** (df = 2; 360)	19.845*** (df = 5; 241)	31.725*** (df = 5; 357)	13.019*** (df = 8; 238)	24.771*** (df = 8; 354)	14.107*** (df = 5; 241)	35.608*** (df = 6; 357)	19.085*** (df = 5; 241)	31.686*** (df = 5; 357)

$^*p < 0.1$; $^{**}p < 0.05$, $^{***}p < 0.01$.

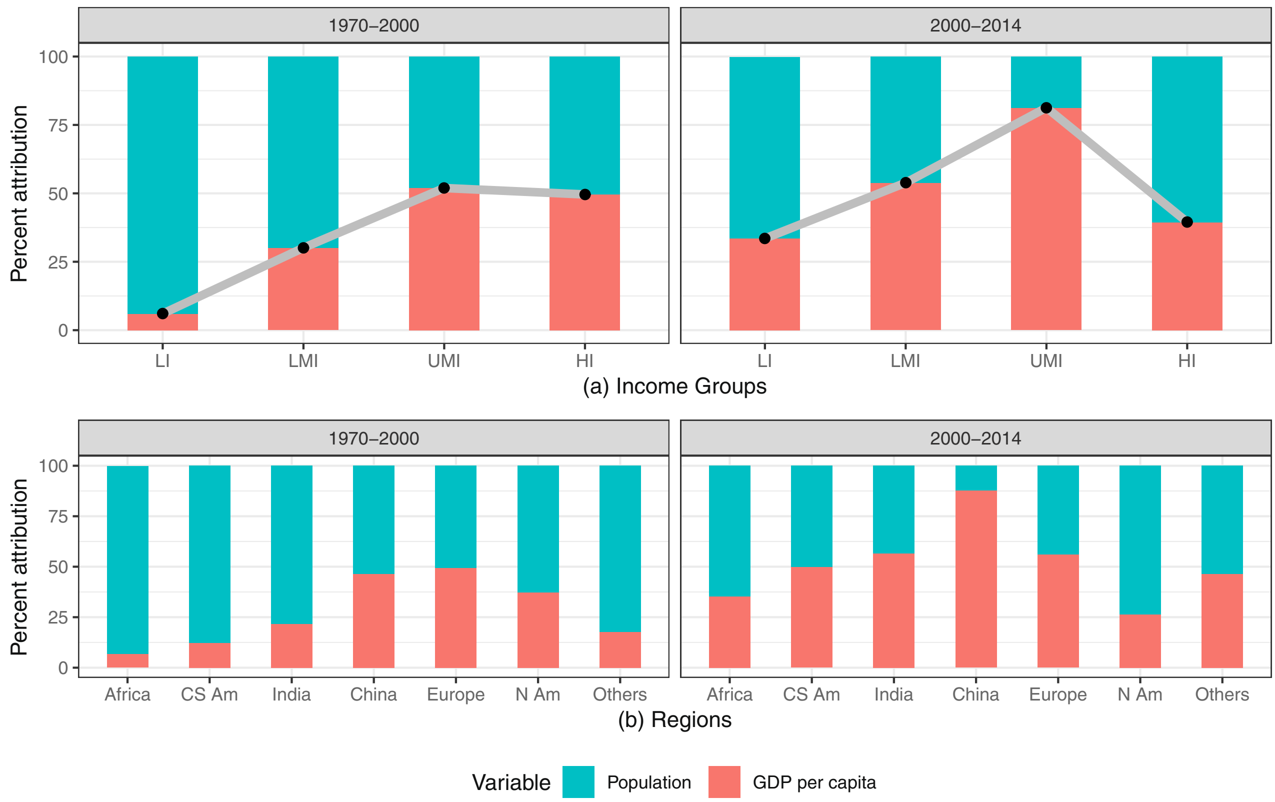

Fig. 2 Percentage of ULE explained by GDP per capita growth rate and population growth rate across income groupings and geography. **a** Country income categories, and **b** region groups in pre-2000 and post-2000.

Urban population, urban land, and income levels

Although countries with comparable national incomes vary significantly in terms of their level of urbanization, there is a clear correlation between percent urban population and national income (Fig. 3a). As urbanization levels rise, national incomes also tend to rise. However, the same does not hold for urban land (%), where we find very little correlation between urban land and national income (Fig. 3b). With few exceptions, the percentage of urban land varies between 25 and 75%, irrespective of national income. Furthermore, in some LI countries such as in Africa (e.g., Liberia, United Republic of Tanzania, Mozambique, and Congo), percent urban land is at similar levels as countries with much higher national incomes. This represents a critical challenge. Even though some African countries have percentage urban land levels comparable to high income countries, their per-capita national income remains low. This suggests that African countries, with some exceptions, are not benefitting from agglomeration economies. These conditions intersect with inadequate infrastructure services, owing to inefficient urban land use.

Governance and ULE

Based on the average institutional score over the study period and difference in the score over the study period, we identified four categories (Supplementary Table 1) for each of the governance indicators, Rule of Law and Governance Effectiveness. *Strong and Getting Stronger* category represents countries with average high governance scores (mean > 2.5) during the study period and increase in governance scores (difference is positive) over the study period. *Strong and Getting Weaker* category is characterized by countries with high average governance scores during the study period but with declining scores over the study period. *Weak and Getting Stronger* category represents countries with low average governance scores during the study and getting higher over the studied time-period. Similarly, *Weak and Getting Weaker* category has countries with low governance scores during the study period and then further lowering scores over the study period.

With few regional trends, we found distinct variations between the countries in different regions as we moved from pre-2000 to post-2000 (Supplementary Table 2). We found that *Strong and Getting Stronger* category is dominated by countries in Europe, North America, and Middle East regions for both the governance indicators in pre-2000. However, Governance Effectiveness has weakened for few countries in Europe (e.g., Netherlands, France, Germany) and North America regions moving them to *Strong and Getting weaker* category in post-2000. Contrary to that, for Rule of Law category, few countries in Middle East region (e.g., Israel, Saudi Arabia) have moved from *Strong and Getting Weaker* in pre-2000 to *Strong and Getting Stronger* category in post-2000. Whereas countries in Africa are concentrated in *Weak and Getting Stronger* and *Weak and Getting Weaker* categories both the indicators except South Africa, Ghana, and Tunisia countries.

Our analysis of the relative contribution of population and economic growth rate on ULE across these categories suggests that strong national governance allows economic growth to contribute more to ULE in countries as compared to the population growth (Fig. 4). Our results suggest that from the pre-2000 to post-2000 period, for countries with more robust governance (*Weak and getting stronger* and *Strong and getting Stronger* categories), ULE can be attributed more to GDP per capita growth (Fig. 4). An exception to this observed trend is the countries in the *Strong and getting Weaker* category under Government Effectiveness indicator.

Further, over 70% of ULE can be attributed to GDP per capita growth rate under the *Weak and Getting Stronger* category in the

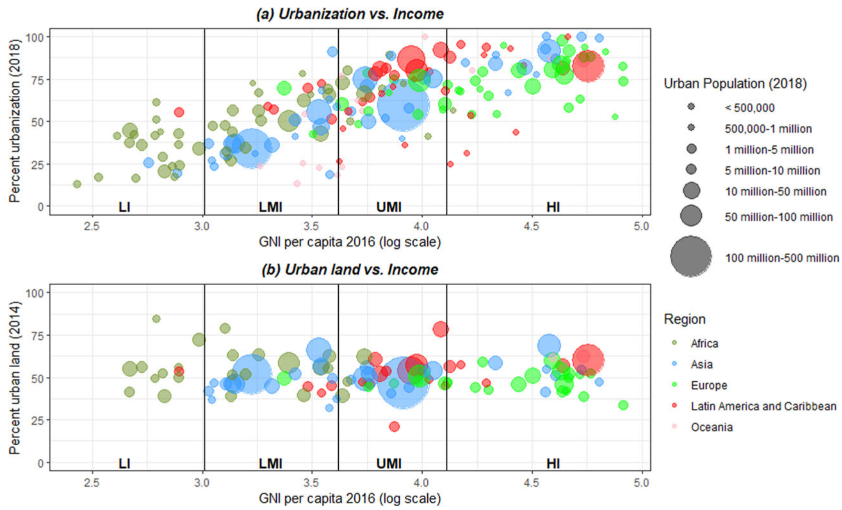

Fig. 3 Association of income levels with urbanization and urban land. **a** Urbanization and per capita national income (adapted from UN DESA[28]), and **b** Urban land and per capita national income (GNI). Urban definitions used to calculate percent urbanization are country specific and listed on the UN website (https://population.un.org/wup/). Each dot represents a country, and the size of the dot is shown by the population for the same in 2018. Percent urban land is calculated from Global Human Settlement Layer (GHSL 2014) dataset as the share of impervious surface to the total urban footprint.

Fig. 4 Percentage of ULE explained by GDP per capita growth rate and population growth rate for governance indicators in pre-2000 and post-2000. **a** Rule of Law and **b** Government effectiveness.

post-2000 period for Rule of Law indicator. This result suggests that for this period, an increase in the Rule of Law has helped GDP per capita to predominantly drive ULE in the *Weak and Getting Stronger* category, whereas it had a negligible effect on the *Strong and Getting Stronger* category where the Rule of Law was already strong.

We found that the rise in the Government Effectiveness indicator—which generally captures the quality of policy formulation and its implementation by the national government—has a profound effect on *Strong and Getting Stronger* countries. The contribution of GDP per capita in explaining ULE has increased substantially in these countries suggesting even strong initial states of Government Effectiveness can be improved and allow urbanization processes to be more closely linked to economic development.

Taken together, there are two key takeaways from the results (Fig. 5). First, the importance of population growth in affecting ULE is consistent over time in context of regions, income levels and governance. This can be interpreted as more urban dwellers equals the need for more urban land. Second, in post-2000, only in a few cases has GDP become more important than population growth in affecting ULE: for instance, China which has stronger governance effectiveness and rule of law and is an upper middle-income country (as highlighted in the Fig. 5). These two results corroborate a recent study by Mahtta et al.[37], which shows that the predominant urban growth pattern is outward expansion. That is, most urban growth worldwide is characterized more by outward low-rise development than upward high-rise development[37]. The primary exceptions to this global trend are countries with strong governance, such as China, South Korea, and few middle eastern countries like Saudi Arabia, Qatar, and the UAE. In these countries there has been a significant increase in the number of high-rise buildings.

DISCUSSION

Across different geographic regions and levels of economic development, ULE is driven more by population than economic growth. The implications of this for multiple dimensions of sustainability and global environmental change are significant given the projected urban population growth in countries with low levels of economic development. High ULE rates with low economic growth can result in negative impacts on the environment. Previous studies have shown a weakening relationship between urbanization and economic growth[38,39] in Africa and Asia[40], compared to observed patterns in Europe and North America. Our results suggest

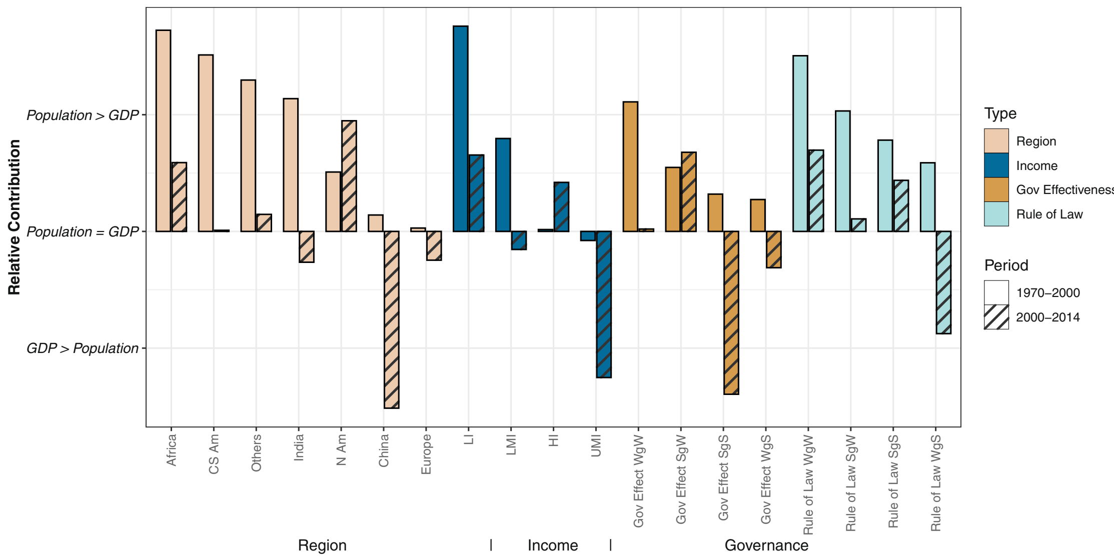

Fig. 5 Differences in the relative importance of population growth and GDP growth for ULE. Color on the bars represents the types of contexts (region, income, governance). First bar for each category represents the pre-2000 period and the one with dashed lines represents the post-2000 period.

a similar decoupling between ULE and economic growth, especially for urban areas in the lowest income regions such as South Asia and Africa.

Our analysis show that the relative contribution of GDP in explaining ULE has increased significantly in LI, LMI, and UMI countries from the pre-2000 to post-2000 period. We observe that the increase in the contribution of economic growth to the expansion of urban land occurs up to a point. When a country enters the highest income category, population growth again becomes an important predictor. Several factors may be driving this trend: we hypothesize that at earlier stages of economic development, GDP per capita growth drives the development of urban infrastructure, providing the foundation for agglomeration economies. This development makes cities attractive to rural populations and thus encourages migration. There are exceptions, however. For example, in Africa, factors like the natural increase in urban population due to higher fertility rates, dissatisfaction with local public services, agricultural distress, natural disasters, etc., push rural dwellers to urban areas[41].

HI countries tend to have well-developed markets with relatively higher labor mobility, significant and established agglomeration economies, high quality urban infrastructure and services, and capitalization of amenities in land and real estate markets. In such settings, migration between cities in search of better amenities explains the relative importance of population growth in shaping ULE. The results also show that strong governance is an important factor for shaping ULE. We found that governance has become weaker over time for most of the low-income and middle-income countries. The results show that effective governance is necessary for GDP growth to affect ULE.

Our understanding of the process of physical urban expansion is enriched if we examine both supply and demand for land simultaneously. On the demand side, households and firms are part of local, regional, and national real estate markets. It is thus not surprising that population and employment growth are major drivers of the demand for urban land. Naturally, preferences of all types of economic agents (households and firms) for space and location as well as public policy are also primary drivers of demand. Similarly, supply is affected by policies such as land use planning or zoning that increase or constrain the amount of buildable land along with geography, demographic factors and market forces[42]. The context in which these market forces operate is important: countries at a higher level of economic development and with a stronger Rule of Law or higher Government Effectiveness will have better functioning and highly efficient markets, thus leading to planned ULE[43].

Similarly, in cities with weak national governance, ULE is primarily attributed to population growth. This is intuitive, considering that with the weak and weakening Rule of Law and Government Effectiveness, we observe uneven economic development within countries, typically favoring cities as locations that concentrate political power and significant rent-seeking activities. Still, even in those cities, physical and other types of infrastructure will either be lacking or in poor maintenance; thus, economic development opportunities will be stunted. Migrants who arrive in these cities are escaping worse rural living conditions—real or perceived—and can most easily occupy undeveloped lands around the metropolitan area in an unplanned and sprawled fashion. As governance quality improves, a more suitable environment that is conducive for economic development emerges, which reduces the relative effect of population growth on ULE.

The contextual factors within which population and economy drive ULE are dynamic and may change in unexpected ways. These include sudden shocks such as a global economic crisis, a pandemic or a natural disaster that may occur as various impacts of ongoing climate change unfold. Therefore, the general trajectory of development we lay out here based on our findings might change with the onset of these sudden shocks. For example, it is highly likely that the current COVID-19 pandemic proves to be simply the first in a succession of pandemics for the foreseeable future. A pandemic can compel national travel restrictions, which make cross-border migration much less likely as seen in the current one.

Similarly, the current pandemic is illustrative of how a large-scale outbreak may reduce within-country mobility and slow down economic activity, which may result in lower rates and levels of ULE, at least temporarily. Cities with limited basic urban infrastructure will undoubtedly be affected more adversely during such a shock. Nevertheless, the slower urban development rates may offer opportunities for a re-assessment of policies in formerly rapidly urbanizing places that might affect public spaces, including public transport, housing, and retail. These realignments along with modern technologies that allow for remote work and autonomous driving may lead to transformational changes in how urban areas grow and function. Such changes will undoubtedly be reflected in real estate markets as we witnessed with COVID-19 where companies relocated offices to cheaper suburban areas or smaller cities (e.g., San Francisco Bay Area firms moving to cities in Texas in the US), creating the opportunity to convert existing office space to housing inside the city. The combined effects of losses in the retail and hospitality sectors, rising real estate vacancy rates, and declining use of public transit, especially in central urban areas will take shape over multiple years as we emerge from the pandemic, and the long-term impacts of these changes on ULE remain uncertain. This would be a valuable area for further research.

Methodologically, our study shows the importance of utilizing city-level statistics to understand urban expansion. While national-level analysis provides useful insights, it also aggregates data such that the variability among large, medium, and small cities is lost. Thus, it is essential to understand the underlying variability because the heterogeneity among cities, even in one region, is high[37,44] and is similar to heterogeneity levels between countries. Our understanding of urban processes such as land expansion can be advanced if we shift our attention towards the city rather than the country as the unit of analysis. Furthermore, understanding the joint dynamics of the urban population, ULE, economic development, and governance quality is also important for identifying a robust suite of policies to manage rates of ULE. Our study indicates that urban growth can be better understood by considering both urbanization (urban demographic share) and the physical expansion of urban areas. The association between urbanization and income growth can vary depending upon how we conceptualize the urban growth process: as a demographic process or as a land change process.

Our findings can be used to inform urban land development policies across distinct geographies, economies, and governance structures. Understanding the urban expansion factor attribution mix can lead to policy interventions that target either population growth or GDP growth differentially. In cities and contexts where economic growth primarily accounts for ULE rates, policies that target local economic growth will have a significant effect on urban expansion; these could involve spatial economic planning (aiming at establishing agglomeration economies through the location choices of firms and infrastructure within the city), investments in human and social capital and expanding opportunities for human interaction and exchange of ideas.

In cities and contexts where population growth primarily accounts for ULE rates, policies that target local population growth will affect rates of urban expansion. Such policies include the establishment or removal of population migration incentive schemes (relocation payments or tax incentives), metro tax exemption schemes for large employers, and urban growth boundaries. Naturally, a mix of instruments can be utilized in cities and contexts, where economic and population growth account for approximately equal portions of ULE. A main takeaway of our analysis is that policies to manage ULE can be implemented indirectly through local policies affecting population and economic growth. This can help in facilitating a transition towards urban sustainability (SDG 11) through participatory, integrated, and sustainable planning.

A main takeaway of our analysis is that policies to manage ULE can be implemented indirectly through local policies affecting population and economic growth. This implies that regional/urban growth and economic development strategies must incorporate ULE considerations and be aligned with participatory, integrated, and sustainable spatial planning processes. This can help facilitate a transition towards urban sustainability (SDG 11).

Over the next thirty years, an additional 2.5 billion urban dwellers will require the construction of more towns and cities, which in turn will require new urban land. The implications for land resources are enormous. Without policies and strategies in place to protect various land ecosystems—farmland, wildlife corridors, sensitive habitats—we can expect to see significant urban-induced land changes that will have negative consequences for both the environment and livelihoods. However, the results also point to the importance of governance in affecting ULE. Whether ULE is driven differentially by population growth or economic growth will be affected by geographic region, the stage of economic development, and the quality of governance. This much is clear: the combination of economic and urban population growth in the next 30 years will result in substantive new urban expansion. The patterns of urban expansion that emerge will depend much on institutions and governance; our results show that much can be done to shape how urban expansion is manifested in the coming decades.

METHODS

Data

We collated ULE and socioeconomic data at city scale from various sources from 1970 to 2014 (Table 2). We selected 2000 as the break year, as city-level data for economic indicator (GDP) was only available after 2000. We refer the two time periods as pre-2000 and post-2000. We combined the data on ULE from two published peer-reviewed papers[37,45]. Güneralp et al.[45] use a bottom-up approach to calculate ULE rates through a meta-analysis of published studies and inputs from a previously published meta-analysis by Seto et al.[1]. In contrast, Mahtta et al.[37] use a top-down approach utilizing the built-up area from the GHSL dataset. Thus, for the pre-2000 period, we calculated the average annual ULE rates by averaging the decadal rates from Güneralp et al.[45]. Here, we selected only city-based studies (251) from the database. Approximately 185 out of 251 cities have more than one million population. GDP data was calculated at the country scale except for China, India, and the United States, where GDP data are at sub-national levels (province, state, and state, respectively). Average annual GDP per capita growth rate was calculated for each of them for 1970–2000 period. We used population data from World Cities database by J. Vernon Henderson (http://www.econ.brown.edu/Faculty/henderson/worldcities.html) to calculate average annual population growth rate for each city.

For the post-2000 period, we used 478 cities with a population threshold of one million as described in Mahtta et al.[37]. We further computed annual ULE rates at the city scale as, (Urban area in t_1/Urban area in t_2)$^{1/n}$ -1) * 100, where t_1 is the final period, t_2 is the initial period, and n is the time interval between these two time periods. Next, we calculated the population and GDP per-capita rates (% annual) at the city scale using

Table 2. Data Sources.

Variables	Pre-2000 (1970–2000)			Post-2000 (2000–2014)
ULE	From meta-analysis[45] *(city scale)*			Outward expansion[37] *(city scale)*
Population	World Cities Database *(city scale)*			Oxford Economic Database[48] *(city scale)*
GDP	China	Province level	Chinese yearbooks[49]	Oxford Economic Database[48] *(city scale)*
	India	State level	Reserve Bank of India[50]	
	North America	State level	Bureau of Economic Analysis	
	Other Countries	Country level	Penn World Table v9.1 Database[51]	

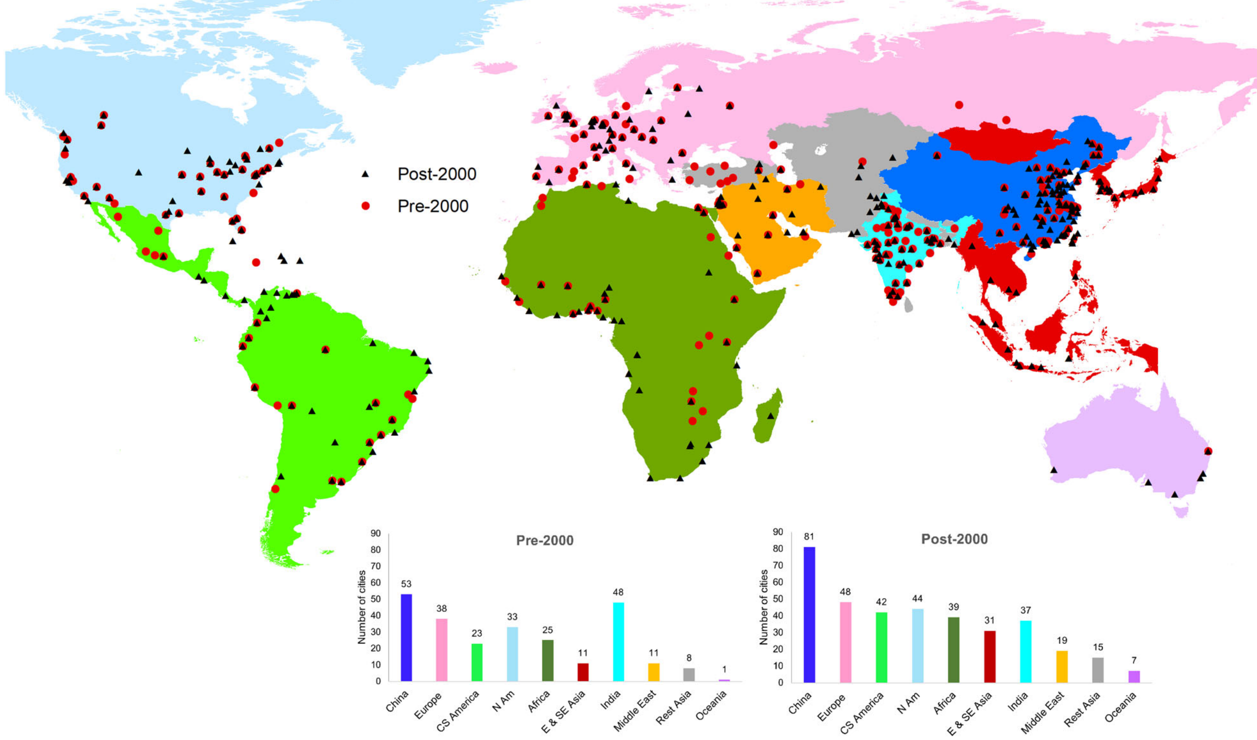

Fig. 6 Geographical distribution of the cities included in this study (pre-and post-2000). Numbers on the bars represent the cities in each region. The total number of cities in the pre-and post-2000 period are 251 and 363, respectively.

the Oxford Economics database. After combining the datasets on these three variables, our sample size was reduced to 363 cities. We assumed that the population and economic development contribute to ULE only during the growth stage. Accordingly, we capped negative values of both population and economic growth rates at zero. Still, our results are consistent across restricted and unrestricted scales of the two variables. For urban expansion variable, however, we consider only positive rates.

Except for Asia, we labeled each city using the UN defined world macro-regions. For cities in Asia, we considered China, India, and the Middle East as distinct regions and kept the rest of Asia as a separate region (Fig. 6). Due to a smaller number of cities in the Middle East, Oceania, E & SE Asia, and the rest of the Asia region, we represented them as one region named "Others" for regression analysis.

Model specifications

We developed descriptive statistical models (Model I to Model V) of urban growth for both the periods (1970–2000 and 2000–2014). In Model I, our baseline specification, we use GDP per capita and population growth as the only independent variables. Models II to V expands the baseline specification by adding dummy variables—region, income level, the Rule of Law indicator, and Government Effectiveness indicator—respectively.

For our income-based dummy variables, we used data from the World Bank. The World Bank classifies countries based on gross national product per capita as HI, UMI, LMI, and LI. The categorization is available annually from 1987 to 2020. We selected the year 2014 country level income-based categorization for both pre-2000 and post-2000 models. Categorization of countries from this study is shown in Supplementary Table 2.

We used the Worldwide Governance Indicators which assesses countries based on institutional qualities to create governance dummy variables. These indicators include six dimensions of governance for 215 countries and territories from 1996 to 2018 time-period: (i) Voice and accountability; (ii) Political stability and absence of violence; (iii) Government effectiveness; (iv) Regulatory quality; (v) Rule of law; and (vi) Control of corruption[46]. For this analysis, we chose two indicators based on both conceptual and statistical factors: Rule of Law and Government Effectiveness. Conceptually, we decided the governance indicators that closely match with fundamental governance attributes of service delivery, policy making and implementation, public confidence in institutional setup, and quality of conflict mitigation and resolution mechanisms; statistically, our exploratory analysis of the set of available indicators revealed a significant correlation between the measures. The Rule of Law indicator measures the perceptions of the extent to which agents have confidence in and abide by society's rules, particularly as they relate to contract enforcement, property rights, the police, and the courts, and the likelihood of crime and violence. Similarly, the Government Effectiveness indicator captures "Perceptions of the quality of public and civil services and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies". Based on the average state during the study period and change in the governance indicators over the study period, we categorized individual countries into four quadrants with weak and strong governance categories. We did this categorization for both the pre-2000 and post-2000 period. In our analysis of the institutional effects, we estimated the impact of institutional quality for a specific time frame by taking average scores across years within each of the two periods.

Relative contribution

The main predictor variables are population growth rate and GDP per capita growth rate across all models; we employ a distinct set of dummies to formulate a multiplicity of regression specifications for our attribution analysis. To calculate the proportion of urban expansion attributed to the growth rate of GDP and the population growth rate, we devise the following technique that relies on our regression's fitted values. We examine the following regression specification in our datasets:

$$rtch_i = \beta_0 + \beta_1 poprtc_i + \beta_2 gdprtc_i + \beta_3 dummyvar_i + \varepsilon_i, \quad (1)$$

where *rtch* is the urban expansion rate of change, *potrtc* is the population rate of change, *gdprtc* is the growth in gdp per capita, and *dummyvar* can be one of the three following dummy variables: a regional dummy variable; a national income category dummy variable; or a governance quality dummy variable—either regarding Government Effectiveness or the Rule of Law.

Applying ordinary least squares regression to our dataset, we arrive at the following estimated fitted regression line:

$$\widehat{rtch_i} = \widehat{\beta}_0 + \widehat{\beta}_1 poprtc_i + \widehat{\beta}_2 gdprtc_i + \widehat{\beta}_3 dummyvar_i \quad (2)$$

For example, when *dummyvar* is the set of regional dummies, the fitted line statistically accounts for the effect of each region. We then subsample the above results for each region (j = China, India, etc.) and create the following two indicators for of the proportion of urban expansion attributed to either population or GDP growth rate for the jth region.

Each indicator measures the mean fitted values of the variable of interest (population rate of change or GDP per capita rate of change) over a specific region as a proportion of the sum of mean fitted values of population and GDP per-capita rate of change. In other words, we extract the average fit emerging from each variable for each region as a proportion to the average fitted value with the two variables. We calculate these indicators for all j regions and with n_j observations of cities within each region. Thus, ULE rate attributed to

$$\text{Population growth rate}: Prop\ POPgr = \frac{\frac{\sum_{i\in j}\widehat{\beta_1}poprtc_i}{n_j}}{\frac{\sum_{i\in j}\widehat{\beta_1}poprtc_i+\widehat{\beta_2}gdprtc_i}{n_j}} \quad (3)$$

$$\text{GDP per capita growth rate}: Prop\ GDPgr = \frac{\frac{\sum_{i\in j}\widehat{\beta_2}gdprtc_i}{n_j}}{\frac{\sum_{i\in j}\widehat{\beta_1}poprtc_i+\widehat{\beta_2}gdprtc_i}{n_j}} \quad (4)$$

We repeat the same analysis for all sets of dummy variables, capturing the attribution of both population growth rate and GDP per capita growth rate for all categories included in the dummy set. The method is further elaborated in SI section.

Statistical analysis

Statistical analyses were conducted in R programming language v. 4.0.3[47]. R packages used for data processing, analysis and visualization were: plyr, RColorBrewer, tidyverse, ggpubr, hrbrthemes, gridExtra, ggrepel, psych, sandwich, and stargazer. lm function was used to conduct the linear regressions. For analyzing gridded GHSL data, we used raster, rgdal and sf packages.

DATA AVAILABILITY

The datasets aggregated and/or analyzed during the current study are available from the corresponding author on reasonable request. GHSL dataset are available at https://ghsl.jrc.ec.europa.eu/ghs_bu2019.php. City-level population data are available at (http://www.econ.brown.edu/Faculty/henderson/worldcities.html). City-level Oxford Economic database is proprietary and is thus not freely available.

CODE AVAILABILITY

The code used to generate the results in this study is available from the authors upon reasonable request.

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AUTHOR CONTRIBUTIONS

R.M., K.C.S., and M.F. designed the research; R.M. led the study and performed the analyses with contribution from M.F. and K.C.S.; R.M., K.C.S., and M.F. interpreted the results and wrote the paper; and A.M., B.G., E.W., and M.R. commented on the draft and final manuscript and provided additional significant edits. All authors approved the manuscript for submission.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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