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Densification without contagion?

Overcrowding and pandemic risk hotspots in Rwanda

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August 2020

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Policy Paper

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Executive summary

In this paper we estimate the location of overcrowding hotspots in Kigali and five secondary cities in Rwanda using a variant of the methodology used recently by the World Bank in Mumbai, Kinshasa and Greater Cairo[1]. This is of interest for three key reasons. First, whilst overcrowding is an imperfect proxy for the type of close interpersonal contact that spreads disease, evidence shows that overcrowding exacerbates the spread of disease in general and pandemics, such as COVID-19, in particular, where social distancing becomes impossible. Second, overcrowding itself is of wider interest in terms of housing, because it has a range of negative effects on welfare and health. Finally, the pandemic risk of overcrowding raises questions around the implementation of the densification pillar of Rwanda's National Urbanisation Policy[2] such as: what is the difference between densification and overcrowding? How can Rwanda's cities take advantage of agglomeration economies generated by densification whilst avoiding the costs?

So far, Rwanda has had some success at stemming the tide of COVID-19; throughout August 2020, Rwanda ranked 178th in the world in terms of cases per million people[3] (the lower the rank, the lower the cases per million people) and had reported just eleven deaths to COVID-19 by 21st August. However, the lingering risk remains of widespread community transmission in Rwanda, which is most likely to take hold in urban areas. Evidence shows that overcrowding is an important predictor of the spread of disease; so it may thus be useful to policymakers to know where overcrowding hotspots – which are also potential pandemic risk hotspots - are. Two further points are worth making. First, and a large number of COVID-19 cases were detected in Nyabugogo and Nyarugenge markets in August; whilst our study is unable to cover overcrowding in locations such as markets or workplaces due to

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[1] Bhardwaj, G., Esch, T., Lall, S.V., Marconcini, M., Soppelsa, M.E., Wahba, S., 2020. Cities, crowding, and the coronavirus: Predicting contagion risk hotspots. Working paper. World Bank. Available at http://documents.worldbank.org/curated/en/206541587590439082/pdf/Cities-Crowding-and-the-Coronavirus-Predicting-Contagion-Risk-Hotspots.pdf
[2] https://www.mininfra.gov.rw/fileadmin/user_upload/Rwanda_National_Urbanization_Policy_2015.pdf
[3] https://www.worldometres.info/coronavirus/#countries

data constraints, those markets are located in or very close to the highly overcrowded city areas that we identify. Second, whilst initial COVID-19 cases were not driven by overcrowding but by international arrivals in Kigali, from the airport, and in land border towns such as Rusizi and Rusumo, as time has passed a much higher proportion of cases have come from the most overcrowded parts of the country.

Overcrowding also has costs other than pandemic risk, and is thus of broader interest and relevance to housing policy. Whilst it is hard to separate the effects of overcrowding from other effects such as quality of housing materials, poverty, education and other socioeconomic factors, a body of literature has emerged that shows that overcrowding has an impact on a wide range of physical health outcomes and to a lesser extent, mental health outcomes, after controlling for other factors[4].

In this paper we first discuss the lingering risk of urban pandemic spread in Rwanda in spite of the strong policy response, we then discuss the definitions and health impacts of density and overcrowding, introduce our methodology for identifying overcrowding and disease risk hotspots, describe our results for Kigali and the secondary cities, and discuss the implications our research have for the form that healthy and productive densification might take[5].

Our paper shows the most overcrowded locations in Rwanda, which we hope may be useful to policymakers in both the housing and public health sectors. A central argument of our paper is that density is not the same as overcrowding and a vital wedge can and must be driven between density and overcrowding, so that Kigali can take full advantage of agglomeration economies, by unleashing the housing market to build enough floor space per person, and by building roads and public spaces through unplanned settlement upgrading and a sites and services approach.

We find that indoor overcrowding, which is associated with the spread of contagious disease, is spread throughout cities and throughout the country. Outdoor overcrowding is concentrated in certain villages and sectors in Kigali city. However, the combination of indoor and outdoor overcrowding is likely to be most important to pandemic risk; when combining both types in a composite measure we find that overcrowding is concentrated in certain parts of Kigali. In the short term, the Government might weight its package of COVID-19 testing and mitigation measures, and eventually, vaccination measures, towards the most overcrowded areas. In the longer term, the densification pillar of Rwanda's urbanisation policy should be pursued whilst avoiding overcrowding; this can be done through building above the first storey and through funding and building appropriate infrastructure. Also in the longer term, access to water and sanitation is the most fundamental investment to prevent COVID-19 and other diseases, especially in the most overcrowded areas.

[4] https://dera.ioe.ac.uk/5073/1/138631.pdf

[5] Annexes contain detailed tables of overcrowding/pandemic hotspots in Rwanda's cities

The lingering risk of COVID-19 for Rwanda

Rwanda's public health response to COVID-19 was robust and rapid[6]. Beginning in January 2020, medical staff were already stationed at Kigali International Airport and land borders to screen for high temperatures. In early March a taskforce was assembled and guidelines were issued on 6 March on social distancing and handwashing, and hand sanitiser was placed outside all major public buildings and shopping centres. Testing began well before the first COVID-19 case, which was verified on 14 March. Once cases emerged, systematic tracing began, with assistance from security organisations. From 20 March to 1 June, the government instituted a nationwide lockdown and all non-essential transport outside homes was banned; from 1 June, inter-province travel was reinstated although a curfew remained, schools and places of workshop remained closed, and localised lockdowns were implemented in locations in which COVID-19 transmission had occurred. The airport re-opened on 1st August.

In an April 2020 BMJ Global Health article, the World Health Organisation characterised four phases of infection intensity: i) sporadic, largely imported, cases; ii) local transmission that can be traced from known cases; iii) clustered community transmission; and iv) widespread community transmission. The article predicts that wide and sustained transmission across the WHO African Region will result in 231 million infections over the coming year[7]. Whilst widespread transmission may be avoided by many African countries[8], the possibility remains that widespread community transmission that takes off in even a few countries could spread to other countries, and across the border into Rwanda.

Although until June 2020, Rwanda was able to limit infection mostly to the second stage, by August some locations had progressed to some version of the third stage of community clusters, especially in some villages and markets in central Kigali. Although many of these clusters seem to have been well-contained so far, there is thus a lingering risk of progression to the fourth stage of widespread community transmission. Whilst initial cases come from cross-border trade and have often started in border locations, widespread community transmission is most likely to occur in Rwanda's more overcrowded urban neighborhoods.

What is the difference between "densification" and "overcrowding"?

Densification is considered largely positive by urban economics and planners, and overcrowding is almost universally considered negative. But, if at root they both encapsulate the idea of more people in less space, what is the difference between them? Overcrowding can be considered as simply "excess densification", and this has some truth to it. However, the relationship between the two is mediated by a range of important factors, especially floor space per person, quality of infrastructure and access to public services.

[6] https://www.theigc.org/blog/rwandas-response-to-covid-19-and-future-challenges/

[7] Joseph Waogodo Cabore, Humphrey Karamagi, Hillary Kipruto, James Avoka Asamani, Benson Droti, Aminata Binetou-Wahebine Seydi, Regina Titi-Ofei, Benido Impouma, Michel Yao, Zabulon Yoti, Felicitas Zawaira, Prosper Tumusiime, Ambrose Talisuna, Francis Kasolo, Matshidiso Moeti. 2020. The potential effects of widespread community transmission of SARS-CoV-2 infection in the WHO African Region: a predictive model. *BMJ Global Health*

[8] https://www.newyorker.com/news/news-desk/what-african-nations-are-teaching-the-west-about-fighting-the-coronavirus

Densification has a range of important benefits, foremost among which is the productivity benefit to workers and firms that proximity can provide through connectivity and learning. Densification also enables the cost-effective provision of infrastructure and public services, and reduces the ecological footprint of a population both in terms of land use and energy use, and can enhance liveability through proximity of amenities. These benefits are well-known to the Government of Rwanda and appear in the National Urbanisation Policy.

However, the COVID-19 pandemic has raised questions about whether densification could promote pandemic risk, a public bad that is normally associated with overcrowding; and whether densification is therefore still worth pursuing.

Overcrowding – or excess density – can take place on two basic levels: at the outdoor level in terms of general population density, and at the indoor level in terms of overcrowded housing. There is evidence that both types of overcrowding are related to contagion. It is also likely that both together complement each other to increase the risk.

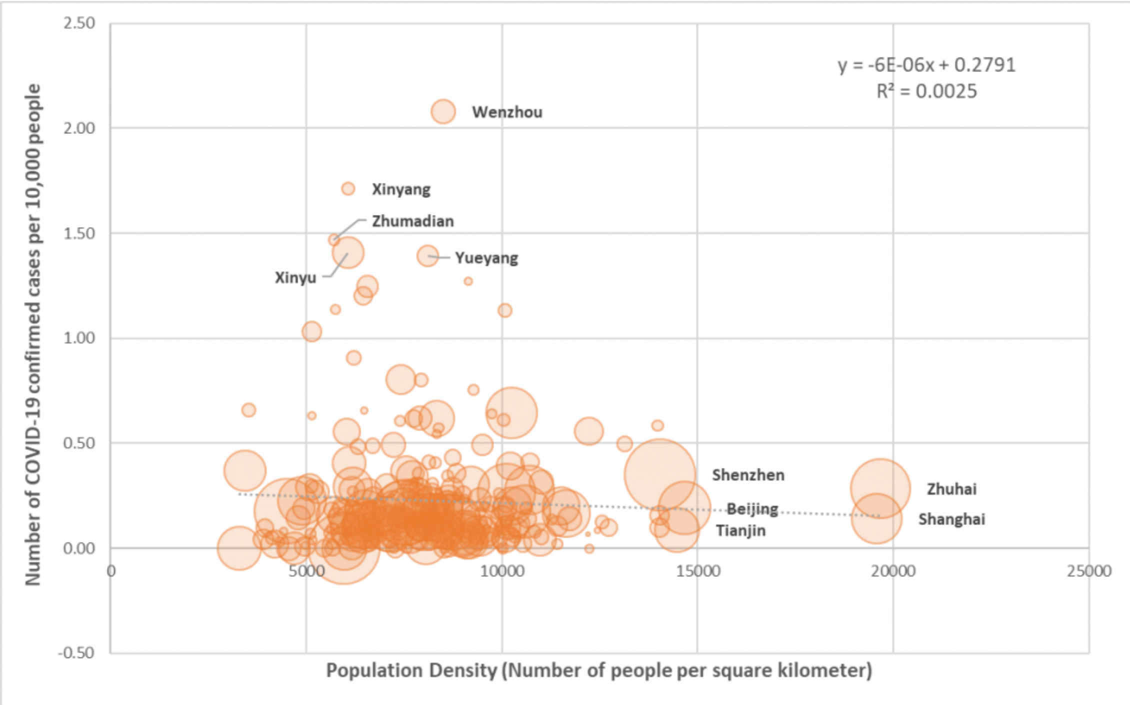
The evidence on high population density and pandemic risk

The evidence on the link between the spread of disease and population density has been mixed, but is on balance a weakly positive one. Whilst Chowell (2008) find no link between the spread of disease and population density for England and Wales during the 1918 pandemic[9], Li et al (2018) criticise their methodology and find a strong link in the US for the same pandemic[10], and Chandra et al (2013) find a similar result for the 1918 pandemic in India[11]. These studies make a case that that all else equal, population density does have some small impact on the spread of disease.

However, in the case of COVID-19, Fang & Wahba (2020) argue that density is not truly a *key* determinant and that other factors are far more important[12]. They make the point that some dense cities such as Singapore, Seoul, and Shanghai have fought COVID-19 far more effectively than many less densely populated places. They construct a graphic reproduced here in Figure 1, showing that there is no statistical link between city population and number of COVID-19 cases per 10,000 people, although they find that close economic and geographic proximity to Wuhan - the city in which COVID-19 first spread at scale - led to a higher number of cases per 10,000 people.

[9] Chowell (G.), Bettencourt (L.M.A.), Johnson (N.), Alonso (W.J.), Viboud (C.) 2008: The 1918-1919 influenza pandemic in England and Wales: spatial patterns in transmissibility and mortality impact. Proceedings of the Royal Society B, 7 March 2008.
[10] Li, Ruiqi & Richmond, Peter & Roehner, Bertrand. (2018). Effect of population density on epidemics. Physica A: Statistical Mechanics and its Applications. 510. 10.1016/j.physa.2018.07.025.
[11] Chandra, S., Kassens-Noor, E., Kuljanin, G., & Vertalka, J. (2013). A geographic analysis of population density thresholds in the influenza pandemic of 1918-19. *International journal of health geographics*, *12*, 9. https://doi.org/10.1186/1476-072X-12-9
[12] https://blogs.worldbank.org/sustainablecities/urban-density-not-enemy-coronavirus-fight-evidence-china

Figure 1: No link between population density and COVID-19 cases per 10,000 people



Source: Fang & Wahba (2020)[13]

The authors conclude that "well-designed institutions, high-quality infrastructure, and effective interventions (e.g., social distancing and lockdown to flatten the curve of disease transmission) will be the ingredients to making cities stronger against infectious diseases". Lall & Wahba (2020), whose methodology we attempt to replicate in this paper, argue that "economic geography, not physical geography, determines contagion risk", finding for New York that it was the poorest and most overcrowded, rather than the densest, neighbourhoods, that have had the highest COVID-19 incidence.

In the Rwandan context, poverty in unplanned settlements may worsen the impact of localised population density on pandemic risk. Seventy-seven percent of Kigali households live in unplanned settlements, most of which have narrow access pathways. Whilst Rwanda's statistics on access to improved water and sanitation are impressive compared to other countries on the continent, sharing is the norm: fifty five percent of Kigali households use shared toilets and a quarter have access to shared, unimproved water sources. Even the improved water sources, such as public standpipes that serve 41% of Kigali households, are shared[14]. This renders frequent handwashing a challenge, and queues for public or shared facilities may also pose challenges for social distancing[15]. These factors may render high population density in unplanned settlements a pandemic risk factor. However, the problem is not merely density itself, but also a lack of outdoor space in which to social distance and a lack of water and sanitation infrastructure leading to a need to share. Whilst masks are widely worn at least in Kigali[16] and this is an important measure, Wasdani &

[13] https://blogs.worldbank.org/sustainablecities/urban-density-not-enemy-coronavirus-fight-evidence-china
[14] https://www.theigc.org/wp-content/uploads/2019/12/Bower-et-al-Working-Paper-2019-1.pdf
[15] https://reliefweb.int/sites/reliefweb.int/files/resources/SSHAP_COVID-19_Key_Considerations_Informal_Settlements_final.pdf
[16] Authors' observation from living in Kigali throughout 2020

Prasad (2020) argue the impossibility of social distancing among the urban poor in India[17] and this is also plausibly the case in Rwanda.

Housing-level overcrowding and health

As noted, overcrowding can also take place at the housing level, for which there are a wide range of measures of overcrowding discussed in the literature. These include floor area per person, floor area per adult equivalent, people or adult equivalents per room, people or adult equivalents per bedroom, percentage of houses with more than two or three people per bedroom[18]. The key indoor overcrowding measure we focus on in this study is people per floor area, as will be explained.

This type of overcrowding is associated with a range of negative physical health impacts including increased instance of colds, asthma, influenza and diarrhoea[19], acute respiratory and gastrointestinal symptoms[20], cholera and tuberculosis; Neiderud (2015) gives a full review of the link between urban overcrowding and physical health outcomes[21]. Overcrowding has also been linked in the literature to mental health outcomes including depression in women, behavioural problems in children, lack of privacy, aggressive behaviour, psychological withdrawal and aggression in men, and other problems; having said this, these mental health factors are often confounded by other factors that correlate with overcrowding such as poverty[22] [23]. Thus overcrowding is of public health interest far beyond being a pandemic risk factor.

Whilst evidence is mixed on the relationship between overall population density and pandemic risk, which is confounded by other important factors, the relationship between housing-level or indoor overcrowding and pandemic risk is clear. Overcrowding within accommodation is associated with a higher risk of mortality from pandemics: Aligne (2016) investigated the causes of severe flu in a US army camp during the influenza pandemic of 1918[24], finding that among the possible causes, “overcrowding stood out, increasing the risk of flu 10-fold and the risk of flu complicated with pneumonia five-fold” for barracks with 4.2 square metres per occupant compared to those with 7.2 square metres per occupant. Epidemiologist Neiderud (2015) also links overcrowding - along with lack of fresh water and poor sanitation which often correlate with it - to the spread of infectious disease[25].

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[17] Kishinchand Poornima Wasdani & Ajnesh Prasad (2020) The impossibility of social distancing among the urban poor: the case of an Indian slum in the times of COVID-19, Local Environment, 25:5, 414-418, DOI: 10.1080/13549839.2020.1754375

[18] Ramalhete, Inês & Farias, Hugo & Pinto, R.s. (2018). Overcrowding-and-Adequate-Housing-The-Potential-of-Adaptability. 12. 1203-1213.

[19] Gray, Alison (2001). Definitions of Crowding and the Effects of Crowding on Health: A Literature Review. Ministry of Social Policy, New Zealand. ISBN: 0-478-25101-7. Retrieved from: https://www.msd.govt.nz/documents/about-msd-and-our-work/publications-resources/archive/2001-definitionsofcrowding.pdf

[20] Nkosi, V., Haman, T., Naicker, N. *et al.* Overcrowding and health in two impoverished suburbs of Johannesburg, South Africa. *BMC Public Health* 19, 1358 (2019). https://doi.org/10.1186/s12889-019-7665-5

[21] Neiderud C. J. (2015). How urbanization affects the epidemiology of emerging infectious diseases. *Infection ecology & epidemiology*, *5*, 27060. https://doi.org/10.3402/iee.v5.27060

[22] Gray, Alison (2001). Definitions of Crowding and the Effects of Crowding on Health: A Literature Review. Ministry of Social Policy, New Zealand. ISBN: 0-478-25101-7. Retrieved from: https://www.msd.govt.nz/documents/about-msd-and-our-work/publicationsresources/archive/2001-definitionsofcrowding.pdf

[23] Mangrio, E., & Zdravkovic, S. (2018). Crowded living and its association with mental ill-health among recently-arrived migrants in Sweden: a quantitative study. BMC research notes, 11(1), 609. https://doi.org/10.1186/s13104-018-3718-6

[24] Aligne C. A. (2016). Overcrowding and Mortality During the Influenza Pandemic of 1918. *American journal of public health*, *106*(4), 642–644. https://doi.org/10.2105/AJPH.2015.303018

[25] Neiderud C. J. (2015). How urbanization affects the epidemiology of emerging infectious diseases. *Infection ecology & epidemiology*, *5*, 27060. https://doi.org/10.3402/iee.v5.27060

Indoor overcrowding in Rwanda's urban areas is increasing or decreasing depending on the measure used. From 2011 to 2017, floor area per adult equivalent, decreased slightly in urban areas from just over 15 square metres to around 14.3 square metres for urban areas overall and 13.7 for Kigali; this is equivalent to 0.072 people per square metre. These are not low averages compared to other developing countries, and probably do not represent overcrowding for the median household. Another measure of densification, the number of rooms per adult equivalent, has also decreased in urban areas and especially in Kigali, from around 1.14 in 2011 to 1.06 in 2017.

On another measure which aims to capture critical overcrowding, the percentage of households that have more than three adult equivalents per bedroom[26], urban areas became less overcrowded, from 12.5% of households in 2011 (11.5% for Kigali) to just under 9.5% of households in 2017 (9% for Kigali). Perhaps surprisingly, according to this measure Kigali is less overcrowded than rural areas or urban areas in general.

Whilst indoor overcrowding has been shown to be strongly linked to disease, we believe the *combination* of indoor overcrowding and overall density in the form of very narrow pathways between houses - a form of outdoor overcrowding - are more risky than indoor overcrowding alone. The presence of both types of overcrowding create an environment in which both outdoor and indoor social distancing are very difficult. It probably also facilitates far more visits between overcrowded houses too, so there is a spillover effect. The spread of infectious disease is thus plausibly far more likely and voluminous in an overcrowded village full of overcrowded houses than an isolated rural village with two or three overcrowded houses; thus our analysis focuses on finding overcrowding hotspots by using , but also using data on total floor area to find the parts of the city where floor area per person is consistently low. The next section elaborates.

Where are the overcrowding/pandemic risk hotspots in Rwanda?

We analyse data in Kigali and in five secondary cities, to find the most overcrowded locations in which social distancing may be impossible and that may be most at risk for the spread of COVID-19, pandemics or other infectious diseases, and which are most likely to suffer from the other public health problems associated with overcrowding that were outlined above.

In epidemiology, a standard method for modelling the spread of infectious disease is to estimate contact rates between individuals, or effective contact rates in which they interact in ways that facilitate the spread of disease[27]. We are not attempting here to explicitly model the spread of disease, but the three measures of overcrowding that we describe below, are an imperfect proxy for a more precise measure of contact rates such as "how many people in a day are you within X feet of without a (good) mask on for more than Y units of time"[28].

[26] see Gray 2001 for a literature review of overcrowding measures, of which this one is at the higher end of standard measures. Gray, Alison (2001). Definitions of Crowding and the Effects of Crowding on Health: A Literature Review. Ministry of Social Policy, New Zealand. ISBN: 0-478-25101-7. Retrieved from: https://www.msd.govt.nz/documents/about-msd-and-our-work/publicationsresources/archive/2001-definitionsofcrowding.pdf
[27] Kirkeby, C., Halasa, T., Gussmann, M. et al. Methods for estimating disease transmission rates: Evaluating the precision of Poisson regression and two novel methods. Sci Rep 7, 9496 (2017). https://doi.org/10.1038/s41598-017-09209-x
[28] Thank you to Dr Jesse Heitner for sharing this insight

We use three types of data: building footprint and building height data from 2015 for the whole Province of Kigali by Bachofer et al (2019); population data from 2015 (Kigali) and 2018 (Secondary cities) produced by WorldPOP[29]; and built-up area data from the Global Human Settlement data produced by the European Commission (2014).[30] An important caveat to our analysis is that especially in Kigali, which has a population growth rate of around 4% (Bower & Murray 2019), the most overcrowded areas may have shifted or expanded. However, we use the best and most up-to-date data currently available.

In order to combine these different data sources, we first break up the entire Kigali Province and secondary cities into a grid of 100m by 100m "pixels". We then overlay building footprint and building height data, population estimates and built-up area estimates onto these gridded pixels to produce estimates of the quantities of each in every 100m x 100m pixel. We then estimate measures of density and overcrowding based on three measures:

1. **Population per square metre of floor area, or *indoor overcrowding*:** We measure overcrowding by estimating the Total Floor Area (TFA), or liveable floor space, of a pixel using building footprint data and building height data. Since data on building heights were not available outside urban Kigali, we assumed a building height of 2.5 metres - or one storey - across all other areas (which have only building footprints).
2. **Population per square metre of "built-up area", or *outdoor overcrowding*:** We measure outdoor density by estimating the amount of space outside the building footprints but within the built up area. This concept is best illustrated by the light grey areas in Figure 2 overleaf, and corresponds to areas where a resident might encounter another resident, for example. streets, sidewalks and public spaces. It also includes any outdoor areas of compounds and gardens, but *excludes* the buildings themselves. Given that not all areas are paved - especially peri-urban areas - to make analysis tractable and eliminate cells falsely calculated to be extremely crowded, we make a small number of plausible assumptions regarding the amount of outdoor space available for households which we explain in a footnote.[31]
3. **Population per total area of liveable indoor space and built up outdoor space), or *total overcrowding*:** This composite measure aims to capture overcrowding on the basis of (i) all indoor living space plus (ii) all outdoor space that people use, as accurately as possible, given the available data. We add the total area of liveable indoor space, or total floor area (TFA) per pixel, to the total built up outdoor area to estimate the total area of a pixel that the population normally occupies. For areas for which 3D data exists, this measure is different to the total built-up area (including buildings) because it includes the floor space on second floors and higher.

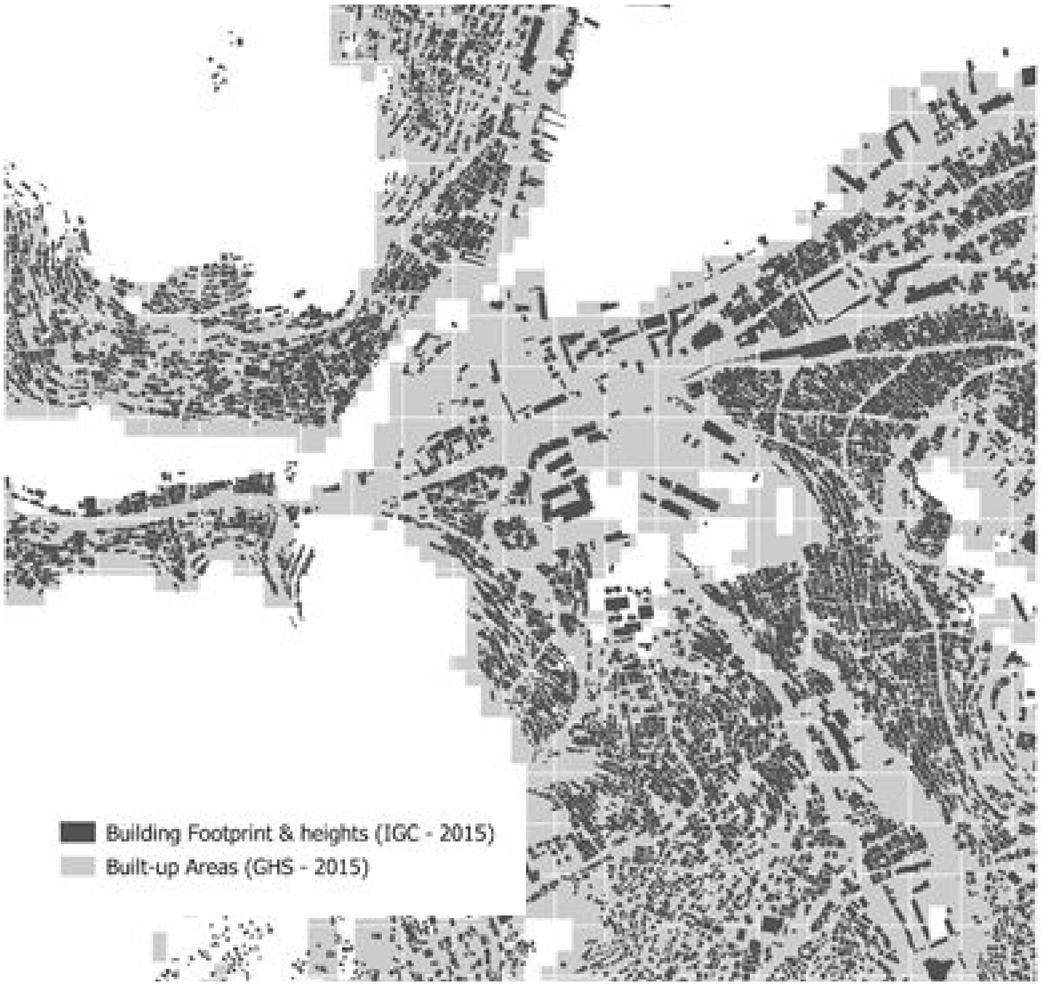
[29] https://www.worldpop.org/methods:The production of WorldPop spatial datasets principally follows the methodologies used in Stevens et al (2015), Alegana et al (2015), Deville et al (2014), Linard et al (2012), Gaughan et al (2013) and Tatem et al (2007). We use WorldPOP people-per-pixel datasets - without UN adjustments - for 2015 (in Kigali) and 2018 (in secondary cities), as it appears to track the settlements visible in satellite photographs and in the IGC building footprint data, better than the adjusted version, or than the Facebook population data.

[30] https://ghsl.jrc.ec.europa.eu/data.php?sl=2; GHSL uses satellite imagery to estimate "man-made objects" and humans settlements that include buildings, and associated structures and civil works.

[31] A small number of anomalous grid cells have buildings but no built up area, or built-up area but no buildings. For the former, we assume outdoor area is the difference between the total grid cell area and the building footprint area. For the latter, we assume that the built up areas constitute the buildings and that the outdoor area is the difference between the total grid cell area and the built up area. Additionally, where the difference between the built-up area and building footprints is less than ¼ of a grid cell's total area, we assume the outdoor area is the difference between the total grid cell area and the building footprint.

For our measure of indoor overcrowding (measure 1 above) we limit our analysis to a static measure of population density per TFA for the pixel in question, to get a measure in terms of people per square metre. However, to measure outdoor and total area density (measures 2 and 3 above) we take into consideration the fact that an individual might move short distances (approx 250 metres radius, covering a 5 x 5 grid of 100 x 100 square metre pixels, becoming a 500 x 500 metre square) from their house and hence average the density of the neighboring eight pixels.[32]

Figure 2: Building footprint data and built up area data: an example from Kigali



Notably, measure 1 of indoor density does not take into account neighbourhoods in which housing is extremely close together, in which pathways are narrow, courtyards are small,

[32] Before producing any estimate, we winsor (limit the extremes of) our density estimates at the 0.5 percent level to ensure that anomalies - caused by abnormally high population estimates or abnormally low liveable area measurements - do not skew our data unrealistically. Additionally, we make slight modifications to the analysis produced by the World Bank. First, instead of using 3.0m as the height of a single storey we use 2.5m, which is more appropriate in Rwanda. Second, we do not use Humanitarian Open Street Map (HOTOSM) data to estimate “service” and “transit” pixels, largely due to the lack of any good publicly available data on these facilities. Third, we use a higher average “travel” distance of 250 metres rather than 150 metres. Finally, we do not add densities of neighboring pixels but rather average them (to aid interpretation).

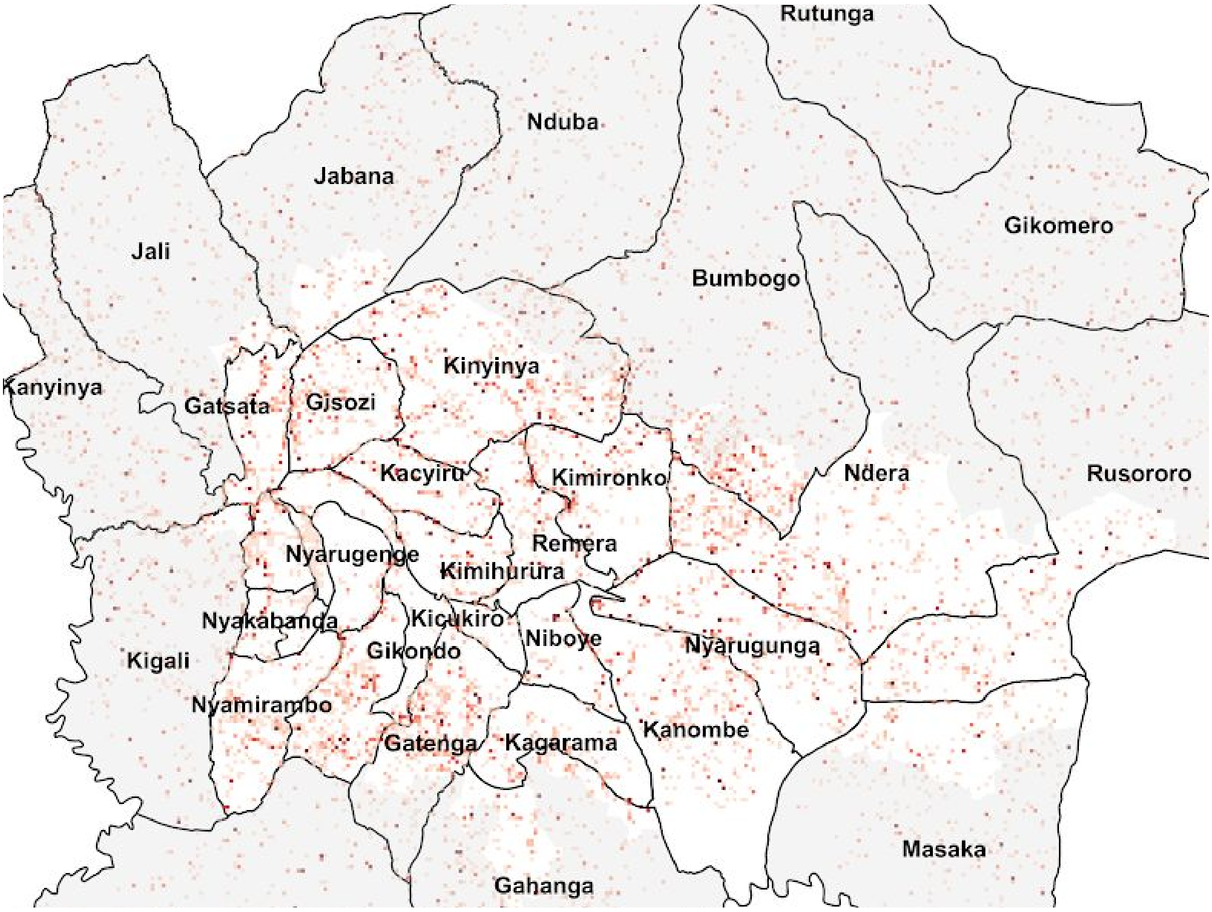
roads and public space are scarce and neighbour visits more frequent; the outdoor measure 2 - and the composite measure 3, does so.

Whilst research shows that COVID-19 and other diseases do not spread as easily outdoors and that raw density is not correlated with its spread, we find four reasons why outdoor overcrowding as we have defined it, increases the risk of COVID-19. First, where houses are very close together even if average indoor overcrowding per pixel is spread evenly throughout the city, the number of overcrowded houses will be higher in dense unplanned settlements simply because the number of houses per pixel is higher. Second, where houses are very close together and pathways are narrow, there is likely to be more close person to person contact and high touch surfaces such as shared toilets, handles and taps. Third, in crowded settlements it is plausible that there are more house-to-house visits and scope for infected people to spread the disease, for reasons including children playing with other children, visits by relatives and friends, neighbours sharing resources and prayer sessions. Fourth, there may be more scope in these overcrowded areas for spread in public or shared buildings - and the spread of COVID in the markets in Nyabugogo and Nyarugenge are good examples, and outdoor overcrowding may be a proxy for the existence or quantity of those types of spaces.

Kigali

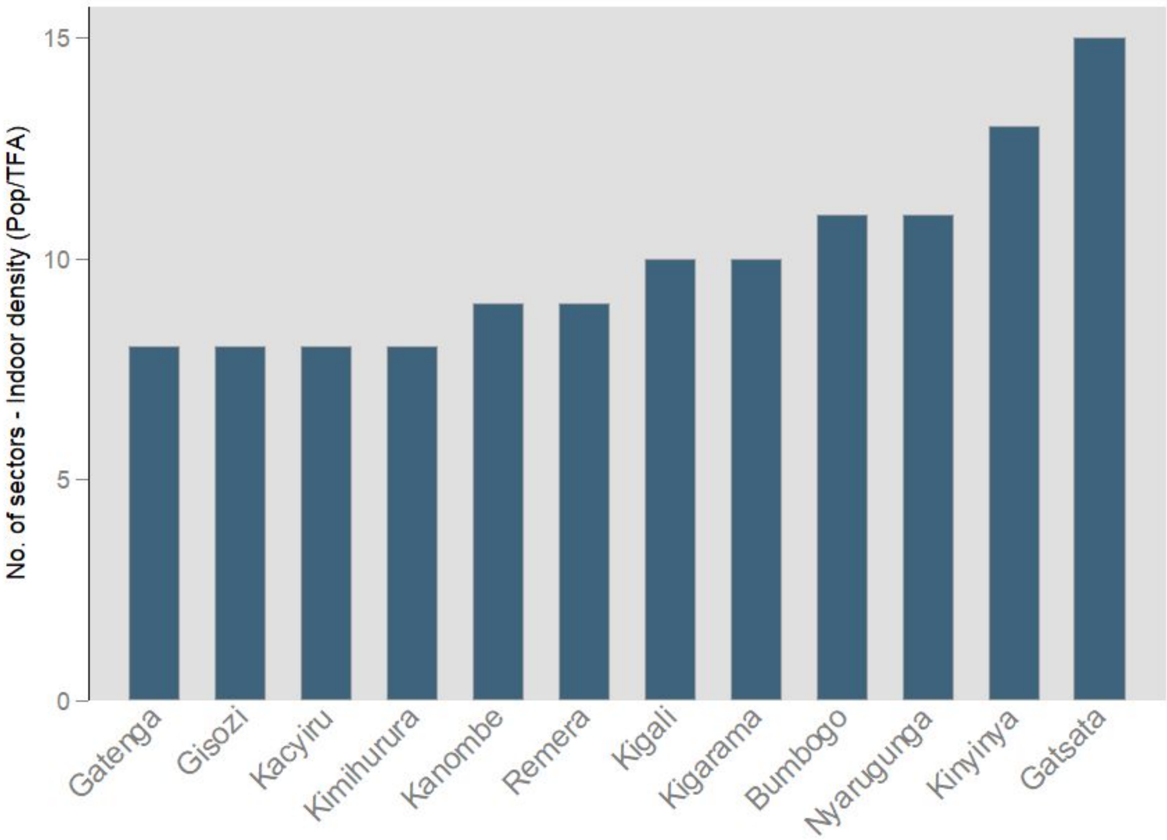
We now present results for Kigali. In Figure 3 below we present the location of indoor overcrowding hotspots in Kigali in which the number of people per square metre per floor area is highest; this is represented by darker shades of red. Our data is imperfect and contains some outliers, but we are confident that the map makes it immediately clear that indoor overcrowding is relatively evenly spread across the city, perhaps proportionately to the quantity of housing - thus whilst there are more overcrowded pixels in central Kigali this is due to the higher quantity of housing - there is also overcrowding in the housing that does exist in rural Kigali.

Figure 3: Indoor overcrowding in Kigali (people per square metre of indoor floor area)



Whilst overcrowding is quite spread out in Kigali where houses exist, some villages experience more of it. Annex 1 shows the top 100 villages out of the 1,163 villages in Kigali according to indoor overcrowding, in the first column. Figure 4 below shows that the top 5 sectors with the most villages in the top 200 are Gatsata, Kinyinya, Nyarugunga, Bumbogo and Kigarama.

Figure 4: Number of villages in the top 200 most overcrowded villages in Kigali on indoor measure, by Sector (ranked)

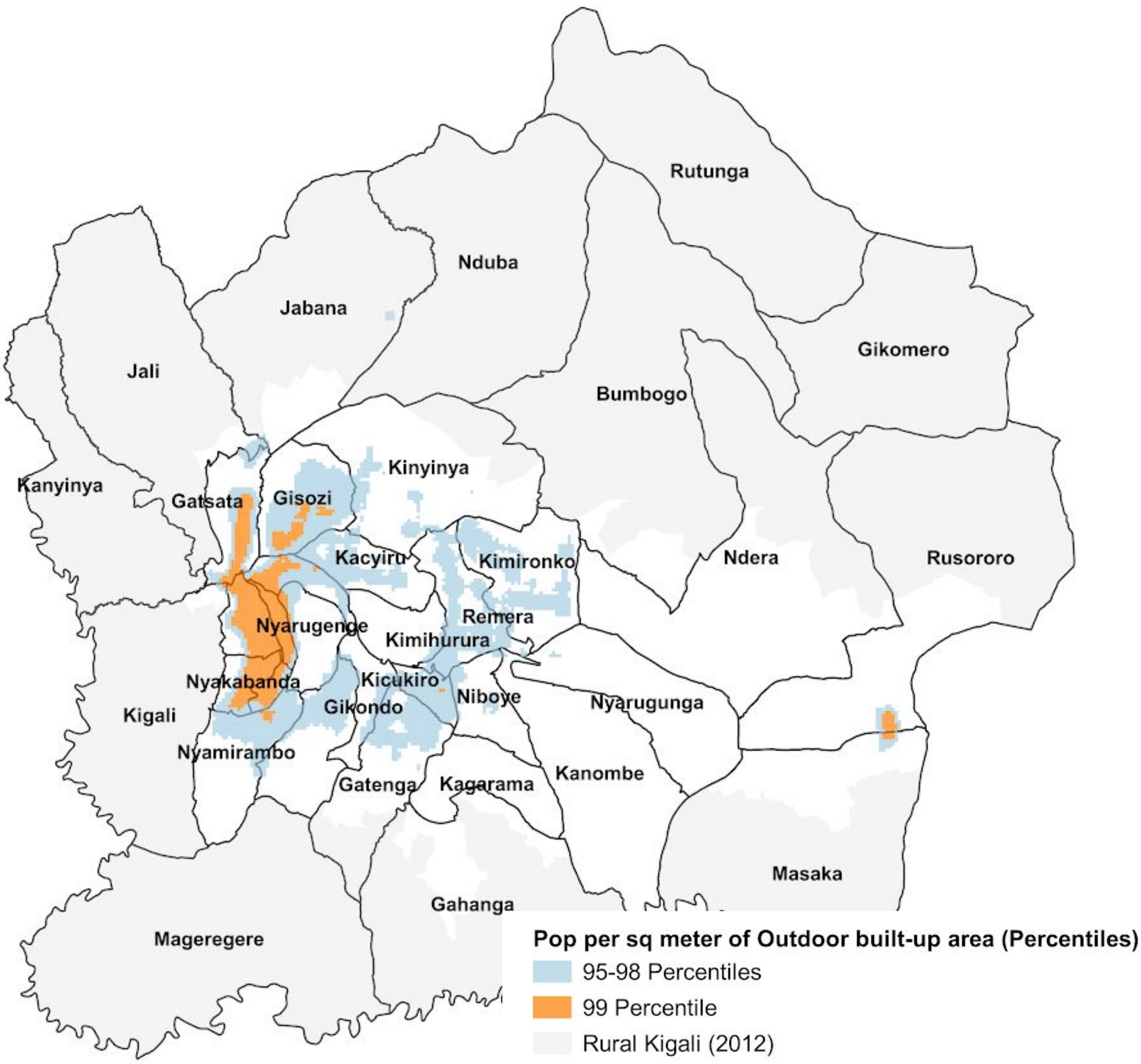


The top 10 most overcrowded villages in Kigali - in indoor, outdoor, and composite measures, are presented in Table 1 later. Overall, we estimate that 19.7% of Kigali residents live in dwellings where the people per square metre is greater than 0.065 (sq metre per person of 15.3); and that 10.1% of Kigali residents live in dwellings in which density is at least double that.[33] A caveat is due: the building footprints we use to calculate these figures include commercial buildings, and whilst these buildings are a very small percentage of the total, they will nonetheless bias these estimates downwards. However, this does not appear inconsistent with our EICV analysis which shows that 13.1% of the population lives in a house with more than three adult equivalents per bedroom.

We now supplement our analysis of "indoor" density in terms of people per floor area with estimates of densities in built up areas (that exclude buildings) in terms of people per square metre of built up outdoor space. Figure 4 shows the locations of the top 1% and top 5% densest areas of the city.

[33] https://www.huduser.gov/publications/pdf/measuring_overcrowding_in_hsg.pdf: HUD estimates the minimum space per person to be 165 sq ft per person or 15.3 sq metres per person.

Figure 5: Areas of Kigali in top 95th and 99th percentile for outdoor overcrowding



Whilst the map visualises the location of the most overcrowded areas, Figure 6 shows the number of villages that each Sector has in the top 200 most overcrowded villages on the outdoor measure, out of a total of 1,163 villages. The top 200 villages are contained within just six sectors, and 42 of them are in Kimisagara Sector; the others are, in order, Gitega, Muhima, Nyakabanda, Gatsata and Rwezamenyo. Thus unlike indoor overcrowding which is spread out further across the city, outdoor overcrowding is packed into a much more concentrated area.

Figure 6: Number of villages in the top 200 most overcrowded villages in Kigali on outdoor measure, by Sector (ranked)

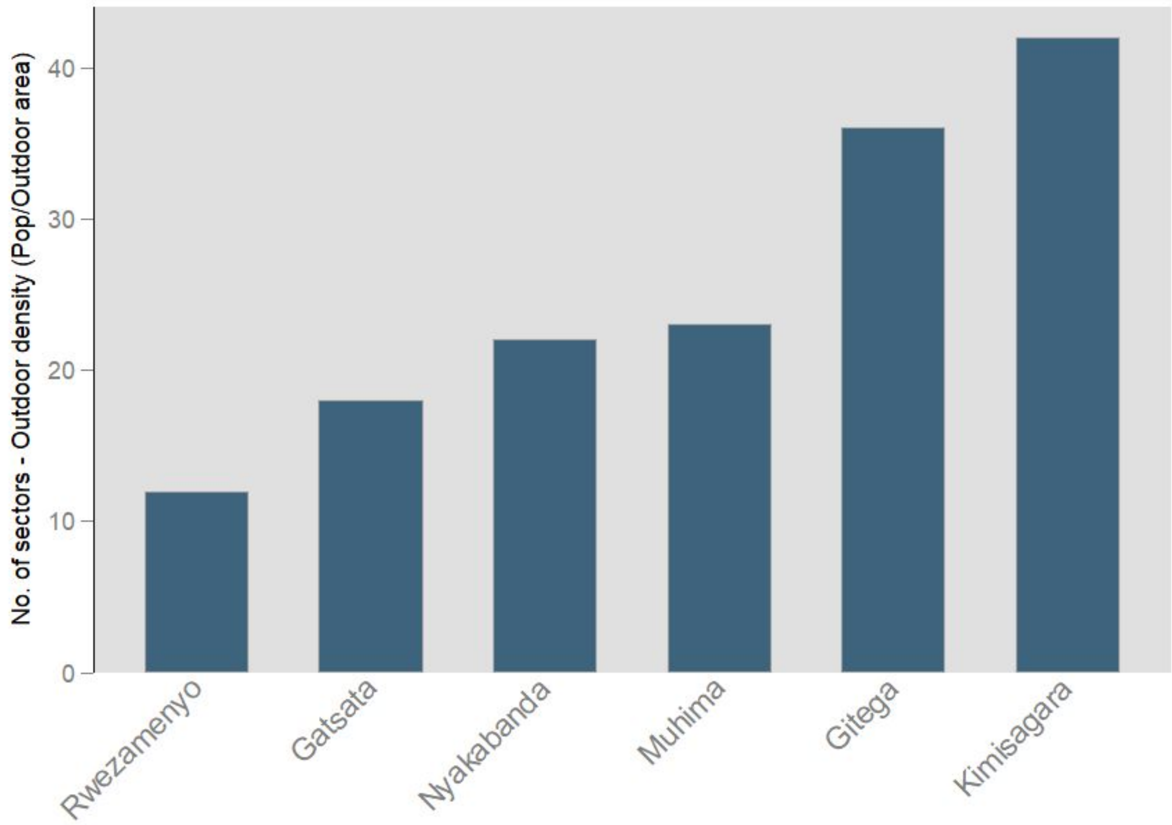


Figure 7 shows the top 1% and top 5% most overcrowded areas in Kigali according to the composite measure (measure 3 described at the start of this section). As mentioned, this measure also takes into consideration both indoor density, outdoor density and the likelihood of residents moving in their vicinity - that is, moving from the central pixel to the 24 neighboring pixels, which represents a square of side 500 metres. The sectors with the most villages in the top 200 most overcrowded villages on the composite measure, has the same rank order as for the pure outdoor measure so we have not shown it. Figure 7 overleaf shows a close-up of the composite measure for one of the densest areas, spanning Gitega, Muhima and Kimisagara.

Figure 7: Composite measure of overcrowding in Kigali (population per total indoor and outdoor liveable area), and the same map zoomed in on the 99th percentile *(see appendix 4 for translations of percentiles into densities)*

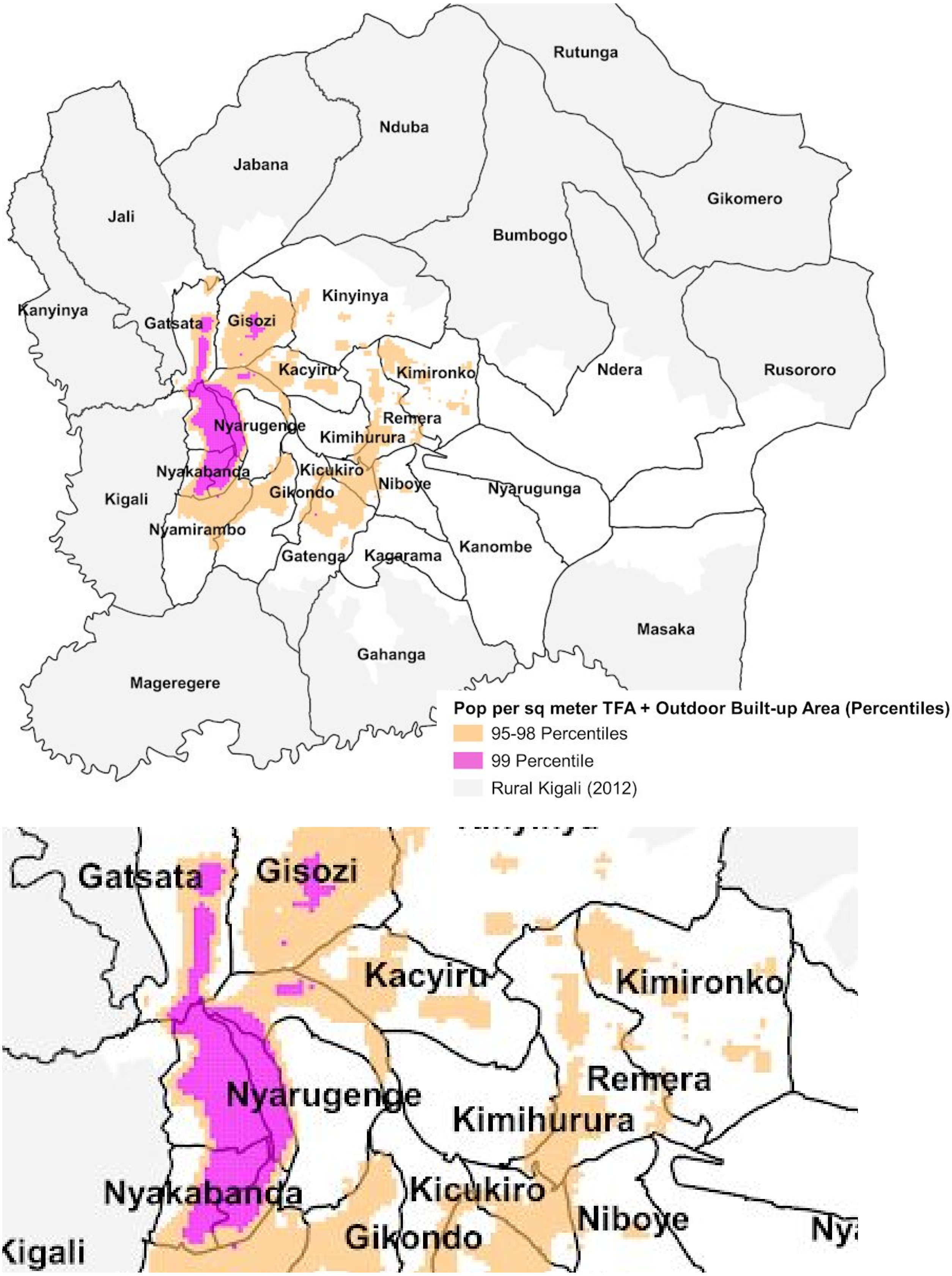
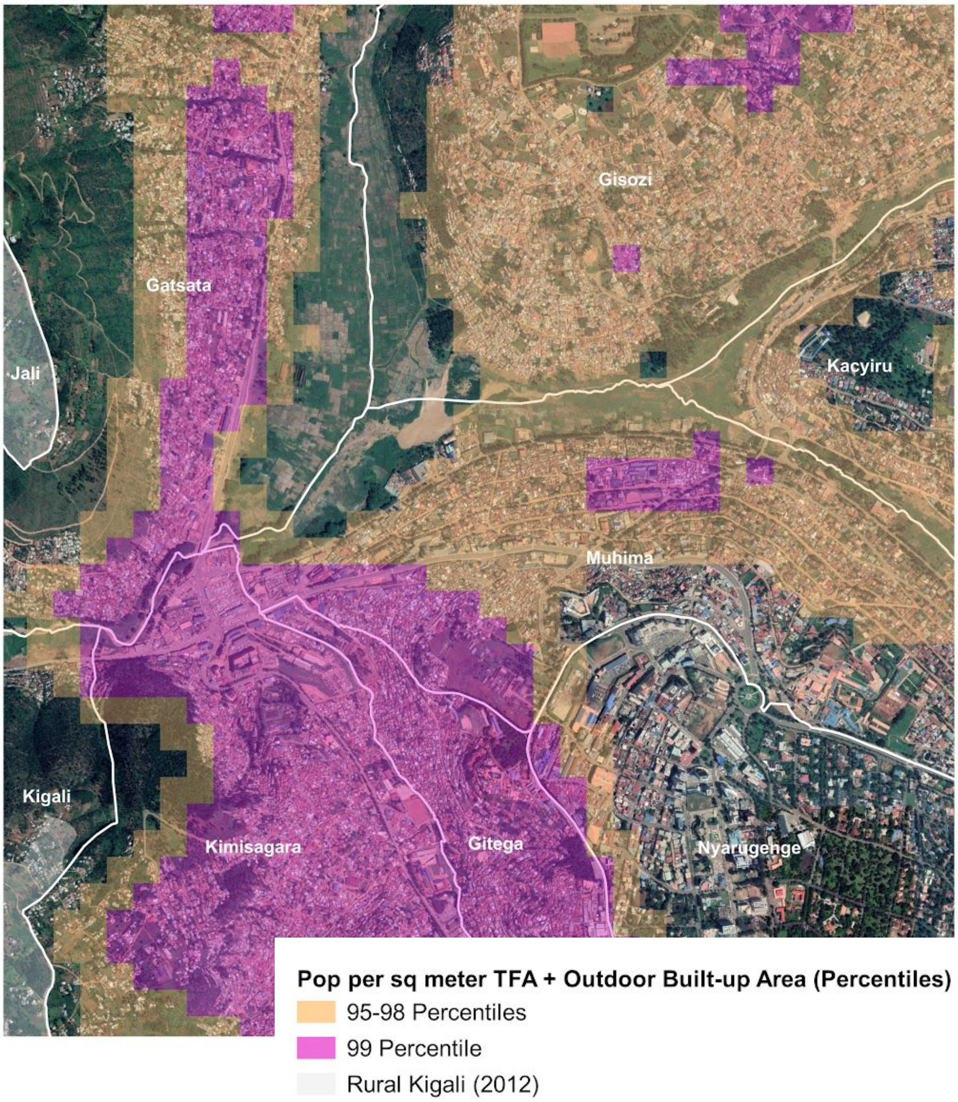


Figure 8: Composite overcrowding measure (population per total indoor and outdoor liveable area) - Zoomed in with satellite photo



Presenting the data differently, we are also able to rank all villages in Kigali by overcrowding in Table 1 overleaf. Technically it is a form of "density" we are mapping - that is, people per square metre of indoor space (measure 1), outdoor space (measure 2), or both (measure 3) - but we call it "overcrowding" because we do not want to confuse positive density resulting from well-planned neighbourhoods and housing with more than one storey - with high density resulting from poorly planned and overcrowded neighbourhoods. In Kigali, with 77% of households living in unplanned settlements, the densest villages are likely to be the most overcrowded villages which are most vulnerable to highly contagious diseases simply by virtue of their population density. The composite density estimate, which takes into account limited outdoor space across a 500 metre square, reveals that the most crowded areas are those located closer to the city centre in sectors with a large quantity of unplanned housing. Annex 2 contains a full list of the top 100 overcrowded villages ranked by all three measures.

We do not present absolute measures of outdoor density because over a 500 metre square, this would result in a low number of people per square metre of outdoor space that would not be very meaningful; we find it more meaningful to simply compare pixels or villages and find those that are top ranked in terms of overcrowding.

Table 1: Kigali village ranking by density measure and ranking

Rank	Indoor overcrowding (Pop/ TFA)[34]	Outdoor overcrowding (Pop/Outdoor built-up area excl buildings)	Composite measure of overcrowding (Pop/(TFA in buildings + outdoor built-up area)
1	Tetero, Karuruma, Gatsata	Vugizo, Akabahizi, Gitega	Mpazi, Akabeza, Gitega
2	Karudandi, Munanira Ii, Nyakabanda	Umuseke, Akabahizi, Gitega	Mpazi, Kora, Gitega
3	Hanika, Nyamabuye, Gatsata	Gihanga, Akabahizi, Gitega	Rugari, Kora, Gitega
4	Gakaraza, Kimisagara, Kimisagara	Mpazi, Kora, Gitega	Gihanga, Akabahizi, Gitega
5	Akakaza, Kinyaga, Bumbogo	Umurabyo, Akabahizi, Gitega	Kanunga, Kora, Gitega
6	Kinyambo, Kora, Gitega	Rugari, Kora, Gitega	Rugano, Kora, Gitega
7	Kingasire, Karuruma, Gatsata	Kanunga, Kora, Gitega	Ituze, Akabeza, Gitega
8	Nyamabuye, Kimisagara, Kimisagara	Mpazi, Akabeza, Gitega	Mpazi, Katabaro, Kimisagara
9	Kumuyange, Karuruma, Gatsata	Ituze, Akabeza, Gitega	Akamahoro, Katabaro, Kimisagara
10	Jyambere, Karambo, Gatenga	Isangano, Kora, Gitega	Vugizo, Akabahizi, Gitega

[34] For indoor overcrowding measures we rank the median density per village to avoid skewing by some pixels with vary high densities

Figure 9: Villages currently or previously under lockdown as at 29th July 2020, compared with composite overcrowding measure

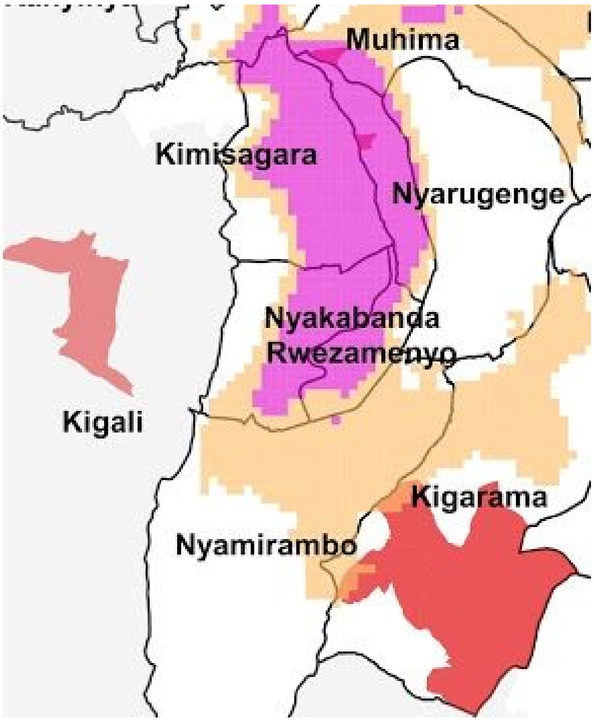
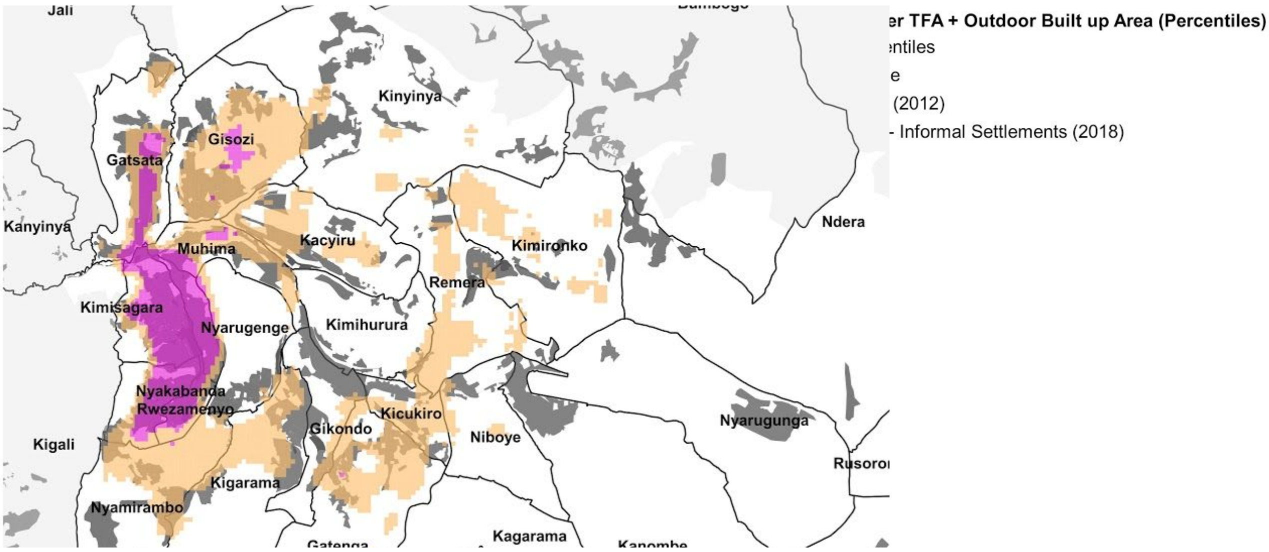


Figure 9 maps villages in Kigali that have been locked down at any point, on to the areas we identified as most overcrowded according to our composite indoor/outdoor measure as in Figure 7. There is not a perfect overlap but most villages are in or very close to the most overcrowded areas.

We also mapped the unplanned settlements identified by UN Habitat on to the areas we estimate to be overcrowded. We find a strong overlap in the 99th percentile but little overlap in other areas, implying that some unplanned settlements are not highly overcrowded.

Figure 10: UN Habitat Informal Settlements map (2018) and overcrowded areas according to composite measure



Secondary cities

Rwanda has six secondary cities for which the Government has ambitious development plans; we thus replicate our overcrowding estimates for Kigali in five out of six secondary cities in the country.[35] The data we use for our analysis of secondary cities are similar to those we use for Kigali. Critically, however, our building data for secondary cities does not include building heights. As such, for our all analysis of secondary cities we assume a building height of 2.5 metres and offer an analysis of crowding and densification with the assumption that most dwellings are single storey. Anecdotally and in our experience, the residential buildings are indeed largely one-storey in secondary cities, except for some government and commercial buildings, so the lack of building heights does not detract too much from our confidence in our estimated locations of the densest hotspots.

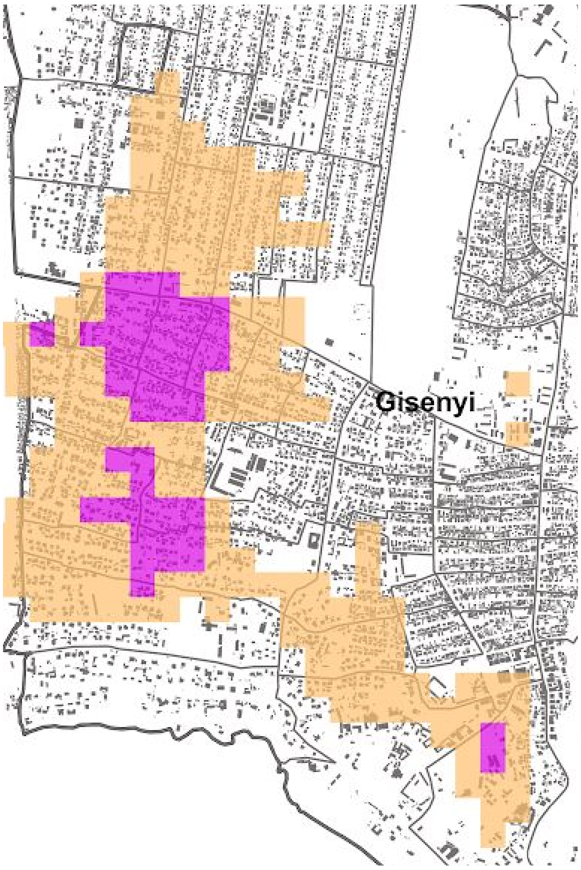
Figure 11: Indoor overcrowding in Rubavu (people per square metre of floor area)

As for Kigali, in secondary cities indoor overcrowding in terms of population per total floor area of indoor space, is fairly evenly spread across secondary cities; and our data also corroborate the conclusion from the Bower et al (2019) analysis of EICV data, that urban indoor overcrowding overall is fairly similar to that in Kigali. Figure 11 shows indoor overcrowding for Rubavu according to 100m x 100m pixels, in a diagram akin to Figure 3 for Kigali. Darker shades of red represent greater overcrowding. Whilst our data is imperfect and contains some outliers, we are confident about the general conclusion that indoor overcrowding is quite spatially dispersed within and across cities, unlike outdoor overcrowding. However, from an outdoor perspective, secondary cities are much smaller both in terms of population and built up area than the city of Kigali, and have far smaller and less dense agglomerations of unplanned housing (See Annex 2). As such we find that they do not exhibit overcrowding hotspots on the same level as the Capital. However, we do identify the most overcrowded hotspots in each city, as shown in Figure 12.

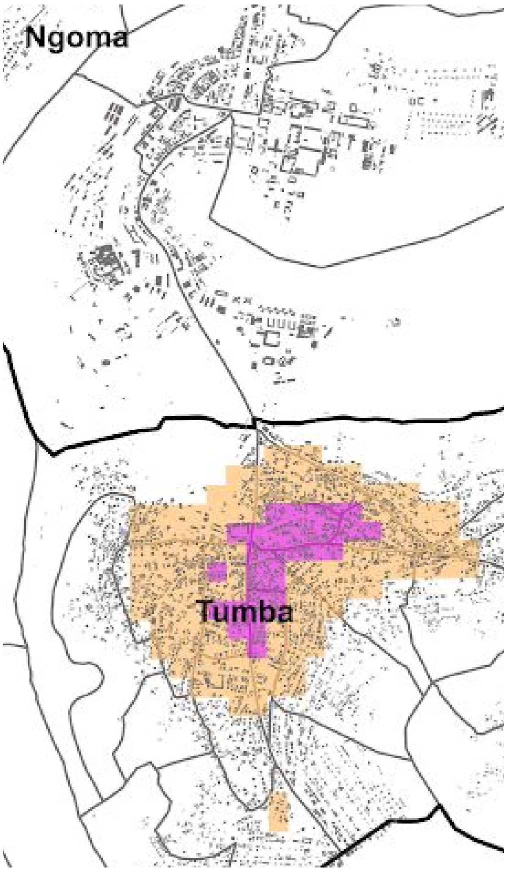
[35] The reason for only including five out of the six secondary cities was because we do not have the building footprint data for Musanze, the sixth official secondary city in Rwanda

Figure 12: Composite (indoor plus outdoor) measure of top 1% and 5% overcrowding hotspots in 5 secondary cities

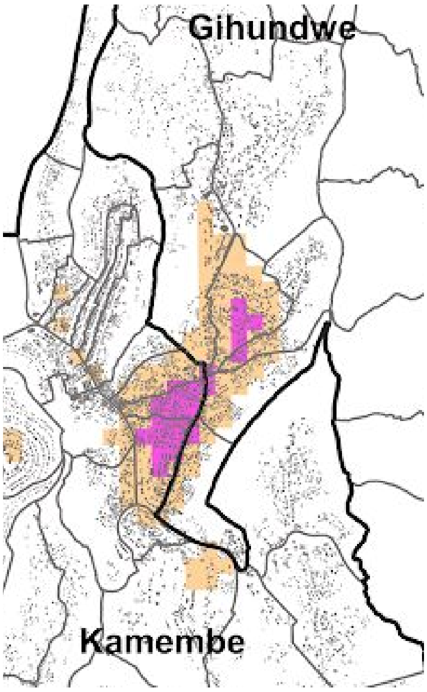
Rubavu



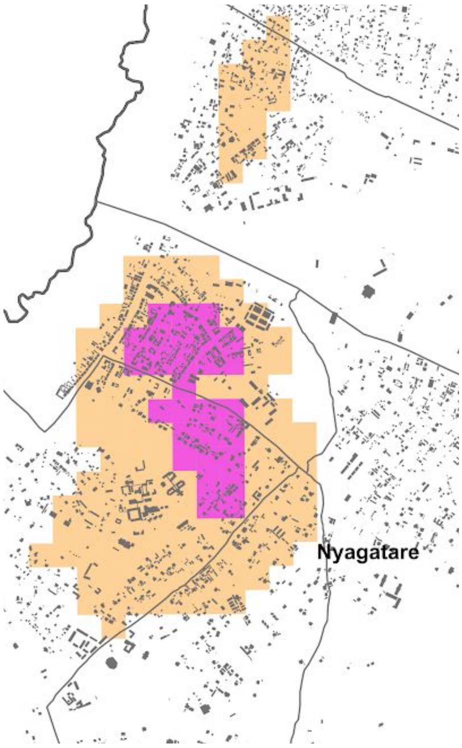
Huye



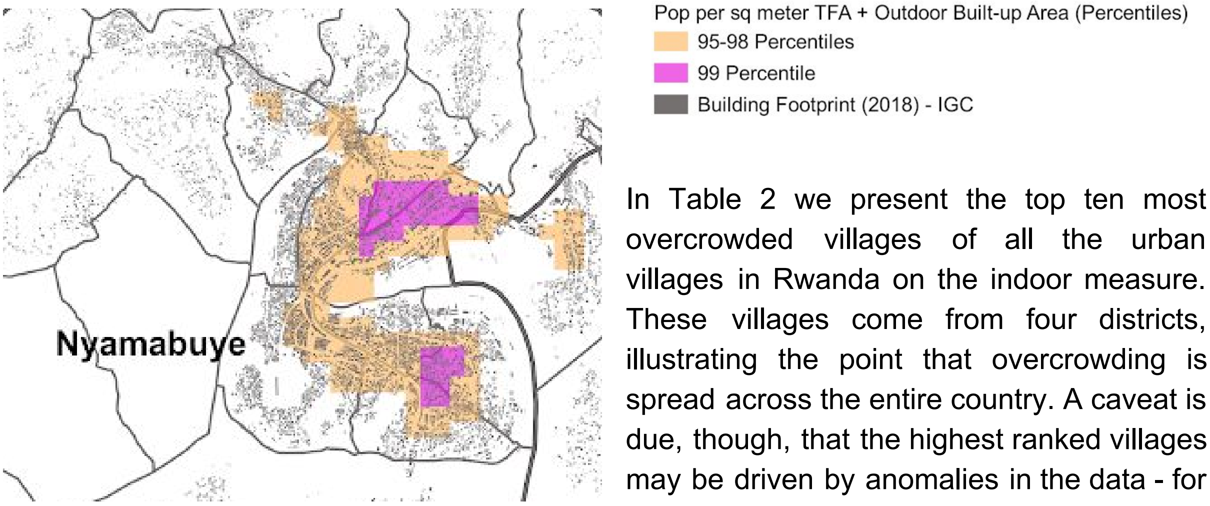
Rusizi



Nyagatare



Muhanga



In Table 2 we present the top ten most overcrowded villages of all the urban villages in Rwanda on the indoor measure. These villages come from four districts, illustrating the point that overcrowding is spread across the entire country. A caveat is due, though, that the highest ranked villages may be driven by anomalies in the data - for instance where there is a normal amount of population but very limited building footprints captured for the village in question. However, even with this caveat, we can still conclude confidently that indoor overcrowding happens all over the country.

Table 2: Top ten most overcrowded villages in Rwanda - indoor measure

Rank	Village	District
1	Kinyami, Shyogwe	Muhanga
2	Ihuriro, Gisenyi	Rubavu
3	Majengo, Gisenyi	Rubavu
4	Mucyamo, Kamembe	Rusizi
5	Kabuga, Gisenyi	Rubavu
6	Tetero, Karuruma, Gatsata	Kigali
7	Kanoga, Gihundwe	Rusizi
8	Umurava, Gisenyi	Rubavu
9	Cyanika, Rugerero	Rubavu
10	Butangi, Rugerero	Rubavu

We do not present the same table for the outdoor measure because these are almost all concentrated in Kigali with the exception of a small number of villages located in Rubavu.

Conclusions and recommendations

We combine the evidence in this paper with other literature to find the following conclusions and recommendations.

1. **Indoor overcrowding, which is associated with the spread of contagious disease, is spread throughout cities and throughout the country.** On our measure of overcrowding at the housing level - people per square metre of indoor floor area (pop/TFA) - the villages with the housing that is on average, the most overcrowded, seem to be spread throughout Kigali city and throughout the country. We have presented rankings of villages in Kigali and five secondary cities and this conclusion holds for all of them and at the national level.

2. **Outdoor overcrowding is concentrated in certain villages and sectors in Kigali city.** The villages with the most overcrowded housing (indoor overcrowding) may not, in fact, contain a large number of households living in very close proximity. On our measure of outdoor overcrowding, defined as population per square metre of outdoor built-up area, one of Kigali's 45 sectors - Kimisagara - contains 42 of the villages in the top 200 most densely populated villages.

3. **The combination of indoor and outdoor overcrowding is likely to be most important to pandemic risk; when combining both types we find that overcrowding is concentrated in Kigali.** Villages or neighbourhoods that contain a small quantity of very overcrowded housing but that is spaced apart and isolated, are less likely to be pandemic risk hotspots than places - likely informal settlements - that are equally overcrowded but also packed with so much housing that pathways are extremely narrow, neighbour visits more frequent and social distancing impossible in many areas. We thus created a composite measure of indoor and outdoor overcrowding to try to find the 500 metre square "pixels" and villages that are most overcrowded in both senses. We find that on this composite measure, overcrowding is also concentrated in Kigali - although in practice, weighting in our measure is dominated by the outdoor measure.

   Two points are worth noting. First, and a large number of COVID-19 cases were detected in Nyabugogo and Nyarugenge markets in August; whilst our study is unable to cover overcrowding in locations such as markets or workplaces due to data constraints, those markets are located in or very close to the highly overcrowded city areas that we identify. Second, whilst initial COVID-19 cases were not driven by overcrowding but by international arrivals in Kigali, from the airport, and in land border towns such as Rusizi and Rusumo, as time has passed a much higher proportion of cases have come from the most overcrowded parts of the country.

4. **The Government might weight its package of COVID-19 testing and mitigation measures, and eventually vaccination, towards the most overcrowded areas.** The Government of Rwanda might consider higher levels of testing per capita for COVID-19 in the most overcrowded villages in the country - most of which are concentrated in a

few Sectors near the centre of Kigali, especially Kimisagara, Gitega, Muhima, Nyakabanda, Gatsata and Rwezamenyo in this order. When a vaccine eventually becomes available, the Government might also consider higher levels of vaccination per capita in overcrowded areas, especially those that had to be locked down previously. However, weighting towards these sectors should not be to the neglect of other areas because indoor overcrowding is spread more evenly throughout the whole country, and is the measure upon which the most research has been conducted on the link with disease. We also mapped the COVID-19 hotspot villages that the Government has had to lock down for brief periods, on to the most overcrowded places and found that some of them match or are close to the most overcrowded areas. The data we provide in this study may have some role in assisting this targeted approach.

5. **In the longer term, the densification pillar of Rwanda's urbanisation policy should be pursued whilst avoiding overcrowding; this can be done through building above the first storey and through funding and building appropriate infrastructure.** The downsides of overcrowding do not nullify the densification pillar of Rwanda's National Urbanisation Policy. Rather, international evidence during the pandemic reinforces the conclusion that many cities that had very high densities per square kilometre also handled the pandemic extremely well - and that there was little correlation between raw density. The key is managing density well. There is a crucial difference between density and overcrowding, and well-functioning high density is usually not achieved through one-storey overcrowding. But neither is it best achieved in Kigali through high-rise blocks; it may be best embarked upon by simply building residential housing up to two, possibly three floors, especially in areas closer to the centre. This increases indoor floor space - but can free up space for outdoor infrastructure too. So, to reduce or avoid an increase in outdoor overcrowding as a result of more floor space, this has to be combined with fitting roads that have adequate space for transit and by well-designed public spaces.

   Professor Schlomo Angel breaks down the "anatomy of density" and vividly shows the many ways in which cities around the world are dense[36]; he urges that infrastructure be built in advance of future needs so that housing in unplanned settlements is not built too close together (Angel et al 2020). Relatedly, Wainer et al (2016) recommend "effective grid and structures for the management of neighbourhood evolution, which promote without forcing neighbourhood density, encourage a managed increase in density over time, and protect public and private open spaces". The twin tools of unplanned settlement upgrading for existing settlements, and sites and services for new settlements, will be vital. The policy discussions in the paper Housing policy in Rwanda: Riding the Urbanisation Whirlwind (Bower & Buckley, 2020) and in the paper "Housing Solutions for Low-Income Urban Communities in Rwanda" (Choi, Held & Berrisford, 2020) lay out more detail on achieving density affordably.

[36] https://www.youtube.com/watch?v=y99wA1JOOGg

6. **Also in the longer term, access to water and sanitation is the most fundamental investment to prevent COVID-19 and other diseases, especially in the most overcrowded areas.** As noted in a discussion on 10th June 2020 by the IGC CIties that Work Council including the Mayor of Accra, the Mayor of Freetown and the former Mayor of Kampala, water and sanitation, to enable frequent handwashing, is very important as a measure to prevent the spread of disease. Whilst absolute levels of access to improved water supply in Rwanda including water piped into the dwelling, the yard or a public standpipe, compare well with other countries on the continent, there was little progress in terms of the percentage of urban households covered by improved water sources between 2014 and 2017. Whilst progress on water and sanitation investments is important, the Cities that Work Council notes that "softer elements around behaviour change, communication and incentives can be used to encourage improved sanitation behaviours".

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Annex 1: Top 100 most overcrowded villages in Kigali ranked by 3 measures

Table 3: Kigali

Rank	Indoor Overcrowding (Pop/ TFA)[37]	Outdoor Density (Pop/Outdoor built-up area excl buildings)	Total Density (Pop/(TFA in buildings + outdoor built-up area)
1	Tetero, Karuruma, Gatsata	Vugizo, Akabahizi, Gitega	Mpazi, Akabeza, Gitega
2	Karudandi, Munanira Ii, Nyakabanda	Umuseke, Akabahizi, Gitega	Mpazi, Kora, Gitega
3	Hanika, Nyamabuye, Gatsata	Gihanga, Akabahizi, Gitega	Rugari, Kora, Gitega
4	Gakaraza, Kimisagara, Kimisagara	Mpazi, Kora, Gitega	Gihanga, Akabahizi, Gitega
5	Akakaza, Kinyaga, Bumbogo	Umurabyo, Akabahizi, Gitega	Kanunga, Kora, Gitega
6	Kinyambo, Kora, Gitega	Rugari, Kora, Gitega	Rugano, Kora, Gitega
7	Kingasire, Karuruma, Gatsata	Kanunga, Kora, Gitega	Ituze, Akabeza, Gitega
8	Nyamabuye, Kimisagara, Kimisagara	Mpazi, Akabeza, Gitega	Mpazi, Katabaro, Kimisagara
9	Kumuyange, Karuruma, Gatsata	Ituze, Akabeza, Gitega	Akamahoro, Katabaro, Kimisagara
10	Jyambere, Karambo, Gatenga	Isangano, Kora, Gitega	Vugizo, Akabahizi, Gitega
11	Rebero, Karambo, Gatenga	Rugano, Kora, Gitega	Isangano, Kora, Gitega
12	Nyaburanga, Akabahizi, Gitega	Nyaburanga, Akabahizi, Gitega	Nyenyeri, Akabahizi, Gitega
13	Rusenyi, Murama, Kinyinya	Nyenyeri, Akabahizi, Gitega	Izuba, Akabahizi, Gitega
14	Muganza, Kimisagara, Kimisagara	Inkurunziza, Kimisagara, Kimisagara	Umurabyo, Akabahizi, Gitega
15	Ubumwe, Akabahizi, Gitega	Buhoro, Kimisagara, Kimisagara	Ingenzi, Kigarama, Gitega
16	Ingenzi, Kigarama, Gitega	Ubwiyunge, Akabahizi, Gitega	Akishuri, Katabaro, Kimisagara
17	Cercle Sportif, Kiyovu, Nyarugenge	Mpazi, Katabaro, Kimisagara	Umuseke, Akabahizi, Gitega
18	Rugano, Kora, Gitega	Akamahoro, Katabaro, Kimisagara	Akinyambo, Akabeza, Gitega
19	Byimana, Masoro, Ndera	Izuba, Akabahizi, Gitega	Buhoro, Kamuhoza, Kimisagara
20	Amayaga, Akabeza, Gitega	Nyakabingo, Kimisagara, Kimisagara	Ubwiyunge, Akabahizi, Gitega
21	Iterambere, Akabahizi, Gitega	Bwiza, Kimisagara, Kimisagara	Umucyo, Akabahizi, Gitega

[37] For indoor overcrowding measures we rank the median density per village

22	Ubukorikori, Akabahizi, Gitega	Ihuriro, Kimisagara, Kimisagara	Umuhoza, Kigarama, Gitega
23	Nyarubande, Niboye, Niboye	Iterambere, Akabahizi, Gitega	Amahumbezi, Katabaro, Kimisagara
24	Kivu, Nyarurama, Kigarama	Karambi, Kimisagara, Kimisagara	Amayaga, Akabeza, Gitega
25	Uburezi, Kinyange, Gitega	Umucyo, Akabahizi, Gitega	Umurava, Kigarama, Gitega
26	Ubumwe, Kora, Gitega	Akishuri, Katabaro, Kimisagara	Uburezi, Kinyange, Gitega
27	Gakokobe, Bwerankori, Kigarama	Ubumwe, Kora, Gitega	Ubumwe, Kora, Gitega
28	Akisoko, Nyamugari, Gatsata	Ingenzi, Kigarama, Gitega	Buhoro, Kimisagara, Kimisagara
29	Akishuri, Katabaro, Kimisagara	Kinyambo, Kora, Gitega	Umubano, Kigarama, Gitega
30	Umurava, Kigarama, Gitega	Amahumbezi, Katabaro, Kimisagara	Kinyambo, Kora, Gitega
31	Mpazi, Akabeza, Gitega	Ubumwe, Katabaro, Kimisagara	Iterambere, Akabahizi, Gitega
32	Vugizo, Akabahizi, Gitega	Akinyambo, Akabeza, Gitega	Akishinge, Katabaro, Kimisagara
33	Sangwa, Kimisagara, Kimisagara	Kimisagara, Kimisagara, Kimisagara	Kove, Kimisagara, Kimisagara
34	Gihanga, Akabahizi, Gitega	Buhoro, Kamuhoza, Kimisagara	Ubumwe, Katabaro, Kimisagara
35	Kanunga, Kora, Gitega	Uruyange, Katabaro, Kimisagara	Nyaburanga, Akabahizi, Gitega
36	Kamabuye, Karambo, Gatenga	Ubukorikori, Akabahizi, Gitega	Nyakabingo, Kimisagara, Kimisagara
37	Byimana, Kigarama, Kigarama	Kove, Kimisagara, Kimisagara	Ntaraga, Kamuhoza, Kimisagara
38	Gitwa, Akabeza, Gitega	Byimana, Kimisagara, Kimisagara	Bwiza, Kimisagara, Kimisagara
39	Nyakabande, Nyamabuye, Gatsata	Akishinge, Katabaro, Kimisagara	Uruyange, Katabaro, Kimisagara
40	Rwintare, Gasharu, Nyamirambo	Uburezi, Kinyange, Gitega	Karambi, Kimisagara, Kimisagara
41	Gikumba, Nyabikenke, Bumbogo	Amayaga, Akabeza, Gitega	Amahoro, Kimisagara, Kimisagara
42	Ruhuka, Karambo, Gatenga	Inkingi, Tetero, Muhima	Inkurunziza, Kimisagara, Kimisagara
43	Taba, Murama, Kinyinya	Umuhoza, Kigarama, Gitega	Kigarama, Katabaro, Kimisagara
44	Kora, Kora, Gitega	Umurava, Kigarama, Gitega	Byimana, Kimisagara, Kimisagara
45	Kimisange, Bwerankori, Kigarama	Umubano, Kigarama, Gitega	Kigina, Kimisagara, Kimisagara
46	Runyonza, Nyamabuye, Gatsata	Ntaraga, Kamuhoza, Kimisagara	Ubukorikori, Akabahizi, Gitega
47	Mpazi, Katabaro, Kimisagara	Gaseke, Kimisagara, Kimisagara	Munini, Kamuhoza, Kimisagara

48	Umubano, Kigarama, Gitega	Indamutsa, Tetero, Muhima	Ihuriro, Kimisagara, Kimisagara
49	Mugina, Katabaro, Kimisagara	Munini, Kamuhoza, Kimisagara	Kabusunzu, Munanira I, Nyakabanda
50	Kabusunzu, Munanira I, Nyakabanda	Kigarama, Katabaro, Kimisagara	Kimisagara, Kimisagara, Kimisagara
51	Munini, Nyakabanda I, Nyakabanda	Ubusabane, Katabaro, Kimisagara	Isano, Kinyange, Gitega
52	Rugarama, Rugarama, Nyamirambo	Amahoro, Kimisagara, Kimisagara	Ntaraga, Munanira I, Nyakabanda
53	Akinyambo, Akabeza, Gitega	Sano, Kimisagara, Kimisagara	Inkingi, Tetero, Muhima
54	Imena, Bwerankori, Kigarama	Kigina, Kimisagara, Kimisagara	Rutunga, Kamuhoza, Kimisagara
55	Kagarama, Kagugu, Kinyinya	Kabusunzu, Munanira I, Nyakabanda	Ubusabane, Katabaro, Kimisagara
56	Amahumbezi, Katabaro, Kimisagara	Isano, Kinyange, Gitega	Nunga, Kamuhoza, Kimisagara
57	Bamporeze Ii, Busanza, Kanombe	Ntaraga, Munanira I, Nyakabanda	Gaseke, Kimisagara, Kimisagara
58	Kabutare, Bwerankori, Kigarama	Rutunga, Kamuhoza, Kimisagara	Indamutsa, Tetero, Muhima
59	Iriba, Ngoma, Kicukiro	Ubumwe, Akabahizi, Gitega	Mumararungu, Kabuguru I, Rwezamenyo
60	Muhuza, Kabuguru I, Rwezamenyo	Kora, Kora, Gitega	Ubumwe, Akabahizi, Gitega
61	Ururembo, Kibenga, Ndera	Nunga, Kamuhoza, Kimisagara	Akabeza, Kimisagara, Kimisagara
62	Akarubimbura, Nyamugari, Gatsata	Mumararungu, Kabuguru I, Rwezamenyo	Nyagasozi, Munanira I, Nyakabanda
63	Inyambo, Agatare, Nyarugenge	Munanira, Munanira I, Nyakabanda	Umubano, Katabaro, Kimisagara
64	Bisambu, Nyarurama, Gatenga	Akabeza, Kimisagara, Kimisagara	Munanira, Munanira I, Nyakabanda
65	Akamahoro, Katabaro, Kimisagara	Tetero, Tetero, Muhima	Sano, Kimisagara, Kimisagara
66	Rugari, Kora, Gitega	Karwarugabo, Kamuhoza, Kimisagara	Ubumwe, Gacyamo, Gitega
67	Nyabugogo, Kimisagara, Kimisagara	Muhoza, Kabuguru I, Rwezamenyo	Karwarugabo, Kamuhoza, Kimisagara
68	Rugoro, Karuruma, Gatsata	Ikaze, Kabeza, Muhima	Kora, Kora, Gitega
69	Ubumwe, Gacyamo, Gitega	Umwezi, Kabeza, Muhima	Isangano, Kinyange, Gitega
70	Isano, Kamukina, Kimihurura	Umubano, Katabaro, Kimisagara	Umurinzi, Katabaro, Kimisagara

71	Mpazi, Kora, Gitega	Nyagasozi, Munanira I, Nyakabanda	Ihuriro, Kinyange, Gitega
72	Isano, Kinyange, Gitega	Rurembo, Munanira I, Nyakabanda	Kigabiro, Munanira Ii, Nyakabanda
73	Amahoro, Kimisagara, Kimisagara	Murambi, Kabuguru I, Rwezamenyo	Ubusabane, Kabuguru Ii, Rwezamenyo
74	Kove, Kimisagara, Kimisagara	Ubusabane, Kabuguru Ii, Rwezamenyo	Kivumu, Kora, Gitega
75	Sabaganga, Nyanza, Gatenga	Ubumwe, Gacyamo, Gitega	Muhoza, Kabuguru I, Rwezamenyo
76	Runyonza, Kibenga, Ndera	Kivumu, Kora, Gitega	Ituze, Kamuhoza, Kimisagara
77	Umubano, Katabaro, Kimisagara	Muhuza, Kabuguru I, Rwezamenyo	Umwezi, Kabeza, Muhima
78	Kamabuye, Nyarurama, Kigarama	Umurinzi, Katabaro, Kimisagara	Murambi, Kabuguru I, Rwezamenyo
79	Umwezi, Kabeza, Muhima	Nyagakoki, Kimisagara, Kimisagara	Muhuza, Kabuguru I, Rwezamenyo
80	Ruhango, Ruriba, Kigali	Ituze, Kamuhoza, Kimisagara	Rurembo, Munanira I, Nyakabanda
81	Ituze, Akabeza, Gitega	Agakomeye, Nyamabuye, Gatsata	Nyakabande, Nyamabuye, Gatsata
82	Murambi, Kabuguru I, Rwezamenyo	Kigabiro, Munanira Ii, Nyakabanda	Inganzo, Katabaro, Kimisagara
83	Kiberinka, Rugarama, Nyamirambo	Uwagatovu, Nyamabuye, Gatsata	Sangwa, Kigarama, Gitega
84	Mumararungu, Kabuguru I, Rwezamenyo	Ingoro, Tetero, Muhima	Umucyo, Kigarama, Gitega
85	Rubungo, Kinyaga, Bumbogo	Inganzo, Katabaro, Kimisagara	Busasamana, Kamuhoza, Kimisagara
86	Uruhongore, Kamatamu, Kacyiru	Isangano, Kinyange, Gitega	Intsinzi, Gacyamo, Gitega
87	Karambi, Kimisagara, Kimisagara	Intsinzi, Gacyamo, Gitega	Gitwa, Akabeza, Gitega
88	Kabirizi, Amahoro, Muhima	Kigabiro, Kamuhoza, Kimisagara	Agakomeye, Nyamabuye, Gatsata
89	Kamuna, Muyange, Kagarama	Busasamana, Kamuhoza, Kimisagara	Nyabugogo, Kimisagara, Kimisagara
90	Rebero, Nyarurama, Kigarama	Intiganda, Tetero, Muhima	Kibaya, Nyamabuye, Gatsata
91	Kigarama, Katabaro, Kimisagara	Ihuriro, Kinyange, Gitega	Kanyange, Munanira Ii, Nyakabanda
92	Umuhoza, Kigarama, Gitega	Ruvumero, Nyamabuye, Gatsata	Uwagatovu, Nyamabuye, Gatsata
93	Muhabura, Cyivugiza, Nyamirambo	Rurama, Kamuhoza, Kimisagara	Sangwa, Kimisagara, Kimisagara
94	Amizero, Amahoro, Muhima	Gitwa, Akabeza, Gitega	Intiganda, Tetero, Muhima
95	Gasiza, Nyakabanda I,	Ituze, Kabeza, Muhima	Runyonza, Nyamabuye, Gatsata

	Nyakabanda		
96	Rugali, Nonko, Nyarugunga	Kanyange, Munanira Ii, Nyakabanda	Kigabiro, Kamuhoza, Kimisagara
97	Rutunga, Kamuhoza, Kimisagara	Sangwa, Kigarama, Gitega	Birama, Kimisagara, Kimisagara
98	Rutagara I, Nzove, Kanyinya	Nyabugogo, Kimisagara, Kimisagara	Tetero, Tetero, Muhima
99	Sano, Kimisagara, Kimisagara	Runyonza, Nyamabuye, Gatsata	Gakaraza, Kimisagara, Kimisagara
100	Kimisagara, Kimisagara, Kimisagara	Nyakabande, Nyamabuye, Gatsata	Rurama, Kamuhoza, Kimisagara

Annex 2: Top 10 overcrowded villages in each of five secondary cities, ranked by three measures

Table 4: Huye

Rank	Indoor Overcrowding (Pop/ TFA)	Outdoor Density (Pop/Outdoor built-up area excl buildings)	Total Density (Pop/(TFA in buildings + outdoor built-up area)
1	Gasenyi, Tumba	Impuhwe, Tumba	Kabeza, Tumba
2	Rimba, Tumba	Kabeza, Tumba	Impuhwe, Tumba
3	Kigarama, Tumba	Nyarurembo, Tumba	Nyarurembo, Tumba
4	Berwa, Tumba	Urugwiro, Tumba	Agateme, Tumba
5	Karambi, Ngoma	Agateme, Tumba	Urugwiro, Tumba
6	Akakanyamanza, Tumba	Agasengasenge, Tumba	Agasengasenge, Tumba
7	Abizerwa, Tumba	Rebero, Tumba	Rebero, Tumba
8	Nyagapfizi, Ngoma	Amahoro, Tumba	Amahoro, Tumba
9	Agasharu, Tumba	Byimana, Tumba	Byimana, Tumba
10	Ubwiyunge, Tumba	Kigarama, Tumba	Kigarama, Tumba

Table 5: Muhanga

Rank	Indoor Overcrowding (Pop/ TFA)	Outdoor Density (Pop/Outdoor built-up area excl buildings)	Total Density (Pop/(TFA in buildings + outdoor built-up area)
1	Kinyami, Shyogwe	Kamugina, Nyamabuye	Kavumu, Nyamabuye
2	Musezero, Shyogwe	Nyarucyamu I, Nyamabuye	Kamugina, Nyamabuye
3	Nyarusiza, Nyamabuye	Kavumu, Nyamabuye	Nyarucyamu I, Nyamabuye
4	Nyakabingo, Shyogwe	Nyarucyamu Iii, Nyamabuye	Gatika, Nyamabuye
5	Biti, Nyamabuye	Gatika, Nyamabuye	Nyarucyamu Iii, Nyamabuye
6	Munyinya, Shyogwe	Biti, Nyamabuye	Biti, Nyamabuye
7	Nyarutovu, Nyamabuye	Ruvumera, Nyamabuye	Nyarucyamu Ii, Nyamabuye
8	Kavumu, Shyogwe	Nyarucyamu Ii, Nyamabuye	Ruvumera, Nyamabuye
9	Nete, Nyamabuye	Rutenga, Nyamabuye	Ruhina, Shyogwe
10	Gasenyi, Nyamabuye	Ruhina, Shyogwe	Rutenga, Nyamabuye

Table 6: Nyagatare

Rank	Indoor Overcrowding (Pop/ TFA)	Outdoor Density (Pop/ Outdoor area)	Total Density (TFA density + Outdoor densities)
1	Nkonji, Nyagatare	Nyagatare I, Nyagatare	Nyagatare I, Nyagatare
2	Rutaraka, Nyagatare	Nyagatare Ii, Nyagatare	Nyagatare Ii, Nyagatare
3	Burumba, Nyagatare	Nyagatare Iii, Nyagatare	Nyagatare Iii, Nyagatare
4	Mirama I, Nyagatare	Barija A, Nyagatare	Barija A, Nyagatare
5	Nyagatare Ii, Nyagatare	Barija B, Nyagatare	Barija B, Nyagatare
6	Gihorobwa, Nyagatare	Kinihira, Nyagatare	Kinihira, Nyagatare
7	Barija A, Nyagatare	Mirama Ii, Nyagatare	Mirama Ii, Nyagatare
8	Kinihira, Nyagatare	Mirama I, Nyagatare	Mirama I, Nyagatare
9	Barija B, Nyagatare	Cyabayaga, Nyagatare	Burumba, Nyagatare
10	Nyagatare Iii, Nyagatare	Burumba, Nyagatare	Gihorobwa, Nyagatare

Table 7: Rubavu

Rank	Indoor Overcrowding (Pop/ TFA)	Outdoor Density (Pop/ Outdoor area)	Total Density (TFA density + Outdoor densities)
1	Ihuriro, Gisenyi	Karisimbi, Gisenyi	Karisimbi, Gisenyi
2	Majengo, Gisenyi	Murisanga, Gisenyi	Murisanga, Gisenyi
3	Kabuga, Gisenyi	Igisubizo, Gisenyi	Igisubizo, Gisenyi
4	Umurava, Gisenyi	Ubutabazi, Gisenyi	Ubutabazi, Gisenyi
5	Cyanika, Rugerero	Urumuri, Gisenyi	Amajyambere, Gisenyi
6	Butangi, Rugerero	Amajyambere, Gisenyi	Urumuri, Gisenyi
7	Gakoro, Rugerero	Kaminuza, Gisenyi	Amataba, Gisenyi
8	Kiroji, Rugerero	Amataba, Gisenyi	Ubutabera, Gisenyi
9	Kabere Ii, Rubavu	Ubutabera, Gisenyi	Kaminuza, Gisenyi
10	Bwiru, Rubavu	Itangazamakuru, Gisenyi	Urubyiruko, Gisenyi

Table 8: Rusizi

Rank	Indoor Overcrowding (Pop/ TFA)	Outdoor Density (Pop/ Outdoor area)	Total Density (TFA density + Outdoor densities)
1	Mucyamo, Kamembe	Munyinya, Kamembe	Munyinya, Kamembe
2	Kanoga, Gihundwe	Murambi, Kamembe	Murambi, Kamembe
3	Nyakayonga, Kamembe	Burunga, Kamembe	Karangiro, Gihundwe
4	Shagasha, Gihundwe	Karangiro, Gihundwe	Burunga, Kamembe
5	Ntemabiti, Kamembe	Nyakayonga, Kamembe	Nyakayonga, Kamembe
6	Rubenga Ii, Gihundwe	Kadasomwa, Kamembe	Cyapa, Gihundwe
7	Karitasi, Gihundwe	Kannyogo, Kamembe	Kannyogo, Kamembe
8	Burunga, Gihundwe	Cyapa, Kamembe	Cyapa, Kamembe
9	Karangiro, Kamembe	Cyapa, Gihundwe	Kadasomwa, Kamembe
10	Kamuhirwa, Kamembe	Umuganda, Kamembe	Burunga, Gihundwe

Annex 3: Urban population statistics and densities in Rwanda

Kigali has the highest population and population densities of any urban area in Rwanda. Much of Kigali’s density is driven by the high proportion of unplanned settlements. Of note is the increase in population density in rural parts of the city suggesting settlement away from the city centre and migration to rural parts of the city from other areas in the country.

Table 9: Population density over time in urban and rural Kigali

Area	Population 2015 (Source: WorldPop)	Area (km2)[38]	Avg. Density (people/ km2) (Source: WorldPop, 2015)	Avg Density (people/ km2): Census 2012
Kigali urban[39]	971,097	514	1,890	1,673
Kigali rural	333,321	249	1,341	1,100

Overall, while areas closer to the city record higher building heights, on average, the total population has decreased over time suggesting two trends: more specialized land uses close to the CBD and a gradual movement of the population into peripheral areas (see Table 2). Regarding the first trend, most tall buildings in and around Kigali are commercial rather than residential. Indeed, many formerly residential areas have given way to commercial areas in areas closer to the city centre.[40] This is despite the fact that the total number of residential buildings have increased in urban Kigali as a whole.[41]

Rwanda also recognizes six official secondary cities across the country: Rubavu, Rusizi, Huye, Musanze, Muhanga and Nyagatare. The largest of these cities in terms of population is Rubavu, located in North Kivu close to the DRC border, while the smallest is Nyagatare, located in the east (see Table 4). Overall, secondary cities are estimated to make up approximately 22% of Rwanda's urban population, compared to Kigali which makes up almost half.[42]

[38] See Republic of Rwanda, *National Roadmap for Green Secondary City Development*, 2015, Kigali for detailed information on the borders demarcating secondary cities. Sectors corresponding to each city were as follows: [1] Rubavu: Rubavu, Gisenyi, Rogerero, Nyundo, Nyakiriba, Kanama, Nyamyumba; [2] Musanze: Cyure, Musanze, Muhoza; Musanze; [3] Rusizi: Gihundwe, Kamembe; [4] Muhanga: Cyeza, Shyogwe, Nyamabuye; [5] Huye: Ngoma, Tumba, Mbazi; & [6] Nyagatare: Rwempasha, Nyagatare, Tabagwe

[39] We use village data from NISR to (i) identify urban parts of kigali and (ii) to estimate the size and population of these urban areas in 2020 (see: http://geodata-nisr.opendata.arcgis.com/datasets/32e1f5c0f5974681ac32d31a9f2cf166_0)

[40] See pp 30 for the change in the residential and commercial buildings between 2008/2009 and 2015.

[41] See pp 23, Murray & Bachofer; there was a 22.7 percentage point increase in the number of rudimentary residential houses, a 42 percentage point increase in bungalows, and a 129 percentage point increase in villas between 2008/2009 and 2015.

[42] World Bank, Rwanda Economic Update: Edition No. 11, December 2017, pp 26 - http://documents.worldbank.org/curated/en/357911513632697178/pdf/122107-WP-PUBLIC-Rwanda-Economic-Update-FINAL.pdf

Table 10: Population and density in secondary cities

Area	Population 2018 (Source: WorldPop)	Total Area (km2)[43]	Avg. Density (people/ km2)(Source: WorldPop 2018)	Avg Density (people/ km2): Census 2012
Gisenyi (Rubavu)	339,690	189	1,798	1,960
Musanze	164,127	113	1,451	1,333
Rusizi	56,033	40	1,390	1,485
Muhanga	133,771	128	1,044	1,092
Huye	103,276	83	1,243	1,285
Nyagatare	176,897	460	385	250.3

Data on building heights is unavailable for secondary cities, although some data is available regarding the built up area. Data purchased by IGC indicate that the built up areas in each of the areas are a small fraction of the overall geographic area in each of these cities. As highlighted in Table 11, the total built up area is highest for the city of Rubavu and Muhanga - although these make up a tiny portion of the overall city area.

[43] See Republic of Rwanda, *National Roadmap for Green Secondary City Development*, 2015, Kigali for detailed information on the borders demarcating secondary cities. Sectors corresponding to each city were as follows: [1] Rubavu: Rubavu, Gisenyi, Rogerero, Nyundo, Nyakiriba, Kanama, Nyamyumba; [2] Musanze: Cyure, Musanze, Muhoza; Musanze; [3] Rusizi: Gihundwe, Kamembe; [4] Muhanga: Cyeza, Shyogwe, Nyamabuye; [5] Huye: Ngoma, Tumba, Mbazi; & [6] Nyagatare: Rwempasha, Nyagatare, Tabagwe

Annex 4: Translation of percentiles in Figure 7 and Figure 12 into densities

In Table 11 we translate the 95th and 99th percentiles of composite indoor/outdoor densities shown in Figure 7 for Kigali and Figure 12 for secondary cities, into actual figures for people per square metre (of TFA plus outdoor built-up area). Whilst it makes sense that Kigali is denser than almost all secondary cities, and that Rubavu's density is borne out in EICV data, the figures are not strictly comparable to each other because the area of pixels does not cover the entire district but only the subset of the district that is covered with major built up area and which our building footprint data covers. However, it is worth noting that for Kigali and Nyagatare, the 99th percentile is around twice as dense as the 95th percentile; the differential is not as great for Rubavu, Rusizi and Muhanga. However the 99th percentile is multiple times more dense than the 80th percentile.

Table 11: Population per square metre for composite indoor/outdoor measure (total floor area plus outdoor built-up area) for each city by selected pixel percentiles

	Kigali	Rubavu	Rusizi	Nyagatare	Muhanga	Huye
99 percentile	0.016	0.017	0.006	0.006	0.008	0.008
95 percentile	0.008	0.014	0.004	0.003	0.006	0.005
80 percentile	0.002	0.006	0.002	0.001	0.002	0.002

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