Assessing the potential impacts of COVID-19 in Brasil: Mobility, Morbidity and Impact to the Health System

Flávio C Coelho[a,b], Raquel M Lana[c,b], Oswaldo G Cruz[c,b], Claudia T Codeço[c,b], Daniel Villela[c,b], Leonardo S Bastos[c,b,d], Ana Pastore y Piontti[e], Jessica T Davis[e], Alessandro Vespignani[e,f], Marcelo F C Gomes[c,b,*]

[a] *Escola de Matemática Aplicada, Fundação Getulio Vargas, Rio de Janeiro, Brazil*
[b] *Núcleo de Métodos Analíticos para Vigilância em Saúde Pública, Rio de Janeiro, Brazil*
[c] *Fiocruz, Scientific Computing Program, Rio de Janeiro, Brazil*
[d] *London School of Hygiene and Tropical Medicine, London, UK*
[e] *Laboratory for the Modeling of Biological and Socio-technical Systems, Northeastern University, Boston, USA*
[f] *ISI Foundation, Turin, Italy*

Abstract

The two largest Brazilian cities, Rio de Janeiro and São Paulo, have declared community transmission of COVID-19 on mid March, 2020. In this study we estimated the most vulnerable areas in Brazil for COVID-19, both in terms of risk of introduction and risk of mortality associated with social vulnerability. We explore the most likely routes of spread through the country, from the already exposed cities, according to human mobility statistics. The resulting maps should help authorities in their efforts to prioritize actions and if resource allocation to mitigate the effects of the pandemic.

Keywords: COVID-19, pandemics, Brazil

1. Introduction

As of 18 March 2020, the pandemic of COVID-19 has reached 166 countries with 191,127 confirmed cases and 7,807 deaths, globally [1]. The first imported case of COVID-19 was confirmed in Brazil on February 26, 2020, in the city of São Paulo [2], after 2 months of the alert issued by China. All Brazilian states

*Corresponding author
Email address: marcelo.gomes@fiocruz.br (Marcelo F C Gomes)

are currently investigating suspected cases of the disease, while 16 states and the Federal District have already confirmed a total of 428 cases (11,278 under investigation) [3].

São Paulo and Rio de Janeiro have declared community transmission in *2020-03-13* [4, 5, 6]. As of *2020-03-18*, the former had registered 240 COVID-19 confirmed cases, 4 deaths, and 5,334 remain under investigation [3]. The latter registered 45 confirmed cases, 0 deaths and 1,254 under investigation, according to the Ministry of Health [3]. São Paulo and Rio de Janeiro are the most populous metropolitan areas of Brazil, with millions of people living in precarious conditions, while being the country's main transportation hubs for both local and international flow of individuals, through which other pathogens were introduced in the country, such as H1N1 in 2009 and various strains of the dengue virus [7].

This study analyzes the COVID-19 spreading risk within the country starting from outbreaks taking place in Rio de Janeiro and São Paulo. We assume a scenario with no mobility restrictions. We are aware that such efforts are ongoing, but our results stress the importance of intensifying them, since population support and adherence to health authorities recommendations is still an open question.

Brazil presents strong spatial heterogeneity in terms of demography, age distribution, access to public health, and poverty indices. Such heterogeneity should affect the impact of COVID-19 epidemic countrywide, since they are related to transmissibility, letality and vulnerability. In this article we intend to provide quantitative metrics to identify regions that are both vulnerable to the arrival of COVID-19 during the start of country-based spread and which are also vulnerable to health care infrastructure overload. We attempt to determine the most vulnerable regions of the country based on national mobility patterns, demographic characteristics of the population and the capacity of local hospitals and other health units to handle the kinds of services demanded by severe cases of COVID-19.

2. Methods

2.1. Data

The analyses were done at the micro-regional administrative level. Brazil has 558 such regions, with population varying from 13 million in the metropolitan area of São Paulo to 2,703 in Fernando de Noronha island, in Pernambuco state. To measure the mobility between micro-regions, we used daily air travel statistics from the Official Airline Guide (OAG) [8] for long-range mobility, and shorter distance pendular travels from the 2010 national census (IBGE) [9].

For each micro-region, demographic data stratified by age were obtained from the 2000 and 2010 national censuses [9] and were used to project the population in 2020 per age group using a geometric growth model.

Infrastructure for COVID-19 hospitalization per micro-region was obtained from DataSUS [10]. We calculated the number of standard hospital beds and complementary beds (Intensive Care Unit and Intermediate Unit) available for each micro-region [10], from the public (SUS) and private (non-SUS) sectors, per 10,000 inhabitants.

2.2. Effective distance

To assess the probability of COVID-19 spread within the Brazilian territory in the absence of mobility restrictions, we calculated the effective distance ($E_f(i,j)$) between micro-regions using air travel data. The value of $E_f(i,j)$ is a measure of proximity between two micro-regions i and j created by the flow of people, which is known to have strong correlation with the time to importation of infectious diseases into new territories from a well-defined origin [11, 12], particularly so for direct transmission diseases. To facilitate comparison between different scenarios, we also calculate a relative effective distance index (e_f), dividing E_f by the distance to the nearest destination: $e_f(i,j) = E_f(i,j)/\min_j\{E_f(i,j)\}$. We computed E_f from São Paulo and Rio de Janeiro separately in order to assess the potential contribution of each. This information is mapped into micro-region origin-destination pairs by summing

over the corresponding airports serving each micro-region based on its municipality of reference.

2.3. Outbreak probability

To calculate the probability of outbreak in each micro-region m, we make use of the reproduction number R_0 and the prevalence I_m during the infection period, giving rise to the expression: $p_{epi} = 1 - (1/R_0)^{I_m}$. In which $I_m = k\tau \sum_i f_{i,m} I_i/N_i$, where $f_{i,m}$ is the total number of travellers arriving from micro-regions with reported cases i into micro-region m, and the notified prevalence in the source region i is given by the incidence I_i/N_i times the infection duration τ and a scaling parameter k, to account for number of undetected asymptomatic participating in the transmission. The parameter R_0 is the basic reproduction number [13]. For the purpose of the results shown, we set $R_0 = 2.5$, which is compatible with previous studies [14, 15, 16, 17].

We computed the outbreak probability per micro-region using two scenarios:

First generation of outbreaks. We assume community transmission taking place only in Rio de Janeiro and São Paulo, with 100 cases notified in a week at each municipality. Prevalence of infection is calculated by multiplying the notification count by an expansion factor $k = 10$ to take into account asymptomatic and under reported cases [18]. This number is then multiplied by the infection duration $\tau = 8$ days [19], resulting in 8000 prevalent infections (infected $\times$ infection duration) in each of the two cities of origin.

Number of travellers per day between micro-regions was computed by adding the air travel data (used to calculate effective distance) and pendular mobility for work and study extracted from the 2010 Census [9]. The inclusion of pendular mobility is important to assess the spreading process between geographically close micro-regions, while still preserving data-driven flow estimates.

Second generation of outbreaks. In this scenario, we assume that all micro-regions with $p_{epi} \geq 0.5$ in the first scenario actually had outbreaks. In each of them, the prevalence is set to the same level stated before for Rio de Janeiro and

São Paulo. Then we compute p_{epi} again, to compute the micro-regions most likely to develop outbreaks in this second generation. Those two outbreaks generations should not be confused with the infections process generation time.

It should be noted that this is a baseline scenario, that does not take into account the ongoing interventions affecting mobility, nor demographic and environmental effects that may affect the magnitude of R_0. It describes the expected initial momentum of the spread in Brazil.

3. Results

3.1. Effective distance from Rio de Janeiro and São Paulo in the absence of travel restrictions

Figures 1(a-b) show the relative effective distance of Brazilian micro-regions from São Paulo and Rio de Janeiro generated by the typical travel movement by air. The majority of state capitals are among the closest areas, together with some important touristic destinations (such as Foz do Iguaçu/PR and Porto Seguro/BA), as well as important urban and industrial centers outside metropolitan areas such as Itajaí/SC and Uberlândia/MG. São Paulo shows a more central role than Rio de Janeiro, evidenced by the larger proportion of closer destinations, which means that it poses a greater risk for earlier and widespread case importation to other states.

3.2. Probability of outbreak

Figure 1(c) shows the probability of outbreak triggered by the increased prevalence of COVID-19 in Rio de Janeiro and São Paulo, in the absence of travel restrictions. The most likely micro-regions to develop an outbreak are the geographic neighboring regions of São Paulo and Rio de Janeiro as well as capital cities of Brasilia/DF, Belo Horizonte/MG, Porto Alegre/RS, and Curitiba/PR. For a complete list, see the Supplementary material.

Figure 1(d) shows the probability of outbreak in a secondary wave of travels, conditioned on the establishment of transmission in the micro-regions at

highest risk during the first phase. After this secondary wave, the establishment of COVID-19 transmission is very likely in all micro-regions along the coast, with an almost contigous range from Porto Alegre/RS (in the south) to Salvador/BA, as well the neighboring areas of Recife/PE and Fortaleza/CE (in the norhteast). To the west, the neighboring areas of Foz do Iguaçu/PR, Cuiabá/MT, Brasilia/DF, and Goiânia/GO are also at high risk.

Health System Overload. Figure 2 shows the availability of hospital beds per micro-region. They indicate the capacity to cope with the increased demand. According to data published by the OECD Health Statistics 2019, the average number of beds per 10,000 people in the OECD countries in 2017 was 47 [20]. Data extracted in 2020 from the Brazilian Ministry of Health database [10] reported a total of $435,258$ beds available in the country. Based on projected population for the year 2020, this amounts to about 22 beds per $10,000$ inhabitants. When stratified by micro-regions, it becomes clear the great heterogeneity of those resources across the national territory. The median for the 558 micro-regions is of 19 beds per 10,000, with the lower 5% having only 6 and the 95% percentile presenting 41 beds per $10,000$ people. This disparity poses an important challenge for resource allocation in the case of diseases that have the potential to spread over a vast part of the territory as shown.

Current data indicates that COVID-19 have an increased case fatality rate (with all the caveats of CFR during the early phase of a novel virus epidemic) for individuals above 60 years of age, with numbers suggesting about 15% CFR for those above 80 years old [21]. Since São Paulo is currently presenting the highest number of confirmed and suspect cases in Brazil [3] and the effective distance distribution shows that it poses the worst-case scenario of time-to-seeding of other micro-regions (see Figs. 1a-b and Fig. 2a for reference), we focused on that source for analysing the relation between effective distance and percentage of population above 60 years old (Fig. 2b), number of overall hospital beds and complementary beds (ICU and intermediary care) per 10,000 individuals by type of service access (Figs. 2c-d).

For the micro-regions in the airline mobility network, the median fraction of population above 60 years is 10% (90% CI [5% – 14%]), with median overall and complementary beds rate of 23 [14 – 36] and 3 [0.3 – 5.7], respectively. When we focus on the 20 closest micro-regions to São Paulo in that network plus the source, the median fraction of population above 60 yo. is 10% (IQ range [8% – 11%]), while the number of overall hospital beds median rate is 26 (IQ range [23 – 28]), and the complementary ones is 4.6 (IQ range [4.1 – 5.6]. We see that, contrary to common belief that metropolitan areas (which comprises the vast majority of those 21 locations) are generally better covered in terms of health care facilities, this seems to be the case only for ICU and intermediate care beds.

According to the National Agency of Supplementary Health (*Agência Nacional de Saúde Suplementar*, ANS), in January 2020 about 24% of the population had some type of health insurance, meaning that around 75% of the Brazilian population rely on the universal public health system (SUS). When stratified by SUS and non SUS overall beds, the median ratio between the two at the micro-regions is 81% [52% – 100%], indicating that most regions have an appropriate ratio based on the population health care access profile average. In terms of complementary beds, the median is incompatible with coverage (65% are SUS), and disparity is significant (90% CI [33% – 100%]. For the 20 closest micro-regions from São Paulo in the airline network plus the source, the scenario is particularly worrisome, since the median is 56% ([34% – 68%]). In Fig. 3 we present the spatial distribution of percentage of population above 60 (a) and 80 (b) years old, as well as the overall (c) and complementary (d) number of beds by 10,000 inhabitants. It is clear that several regions combine relatively high percentage of population at risk and relatively low rate of hospital beds, which is an important indication of vulnerability for overcrowding.

4. Discussion

The probabilistic analysis of the initial spread of COVID-19 presented here has intentionally disregarded the effects of any efforts at social distancing, and mobility restrictions. In this respect, it represents a worst case scenario which is not very far from reality, since the implementation of control measures and the establishment of behavioral changes in the population at large is likely to take more than a couple of weeks and people adherence is uncertain, specially so for workers that do not have payed leave or whose work limits the possibility of work-from-home. On the other hand, we have tried to be conservative with the parameters of the model such as the R_0 of 2.5 and the initial number of reported cases in Rio and São Paulo, which are already larger than the hundred cases we postulated.

We believe that after the two spread waves described here, the effects of the containment efforts by health authorities will begin to influence the transmission dynamics, but by then the country will be managing a considerable number of (potentially serious) cases, leading to a big impact on public and private health services. We have demonstrated that the heterogeneous per-capita distribution of hospital beds is likely to cause an uneven burden distribution which can be minimized by the authorities through preemptive differential investments in the the public health care system (SUS). We hope the analysis presented here can help the governments decision-making regarding optimal course of action and resource allocation. Although these results are specific to Brazil, they can also help guide similar analysis in other countries.

References

[1] World Health Organization . Coronavirus disease (covid-19) outbreak. 2020. URL: `https://www.who.int/emergencies/diseases/novel-coronavirus-2019`.

[2] Ministério da Saúde . Linha do tempo coronavírus. 2020. URL: `http://coronavirus.saude.gov.br/linha-do-tempo`.

[3] Ministério da Saúde . Notificação de casos pelo novo coronavírus (COVID-19) - Plataforma Integrada de Vigilância em Saúde. 2020. URL: http://plataforma.saude.gov.br/novocoronavirus/.

[4] Brasil confirma transmissão comunitária de coronavírus; entenda o que é. 2020. URL: https://noticias.uol.com.br/saude/ultimas-noticias/redacao/2020/03/13/brasil-confirma-transmissao-comunitaria-de-coronavirus-entenda-o-que-e.htm.

[5] Capitais de SP e RJ têm transmissão comunitária do coronavírus. 2020. URL: https://noticias.r7.com/saude/capitais-de-sp-e-rj-tem-transmissao-comunitaria-do-coronavirus-13032020; library Catalog: noticias.r7.com Section: Saúde.

[6] Ministério da saúde confirma transmissão comunitária no RJ e em SP. 2020. URL: https://veja.abril.com.br/saude/ministerio-da-saude-confirma-transmissao-comunitaria-no-rj-e-em-sp/; library Catalog: veja.abril.com.br.

[7] Codeço CT, Cordeiro JdS, Lima AWdS, Colpo RA, Cruz OG, Coelho FC, et al. The epidemic wave of influenza A (H1N1) in Brazil, 2009. Cadernos de Saúde Pública 2012;28:1325–36. URL: https://www.scielosp.org/article/csp/2012.v28n7/1325-1336/. doi:10.1590/S0102-311X2012000700011.

[8] Official Airline Guide . OAG. 2020. URL: http://www.oag.com.

[9] IBGE - Instituto Brasileiro de Geografia e Estatística . Censo demográfico 2010: Resultados gerais da amostra. 2010. URL: http://www.ibge.gov.br/home/estatistica/populacao/censo2010/resultados_gerais_amostra/resultados_gerais_amostra_tab_uf_microdados.shtm.

[10] Ministério da Saúde . DATASUS - Informações de Saúde - Rede Assis-

tencial. 2020. URL: http://www2.datasus.gov.br/DATASUS/index.php?area=0204&id=11663.

[11] Gautreau A, Barrat A, Barthélemy M. Global disease spread: Statistics and estimation of arrival times. Journal of Theoretical Biology 2008;251(3):509–22. URL: http://www.sciencedirect.com/science/article/pii/S002251930700608X. doi:10.1016/j.jtbi.2007.12.001.

[12] Brockmann D, Helbing D. The Hidden Geometry of Complex, Network-Driven Contagion Phenomena. Science 2013;342(6164):1337–42. URL: https://science.sciencemag.org/content/342/6164/1337. doi:10.1126/science.1245200.

[13] Allen LJ, Brauer F, Van den Driessche P, Wu J. Mathematical epidemiology; vol. 1945. Springer; 2008.

[14] Wu JT, Leung K, Leung GM. Nowcasting and forecasting the potential domestic and international spread of the 2019-nCoV outbreak originating in Wuhan, China: a modelling study. The Lancet 2020;395. URL: https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(20)30260-9/abstract. doi:10.1016/S0140-6736(20)30260-9.

[15] Li Q, Guan X, Wu P, Wang X, Zhou L, Tong Y, et al. Early transmission dynamics in wuhan, china, of novel coronavirus–infected pneumonia 2020;URL: https://doi.org/10.1056/NEJMoa2001316. doi:10.1056/NEJMoa2001316; publisher: Massachusetts Medical Society _eprint: https://doi.org/10.1056/NEJMoa2001316.

[16] Abbott S, Hellewell J, Munday J, CMMID nCoV working group , Funk S. The transmissibility of novel coronavirus in the early stages of the 2019-20 outbreak in wuhan: Exploring initial point-source exposure sizes and durations using scenario analysis ????;5:17. URL: https://wellcomeopenresearch.org/articles/5-17/v1. doi:10.12688/wellcomeopenres.15718.1.

[17] Chinazzi M, Davis JT, Mu K, Ajelli M, Dean NE, Gioannini C, et al. Estimating the risk of sustained community transmission of COVID-19 outside mainland china 2020;:11URL: https://www.mobs-lab.org/uploads/6/7/8/7/6787877/estimating_the_risk_of_sustained_community_transmission_of_covid-19_outside_china.pdf.

[18] Li R, Pei S, Chen B, Song Y, Zhang T, Yang W, et al. Substantial undocumented infection facilitates the rapid dissemination of novel coronavirus (covid-19). medRxiv 2020;.

[19] Liu T, Hu J, Kang M, Lin L, Zhong H, Xiao J, et al. Transmission dynamics of 2019 novel coronavirus (2019-nCoV). bioRxiv 2020;:2020.01.25.919787URL: https://www.biorxiv.org/content/10.1101/2020.01.25.919787v1. doi:10.1101/2020.01.25.919787.

[20] Health at a glance 2019: OECD indicators. 2019. URL: https://www.oecd-ilibrary.org/social-issues-migration-health/health-at-a-glance-2019_4dd50c09-en; library Catalog: www.oecd-ilibrary.org.

[21] The Novel Coronavirus Pneumonia Emergency Response Epidemiology Team . The epidemiological characteristics of an outbreak of 2019 novel coronavirus diseases (COVID-19) in China. Chinese Journal of Epidemiology 2020;41(02):145–51. URL: http://rs.yiigle.com/yufabiao/1181998.htm. doi:10.3760/cma.j.issn.0254-6450.2020.02.003.

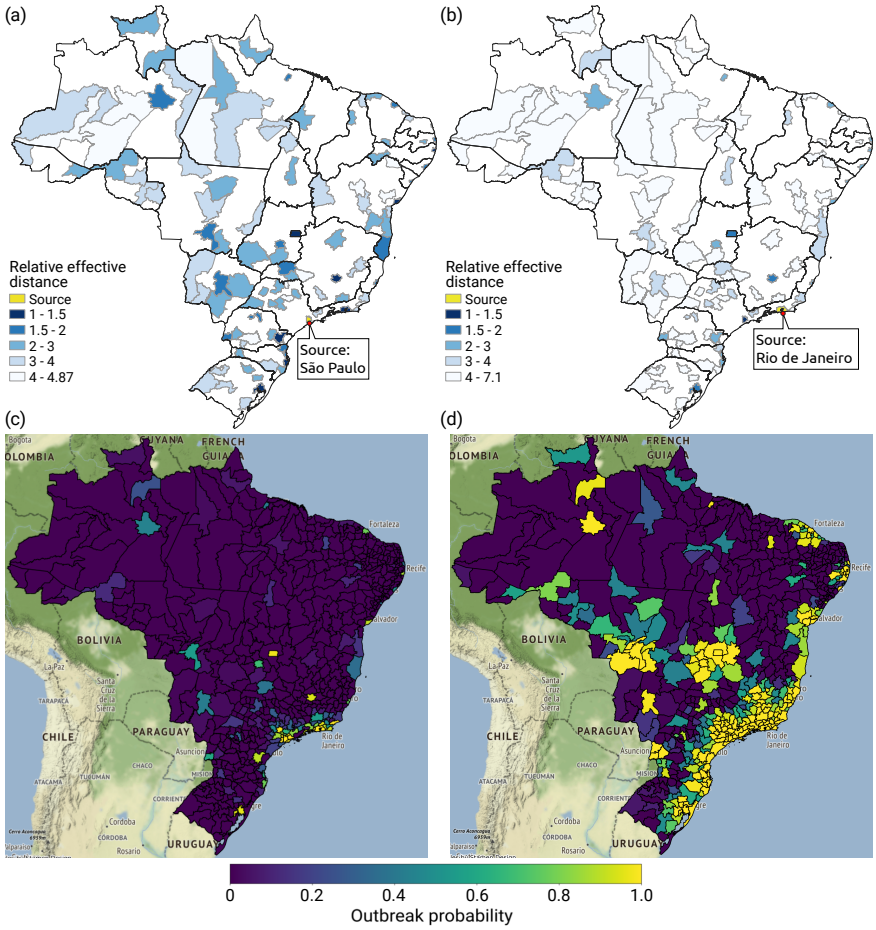

Figure 1: (a) Relative effective distance (e_f) of Brazilian micro-regions from São Paulo based on airline network in the absence of travel restrictions; (b) the same from Rio de Janeiro, with blue gradient from closest (dark blue) to farthest (light blue) destinations, limited to those present on the airline network. Bottom panel uses both local and long-range mobility networks to estimate the (c) probability of COVID-19 outbreak per micro-region as Rio de Janeiro and São Paulo sustain high prevalence of infection; (D) second wave of outbreaks after the micro-regions infected in (d) begin to contribute cases, with a gradient from dark purple ($p = 0$) to bright yellow ($p = 1.0$).

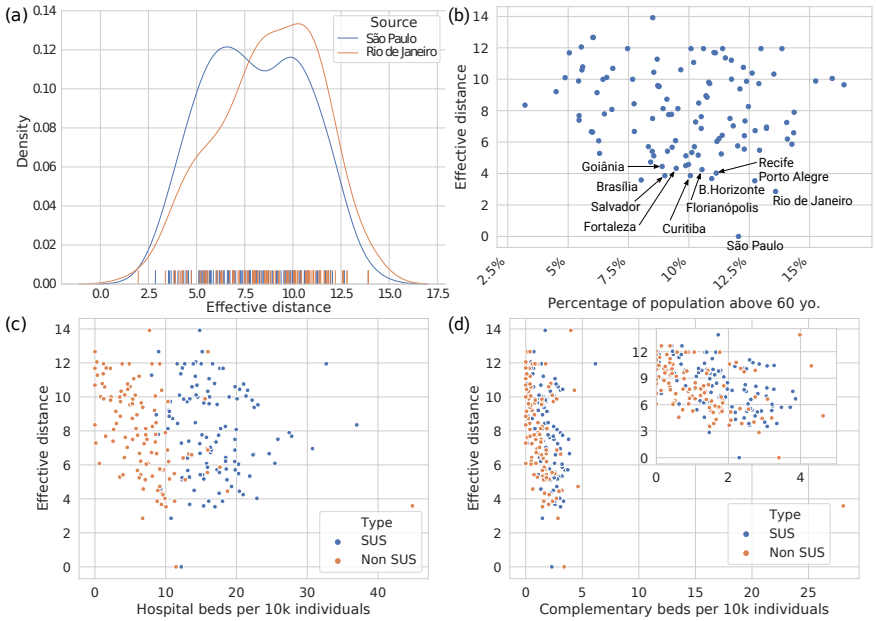

Figure 2: Effective distance and potential impact for micro-regions in the airline network. Distribution of effective distance to each micro-region based on airline network (a) from São Paulo (blue line) and Rio de Janeiro (orange line). Relationship between effective distance from São Paulo and percentage of population above 60 years old (b) for each micro-region, with the source and 10 closest micro-regions highlighted for reference. Bottom panels (c-d) show effective distance from São Paulo by (c) number of hospital beds, and (d) number of complementary beds (ICU and intermediary care) per 10,000 individuals in each micro-region, by health care category: SUS (blue circles) and non SUS (orange circle).

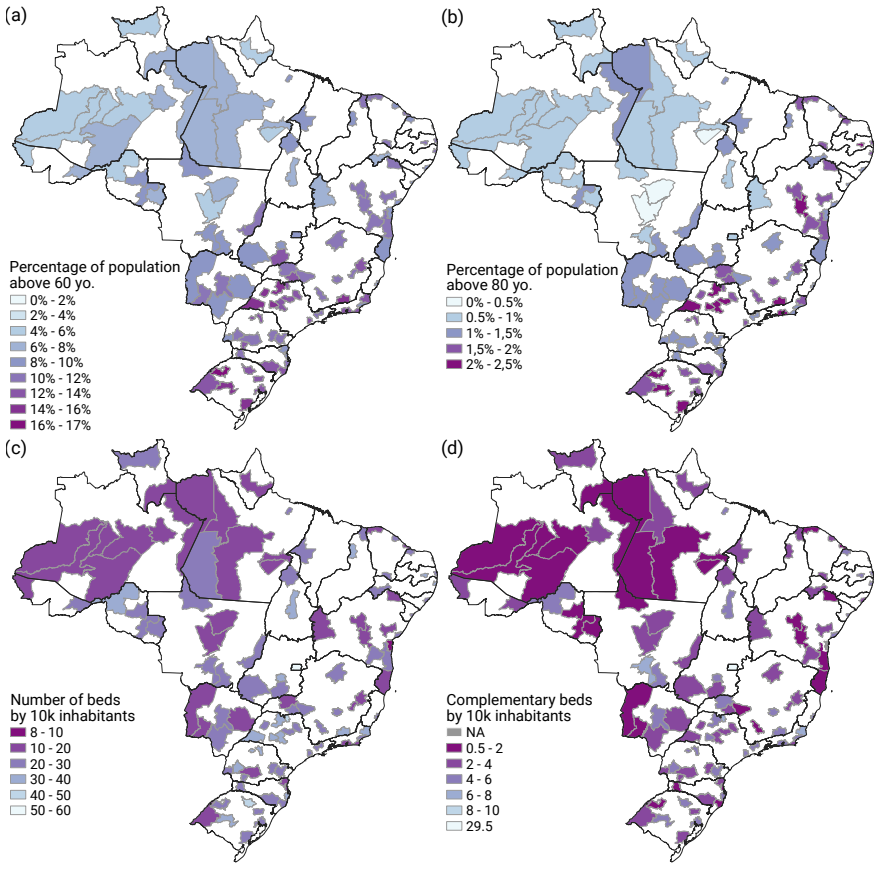

Figure 3: (A) Distribution of population above 60 years of age. (B) Same as (A) for people above 80 years of age. (C) Number of standard hospital beds per 10,000 inhabitants. (D) Number of complementary beds per 10,000 inhabitants. In all maps, only the micro-regions present in the airline network are shown.