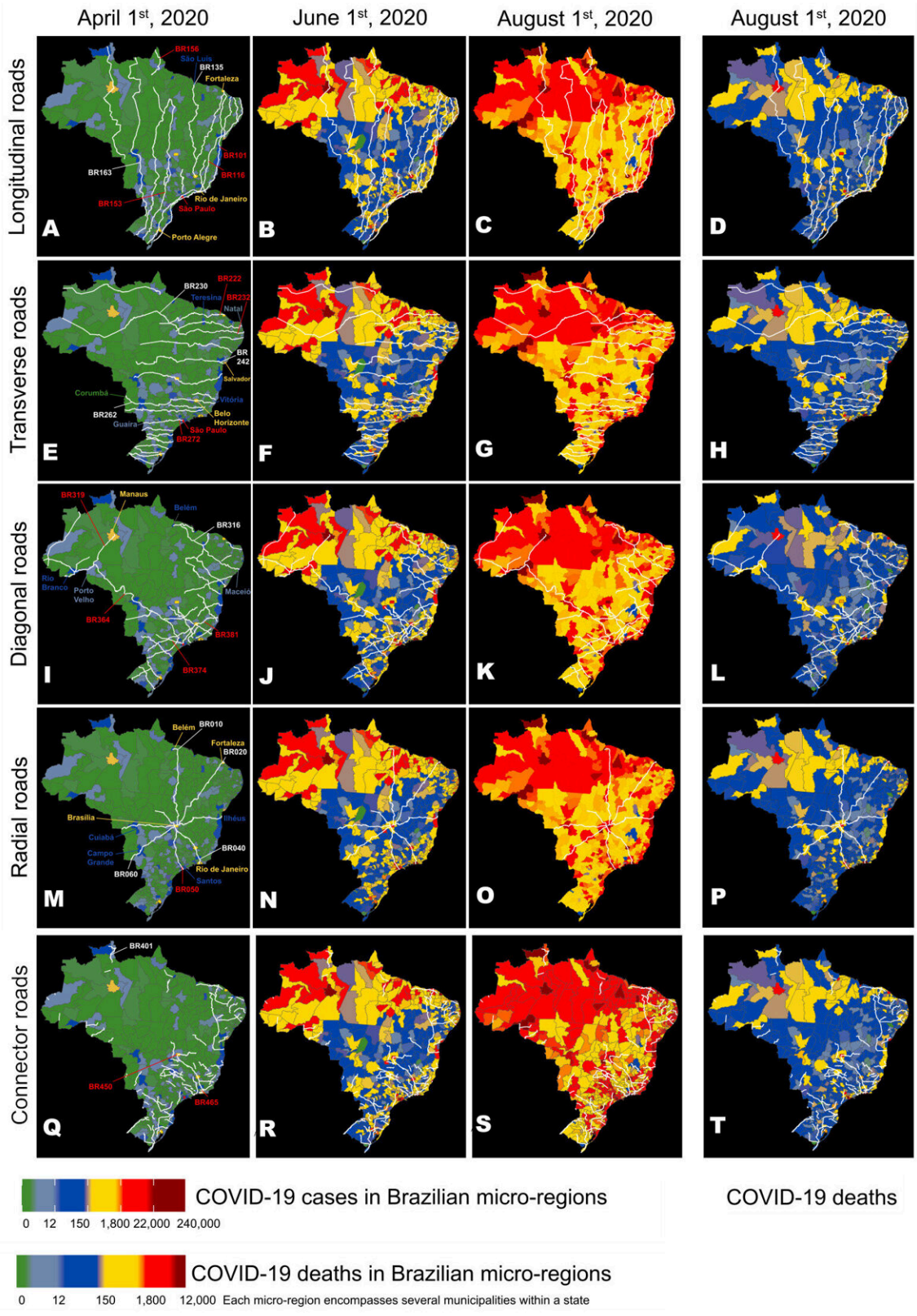
The paths through which COVID-19 spread across Brazil

June 21 2021


April 1st, 2020
June 1st, 2020
August 1st, 2020
August 1st, 2020
Longitudinal roads
Transverse roads
Diagonal roads
Radial roads
Connector roads
BR156
São Luís
BR135
Fortaleza
BR101
BR116
BR163
BR153
Rio de Janeiro
São Paulo
Porto Alegre
A
B
C
D
BR230
BR222
Teresina
BR232
Natal
BR 242
Salvador
Corumbá
Vitória
BR262
Guaira
Belo Horizonte
São Paulo
BR272
E
F
G
H
BR319
Manaus
Belém
BR316
Rio Branco
Porto Velho
Maceió
BR364
BR381
BR374
I
J
K
L
Belém
BR010
Fortaleza
BR020
Brasília
Ilhéus
Cuiabá
BR040
Campo Grande
BR060
Rio de Janeiro
Santos
BR050
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O
P
BR401
BR450
BR465
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T
COVID-19 cases in Brazilian micro-regions
0 12 150 1,800 22,000 240,000
COVID-19 deaths
COVID-19 deaths in Brazilian micro-regions
0 12 150 1,800 12,000 Each micro-region encompasses several municipalities within a state

Maps of Brazil were used to represent the routes of the main longitudinal (A-D), transversal (E- H), diagonal (I-L), radial (M-P), and connector (Q-T) federal highways, as well as the evolution of the geographic distribution of COVID-19 cases on three dates (April 1st, June 1st, and August 1st), and the distribution of COVID-19 deaths on August 1st (D). Overall, 26 highways (see text) from all five road categories contributed to approximately 30% of the COVID-19 case spreading throughout Brazil. The numbers of some of these spreading highways are highlighted in red. Notice how many hotspots (red color) for COVID-19 cases occur in micro-regions containing cities located along major highway routes like BRs 101, 116, 222, 232, 236, 272, 364, 374, 381, 010, 050, 060, 450, and 465. Although the distributions for COVID-19 cases and deaths were correlated, geographic discrepancies between the two distributions can be seen by comparing them on August 1st (C and D). A color code (See Figure bottom) ranks Brazilian micro-regions (each comprising several tows) according to their number of COVID-19 cases and deaths. Credit: Nicolelis, M.A.L. et al. 2021. *Scientific Reports*, doi.org/10.1038/s41598-021-92263-3

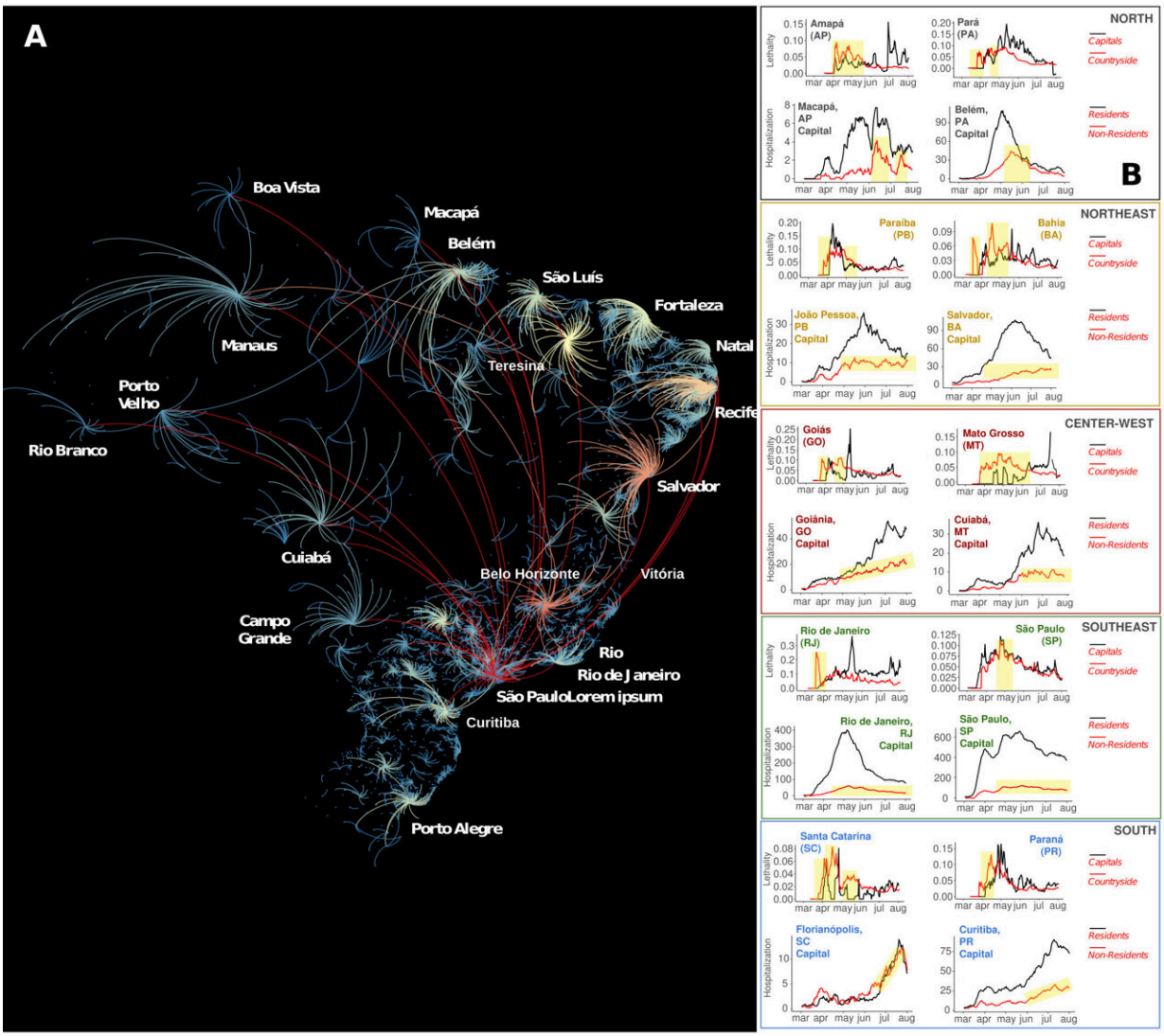
A multidisciplinary analysis by a group of Brazilian scientists, published online in the journal *Scientific Reports* on June 21, 2021, found that three major factors account for the geographic spread of SARS-COV-2 across Brazil, as well as the massive flow of people in search of hospital care throughout the country during the first wave of the pandemic in 2020. SARS-CoV-2 entered Brazil at the end of February 2020 through the country's international airports. Mathematical modeling reveals that during the first weeks of March 2020, the super-spreader city of São Paulo, located next to both the largest Brazilian international airport and the busiest highway hub in the country, accounted for more than 85% of COVID-19 cases throughout Brazil.

By considering only 16 other spreader cities, the authors were able to

account for 98-99% of the cases reported during the first three months of the Brazilian pandemic in 2020. Most of this spread of COVID-19 cases resulted from people traveling across the country's major highways and on plane flights, which continued throughout the entire month of March 2020. For instance, a group of 26 major federal highways alone accounted for about 30% of SARS-CoV-2's case spread during this period.

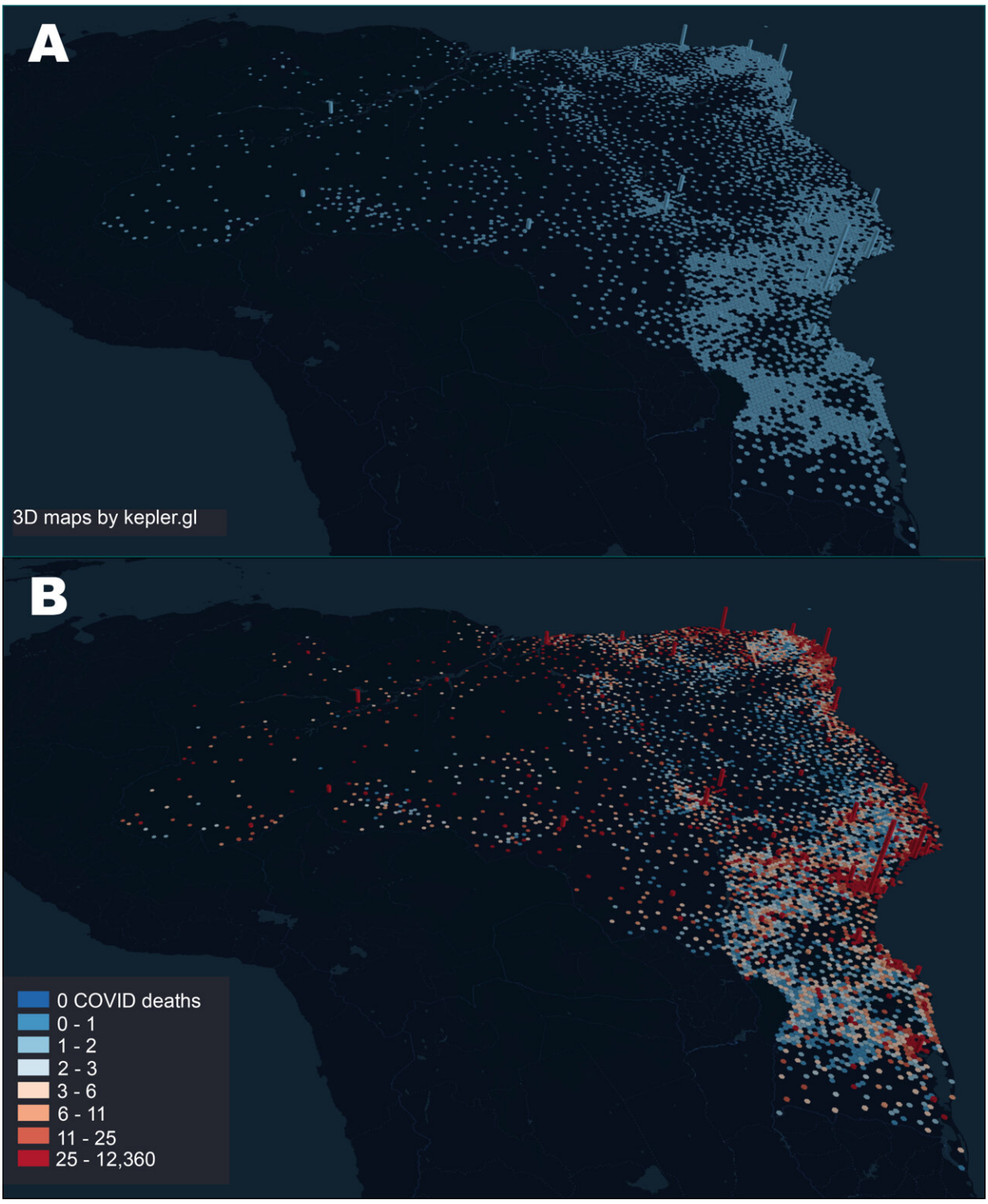
Following the emergence of community transmission in the major 16 super-spreader, SARS-CoV-2 cases spread to the Brazilian countryside through the country's federal and state highways. As cases increased exponentially in the Brazilian interior, severely ill patients from the country's interior had to be transported to state capitals to access ICU beds, creating a "boomerang effect" that contributed to skewing the distribution of COVID-19 deaths. Therefore, the distribution of COVID-19 deaths began to correlate with the allocation of the country's highly uneven distribution of intensive care units, which is heavily weighted toward state capitals.

According to Miguel Nicolelis, one of the authors of the study, "our analysis clearly showed that if a national lockdown and mandatory road traffic restrictions had been enforced around the main Brazilian super-spreader cities, particularly in the city of São Paulo, the impact of COVID-19 in Brazil would be significantly lower during the first wave, but also during the even more damaging second wave that hit the country a year later in the summer of 2021. From June 2020 to June 2021, Brazil went from 50,000 to 500,000 deaths, a tenfold increase in 12 months. This alone illustrates the utter failure of the Brazilian federal government to protect Brazilians from the worst humanitarian tragedy in the country's entire history."



(A) Representation of all "boomerangs" that occurred around major Brazilian state capitals (see labels for names) and mid-size cities across the whole country. In this map, arcs represent the flow of people from the interior towards the capital. The arc color code represents the number of interior cities that sent severely ill patients to be admitted in hospitals in a capital or mid-size town; red being the highest number of locations, orange and yellow next, while a smaller number of locations are represented in light blue. Most of the flow of people represented in this graph took place through highways. Red arcs likely represent long-distance flow by airplanes. In the Amazon, most of the flow of people towards Manaus occurred by boats through the Amazon River and its tributaries. Notice that again São Paulo appears as the city with the highest boomerang

effect, followed by Belo Horizonte, Recife, Salvador, Fortaleza, and Teresina. (B) Lethality and hospitalization data, divided for capital and interior (for lethality) and capital resident and non-resident (hospitalization), for a sample of state capitals in all five regions of Brazil. Yellow shading in the lethality graphs represent periods in which more deaths occurred in the interior, in relation to the capital. In the hospitalization graphs, yellow shading depicts periods of increasing admission of people residing in the countryside to the capital hospital system. The overall flow of people from capital to the interior and back to the capital characterized the boomerang effect, targeting the hospital system of the capital city. Notice that the boomerang effect was pervasive all over the country, occurring in every Brazilian state. Credit: Nicolelis, M.A.L. et al. 2021. *Scientific Reports*, doi.org/10.1038/s41598-021-92263-3



(A) Distribution of ICU beds across all Brazil. Bar height is proportional to the number of ICU beds in each city. Notice how the coastal state capitals accumulate most of the ICU beds in the whole country, with much fewer beds

available in the interior of most states. The city of São Paulo exhibits the larger number of ICU beds in the whole country. (B) Superimposition of the COVID-19 death distribution (color code legend on the left lower corner) on top of the ICU bed distribution as seen in (A). For each bar, its height represents the number of ICU beds in a city, while color represents the number of deaths that occurred in that city. Again, the city of São Paulo, which has by far the highest number of ICU beds, accumulated the highest number of COVID-19 related fatalities, followed by state capitals like Rio de Janeiro, Fortaleza, Brasilia, Salvador, Manaus, Recife, and Belém. The 3D maps were made using the online resources available at http://kepler.gl/. Credit: Nicolelis, M.A.L. et al. 2021. *Scientific Reports*, doi.org/10.1038/s41598-021-92263-3

In Brazil, the vast majority of tertiary hospitals, and hence the largest share of critical care beds, are located in large cities that serve as state capitals, their metropolitan areas, and a handful of mid-sized towns in each state's interior. As a result of the highly pervasive "boomerang effect" throughout the country, Brazil experienced the largest hospital admission surge in its history, leading to fatality peaks in each of the cities with a large number of critical care units.

This "boomerang flow" was not restricted to roads and highways. For instance, in the Amazon rain forest, located in the north region of Brazilian, severely ill COVID-19 patients from many small riverside communities were transported by boats of all sorts via its large rivers toward the two largest Amazon cities, Manaus and Belém. Overall, analysis of the geographic flow of COVID-19 patients revealed that São Paulo, the largest Brazilian super-spreader city, received patients from 464 different cities all over Brazil, followed by Belo Horizonte (351 cities), Salvador (332 cities), Goiânia (258 cities), Recife (255 cities), and Teresina (225 cities). São Paulo was also the city that sent more residents to be hospitalized in other cities (158 cities), followed by Rio de Janeiro (73 cities), Guarulhos (41 cities), Curitiba (40 cities),

Campinas (39 cities), Belém (38 cities) and Brasília (35 cities).

Overall, cities that were highly connected to the health system network, either by receiving from or sending patients to other cities, also experienced a higher number of COVID-19 deaths. Therefore, as a result of the "boomerang effect," a significant number of severely ill patients had to migrate to larger cities for treatment and, eventually, a significant number of them perished there. Combined with the deaths of the residents of large cities, the widespread "boomerang effect" contributed decisively to the geographic skewing of the COVID-19 death distribution in all of Brazil.

Commenting on the study's findings, Rafael Raimundo, another author, said, "Our analysis elucidated in great detail the mechanisms through which COVID-19 quickly spread throughout Brazil. Our findings also indicate that if non-pharmacological measures, such as highways blocks and lockdowns, had been enforced early on at a national or even regional level thousands of lives could have been saved at the onset of the COVID-19 pandemic in Brazil."

The authors also emphasized in their conclusions the fundamental importance of the Brazilian Public Health System, known as SUS. According to Rafael Raimundo "without the public health infrastructure of SUS, built during the past 40 years, the impact of COVID-19 would certainly be even more devastating. Yet, our data also show that the high magnitude of the "boomerang effect" highlights the need for SUS to install more hospital infrastructure, including more critical care unit beds, in the Brazilian interior to better assist and serve the population in the countryside."

"Certainly, the widespread absence of adequate hospital infrastructure and health professionals in the Brazilian countryside contributed decisively to a high number of deaths that could have been avoided

altogether. Yet, if the Brazilian federal government had reacted quickly and properly to the arrival of SARS-CoV-2, by creating a national scientific task force in charge of fighting the pandemic, while implementing a national communication campaign to alert the population, and had closed the country's air space, while implementing a national lockdown in early March 2020, including establishing roadblocks on the major federal and state highways, Brazil would almost certainly have avoided the loss of tens of thousands of lives," added Miguel Nicolelis.

More information: Miguel A. L. Nicolelis et al, The impact of super-spreader cities, highways, and intensive care availability in the early stages of the COVID-19 epidemic in Brazil, *Scientific Reports* (2021). DOI: 10.1038/s41598-021-92263-3