Emergência matemática: modelagem da dinâmica epidemiológica na pandemia

Prof. Dr. Pedro da Silva Peixoto

Applied Mathematics
Instituto de Matemática e Estatística
Universidade de São Paulo

CNMAC - Setembro 2023

Emergência Sanitária (matemática?)

Fevereiro de 2020:



- De onde veio?
- Para onde vai?
- Como se espalha?
- Para onde mandar recursos?
- Quantos leitos?
- Quanto tempo vai durar?
- Quantos vão adoecer/morrer?
- Vacinar quem primeiro?
- **Isolar? Lockdown??**

Com recursos escassos e impacto econômico, como fazer uma melhor administração de crise na pandemia?

Overview

Background
- Why?
- What ?
- With whom ?

Mobility data and dynamics



Modelling the spread

$$\frac{dI_i}{dt}(t) = (1+r)I_i(t)\left(\frac{N_i - I_i(t)}{N_i}\right)$$

Relevant Scientific Results

Science AAAS

PLOS ONE

Patterns — A Cell Press journal

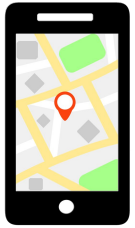
THE LANCET

nature

SCIENTIFIC REPORTS

Final remarks
- What have we learned?

Background



Main partners:

inloco

Main stakeholders:

SÃO PAULO GOVERNO DO ESTADO

INSTITUTO BUTANTAN A serviço da vida

CONSÓRCIO NORDESTE O BRASIL QUE CRESCE UNIDO

Participation in scientific committees of policymakers

Main collaborators:

OBSERVATÓRIO COVID-19 BR

Centre for Arbovirus cadde Discovery, Diagnostics, Genomics & Epidemiology

CeMEAI CEPID - Centro de Ciências Matemáticas Aplicadas à Indústria

LM | Assessoria Estatística

SAÚDE COVID RADAR

Funding:

FAPESP FUNDAÇÃO DE AMPARO À PESQUISA DO ESTADO DE SÃO PAULO

Itaú | todos pela saúde

\+ several researchers from USP and other universities!

inloco

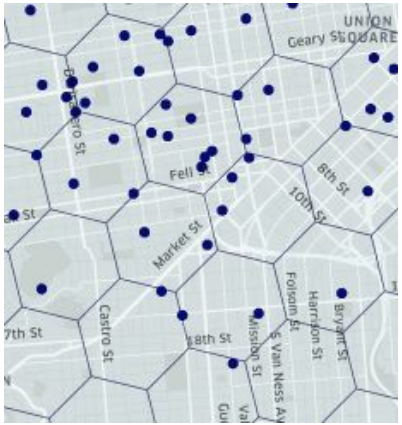
Data

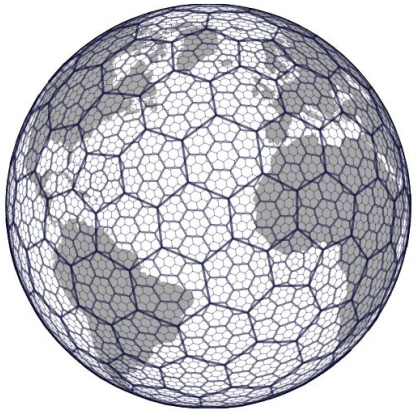
During 2020, the inloco Software Development Kit – SDK was installed in over 1 fourth of the Brazilian population.

- GPS
- Wi-Fi
- Bluetooth-LE
- Phone
- Activity

Time and space resolution is very high, but no personal information is tracked.

H3 Grids (https://h3geo.org/)



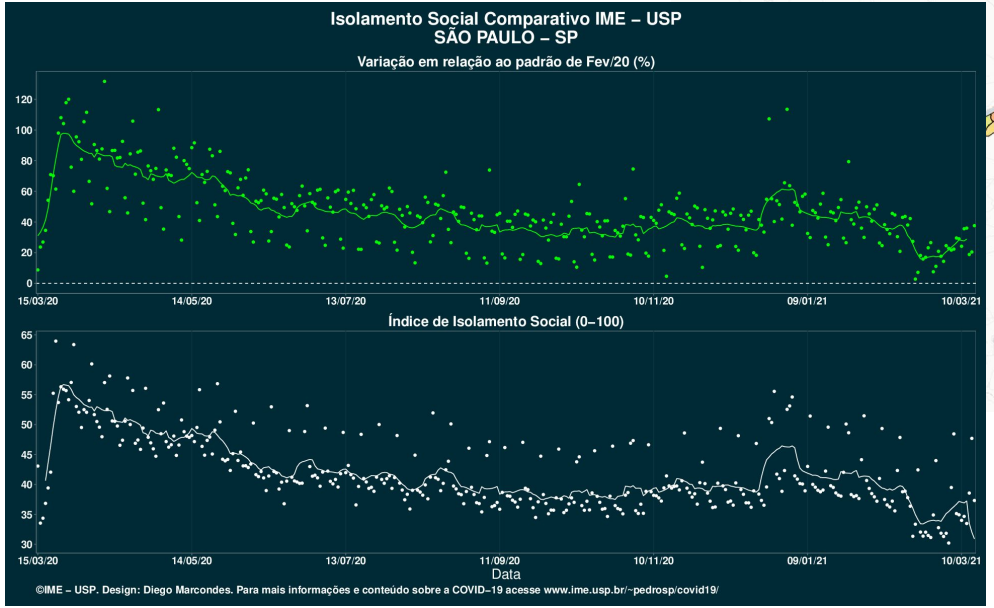


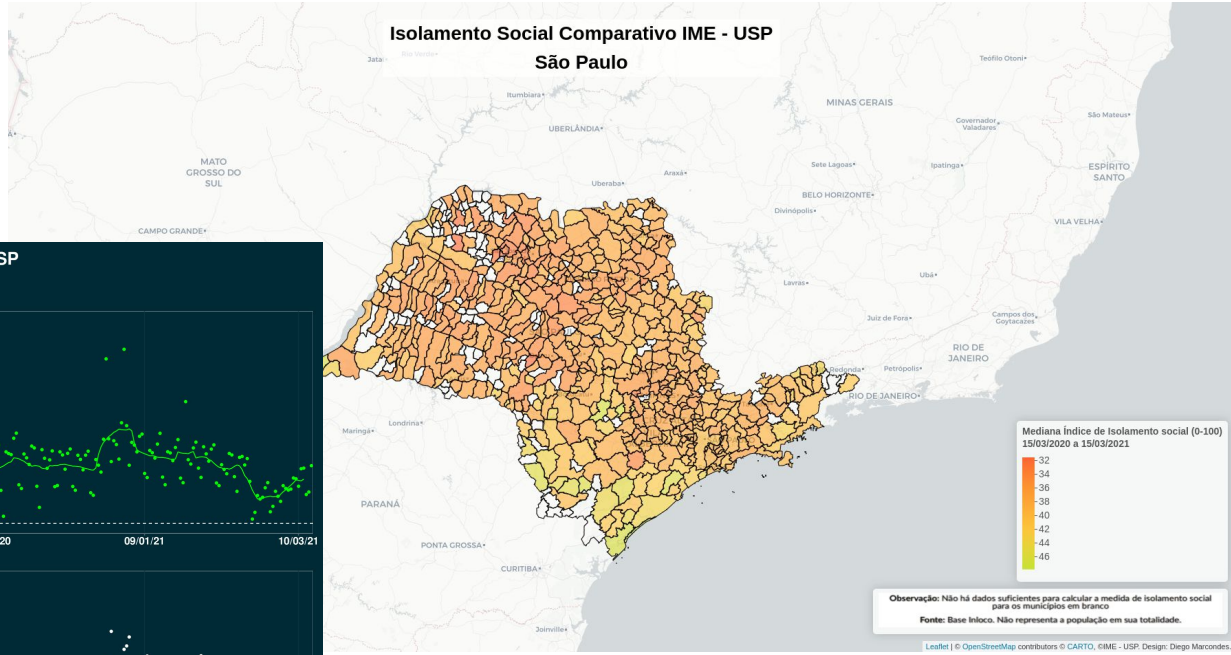
The company has a great concern for data safety and privacy (https://www.incognia.com/pt/politicas/covid) and opened aggregated and anonymous data only for research during the pandemic.

Social Isolation

Social Isolation Index:

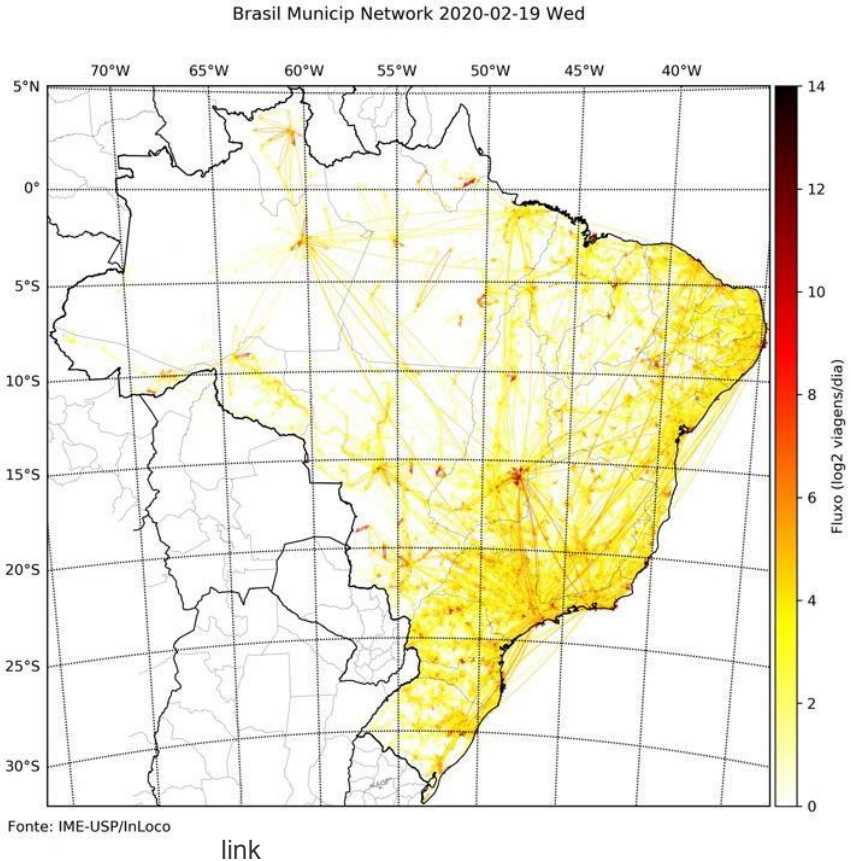
Percentage of people leaving their homes (H3 cell) during a given day for more than 4k cities in Brazil.



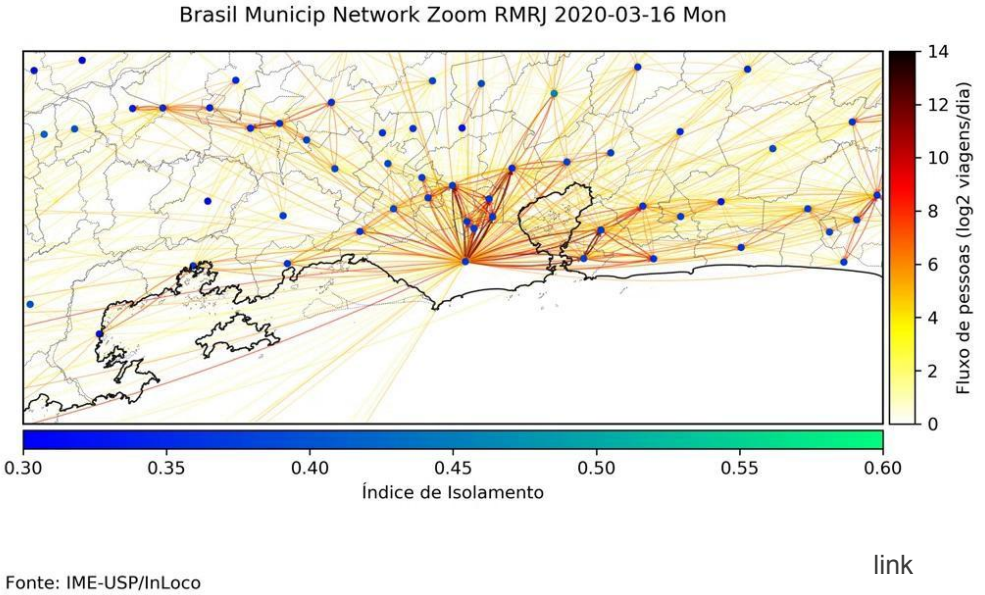


https://www.ime.usp.br/~pedrosp/covid19/

Mobility



link



link

Used for risk assessment and prediction of potential new risk areas

Modelling Spread

Classic compartmental models assume a fixed location on spatial homogeneous mixing

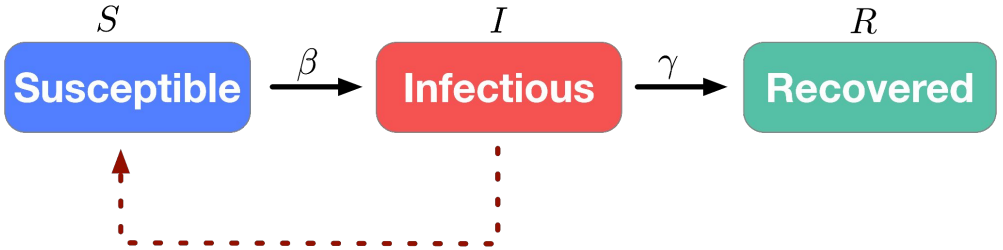


Figure credits:
https://covid19.uclaml.org/model.html

How to build compartmental models in complex networks? (Countries/Cities/Neighbourhoods)

Connecting multiple compartmental models into a network!

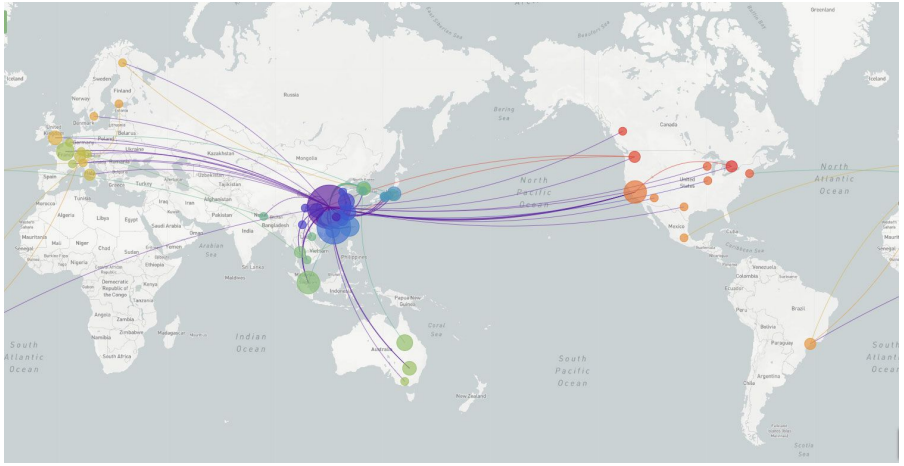
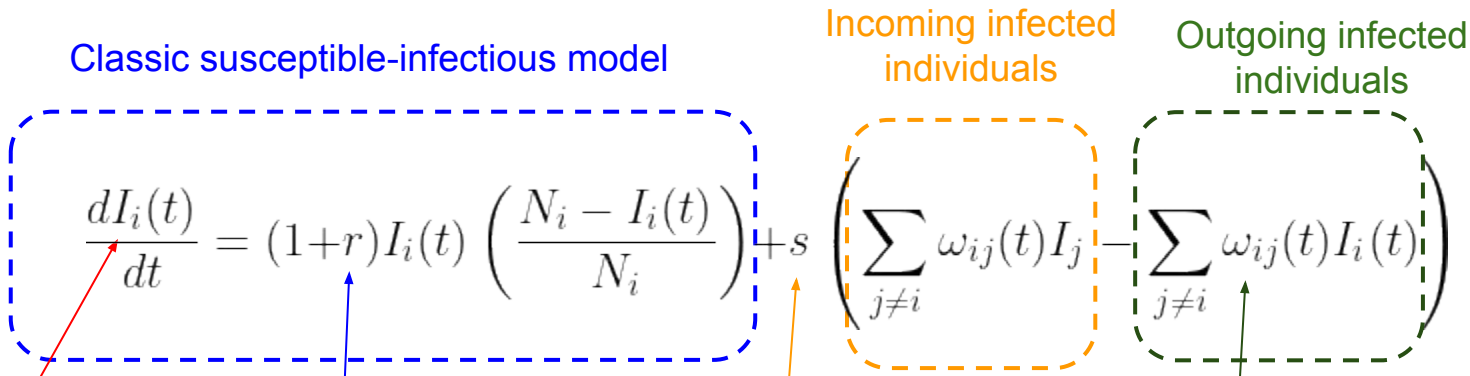


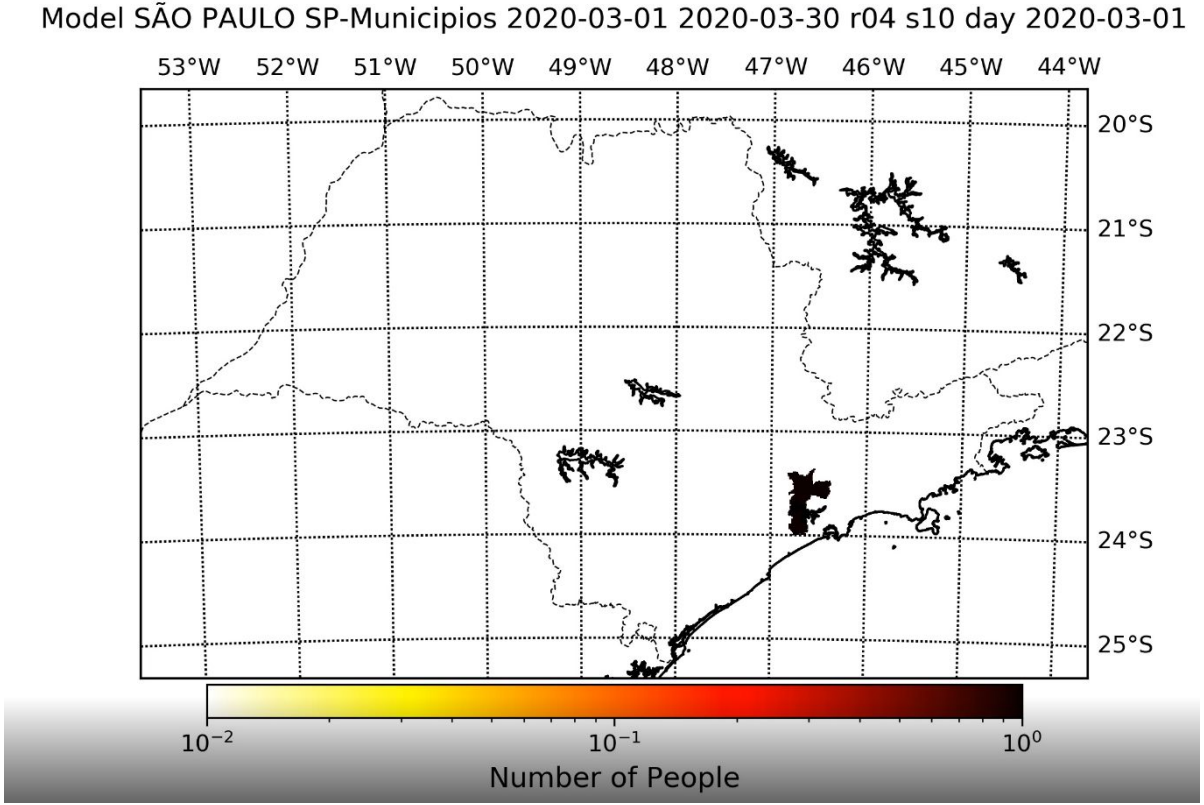
Figure credits:https://evolution.berkeley.edu/evo-news/evolution-of-an-outbreak/

Network dynamic model



This is a coupled multidimensional ordinary differential dynamical system!

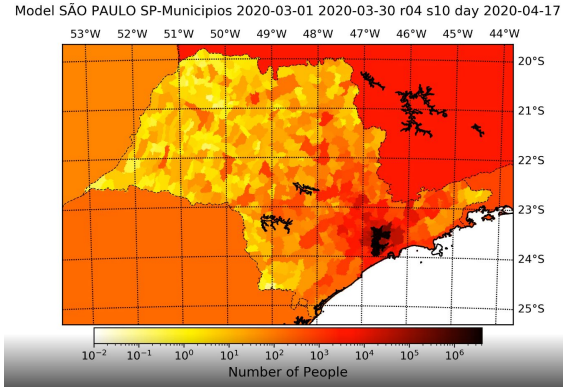
Simulations (predictions?)



Let 1 infected individual reach São Paulo city in 1st of March 2020.

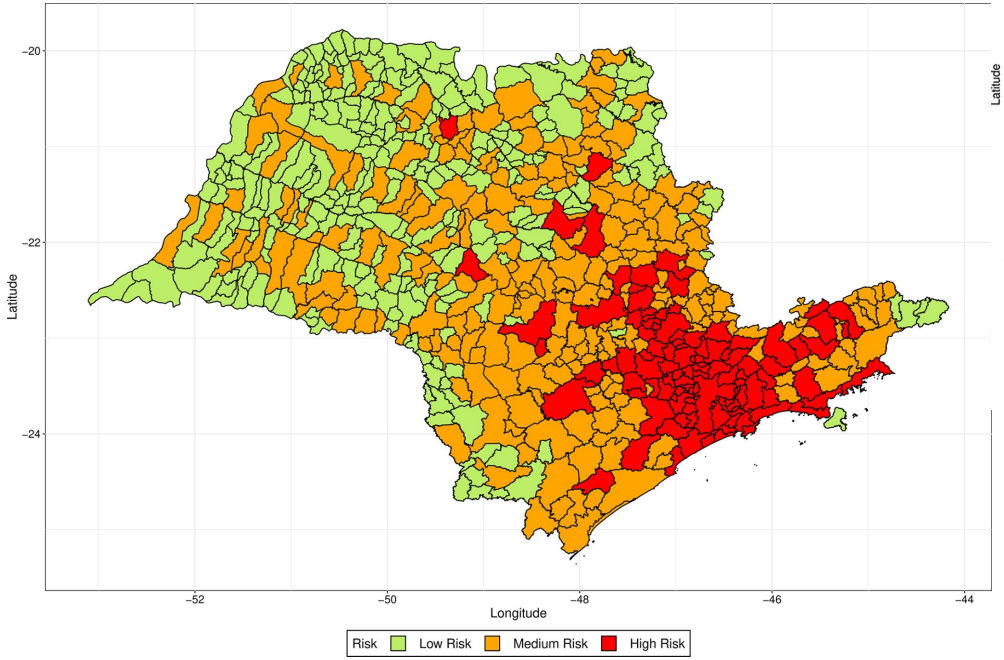
Transmission rate r=0.4
(equiv to R0~2.68)

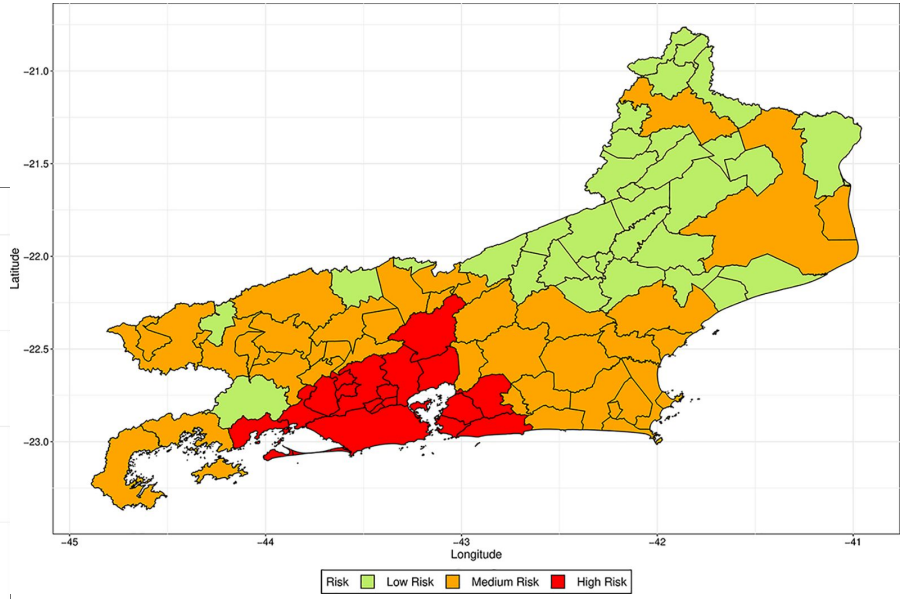
Network relevance s=1.0



Time until impact risk model

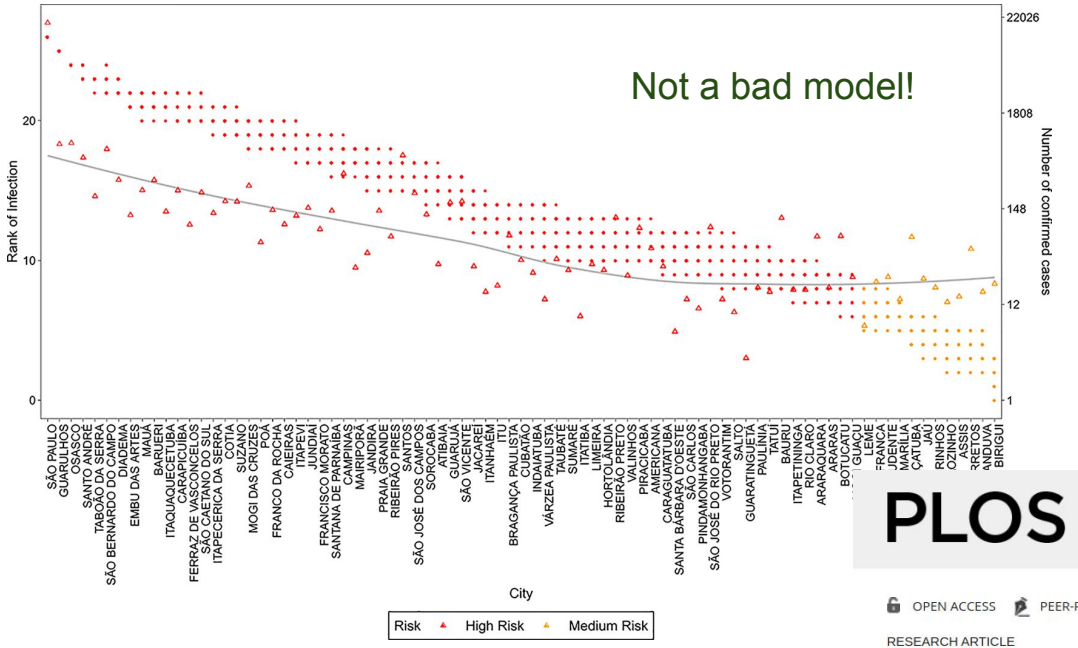
Who will be hit first?
We used non-parametric analysis to avoid strong dependency on “r” and “s” parameters





These risk models were generated almost in real-time with the first days of the pandemic in Brazil!

Post validation



Model also tested for RS state:
Sibemberg, L.S., Allem, L.E., Hoppen, C. and Peixoto, P., 2021. Classificação de risco em redes complexas: o caso da COVID-19 no Rio Grande do Sul. Ciência e Natura, 43, p.1.

PLOS ONE

OPEN ACCESS PEER-REVIEWED

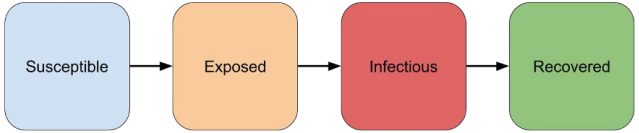
RESEARCH ARTICLE

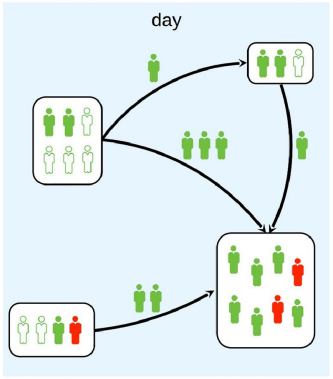
Modeling future spread of infections via mobile geolocation data and population dynamics. An application to COVID-19 in Brazil

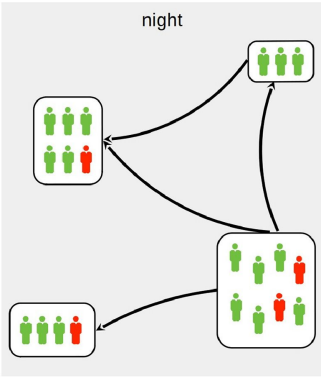
Pedro S. Peixoto, Diego Marcondes, Cláudia Peixoto, Sérgio M. Oliva

Published: July 16, 2020 • https://doi.org/10.1371/journal.pone.0235732

SEIR Dynamic Network Model





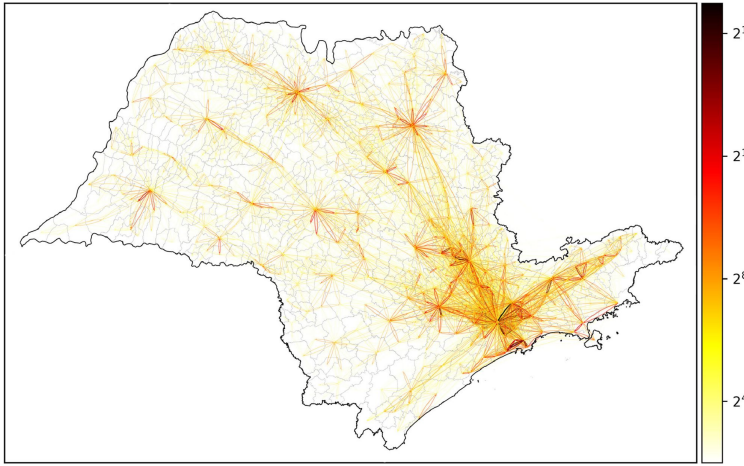


$$
\begin{aligned}
\dot{\mathscr{S}}^i(t) &= -\frac{\alpha(t)}{T_{\inf}} r^i(t)\, y^{ii}(t) + \frac{(1-\alpha(t))}{T_{\inf}} \sum_{j \in I} \zeta^j p^{ij} u^j(t)\, z^{ij}(t) \\
\dot{\mathscr{E}}^i(t) &= \frac{\alpha(t)}{T_{\inf}} r^i(t)\, y^{ii}(t) + \frac{(1-\alpha(t))}{T_{\inf}} \sum_{j \in I} \zeta^j p^{ij} u^j(t)\, z^{ij}(t) - \frac{1}{T_{\inc}} \mathscr{E}^i(t) \\
\dot{\mathscr{I}}^i(t) &= \frac{1}{T_{\inc}} \mathscr{E}^i(t) - \frac{1}{T_{\inf}} \mathscr{I}^i(t) \\
\dot{\mathscr{R}}^i(t) &= \frac{1}{T_{\inf}} \mathscr{I}^i(t).
\end{aligned}
$$

Day cycles

Mobility

$$
y^{ik}(t) := \mathscr{S}^i(t)\, \mathscr{I}^k(t) \qquad z^{ij}(t) := \frac{\sum_{k \in I} p^{kj} y^{ik}(t)\, N^k}{\sum_{k \in I} p^{kj} N^k}
$$



Optimal control problem

$$
\begin{cases}
\min\limits_{r(t)\in[0,\bar{r}]} & \displaystyle\int_{\mathbb{T}_0}^{\mathbb{T}_1} (\varphi(x(t)) + \psi(r(t)))\, dt \\
\text{s. t.} & (x(t), y(t), z(t), r(t), u(t)) \quad \text{satisfy} \quad (10) \text{ for a.e. } t \in [\mathbb{T}_0, \mathbb{T}_1] \\
& (y(t), z(t)) \quad \text{satisfy} \quad (11) \text{ for a.e. } t \in [\mathbb{T}_0, \mathbb{T}_1] \\
& u(t) \quad \text{satisfies} \quad (12) \text{ for a.e. } t \in [\mathbb{T}_0, \mathbb{T}_1] \\
& x(\mathbb{T}_0) = x_0, r(\mathbb{T}_0) = r_0 \quad \text{are given initial conditions;}
\end{cases}
$$

Functions of state (x = S,E,I,R) and control (infection rate - r)

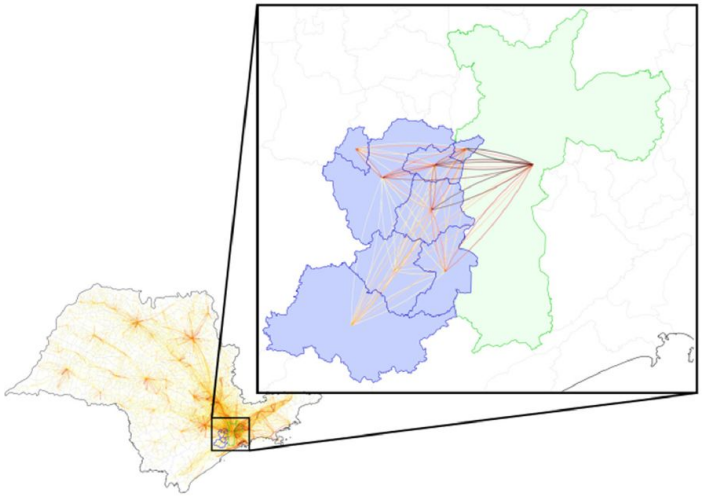
SEIR model on network

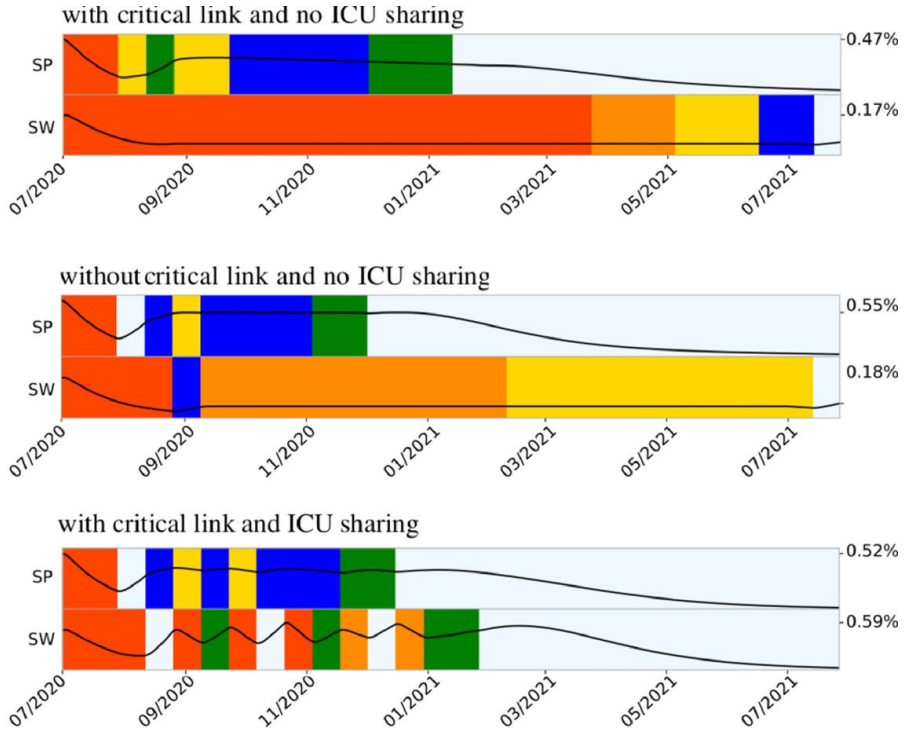
Control functions can represent:

- Open circulation of people
- Lockdowns
- Alternating restrictions
- ....

Include hospital capacity modelling

Optimal control problem: Example





Optimal solution is to have hospital bed sharing between regions and keep the mobility link between regions

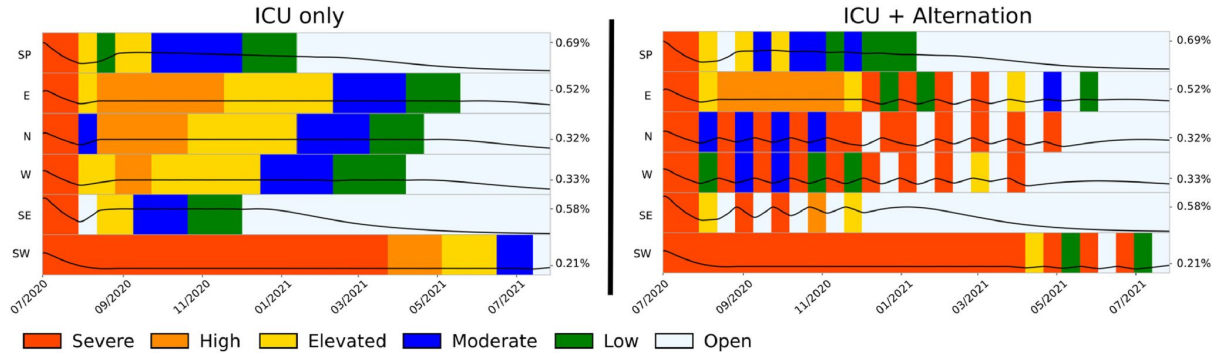
More information

EURO Journal on Computational Optimization
Volume 10, 2022, 100025

Won the Marguerite Frank award for Best EJCO 2022 Paper

Robot Dance: A mathematical optimization platform for intervention against COVID-19 in a complex network

Luis Gustavo Nonato [a], Pedro Peixoto [b], Tiago Pereira [a], Claudia Sagastizábal [c], Paulo J.S. Silva [c]

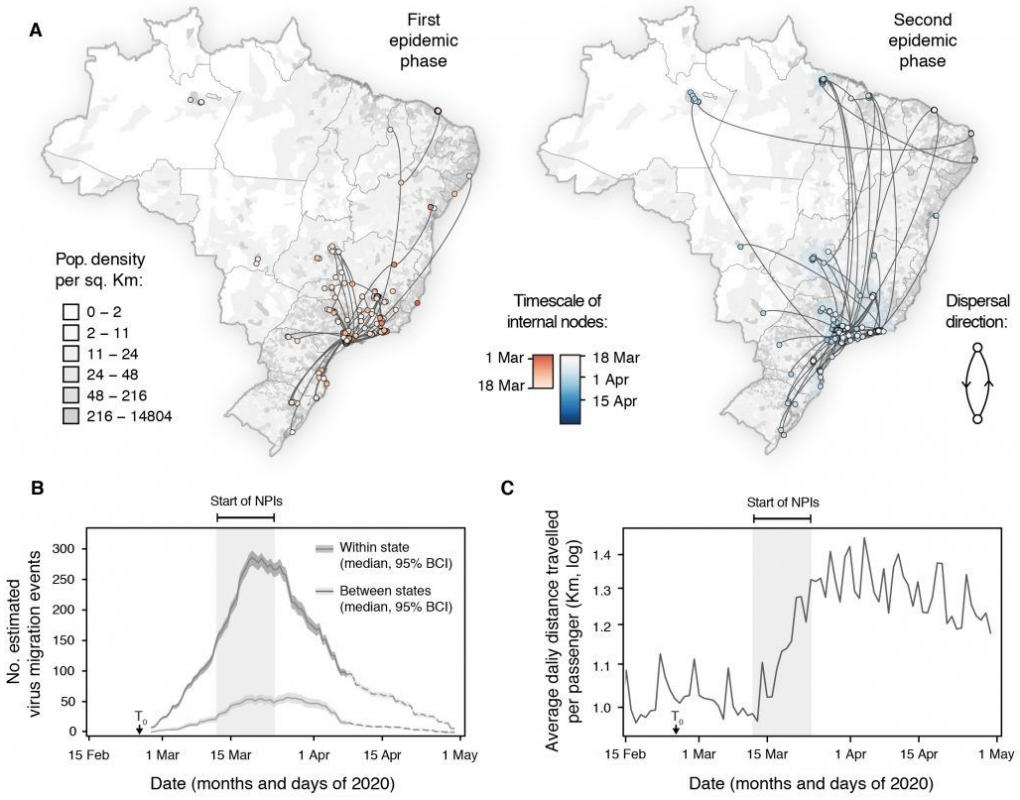


Robot Dance was also used in other scientific studies:

- Silva et al. Optimized delay of the second COVID-19 vaccine dose reduces ICU admissions. PNAS 2021

- Silva et al. Smart testing and critical care bed sharing for COVID-19 control. PLoS One. 2021

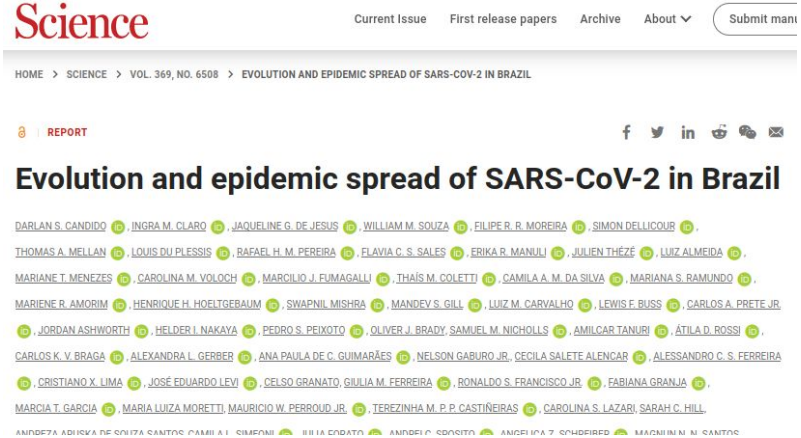
Mobility and Genomic Spreading



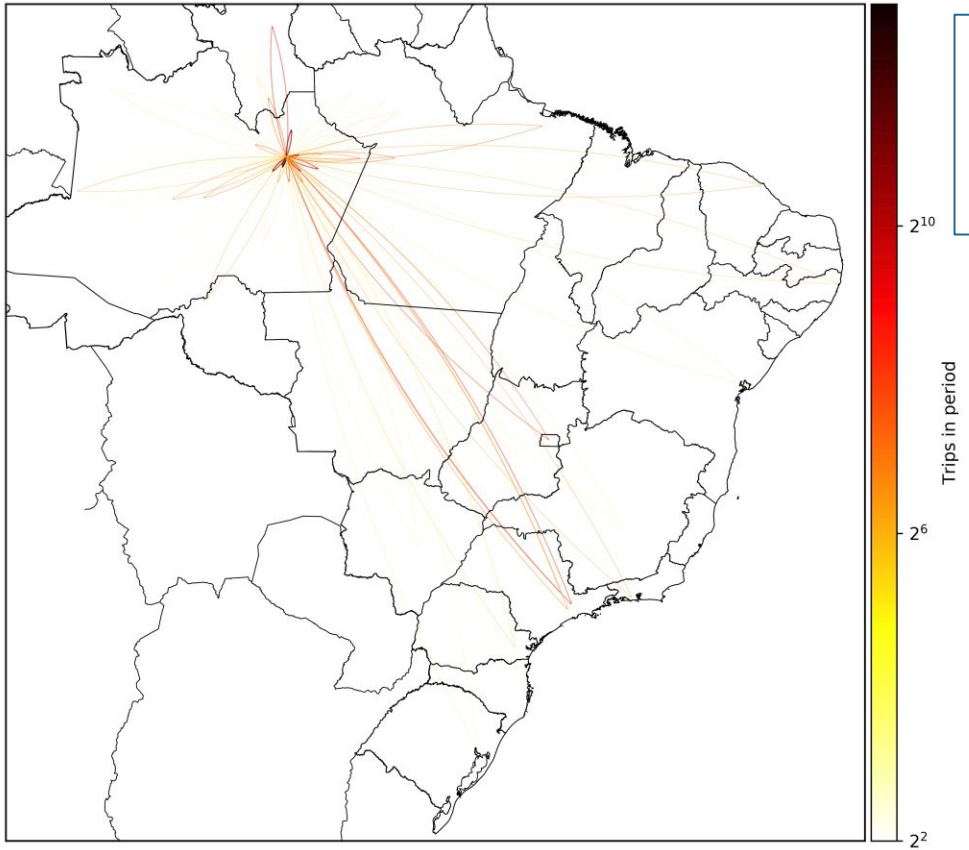
The virus moves with people…

... it evolves/mutates within people

… and spreads as people move!



A new variant!



The Manaus case of dissemination of P1 variant:

- Where is it heading?
- Can we control it?
- What are its characteristics?

Science

Current Issue First release papers Archive About Submit m

HOME > SCIENCE > VOL. 372, NO. 6544 > GENOMICS AND EPIDEMIOLOGY OF THE P.1 SARS-COV-2 LINEAGE IN MANAUS, BRAZIL

RESEARCH ARTICLE

Genomics and epidemiology of the P.1 SARS-CoV-2 lineage in Manaus, Brazil

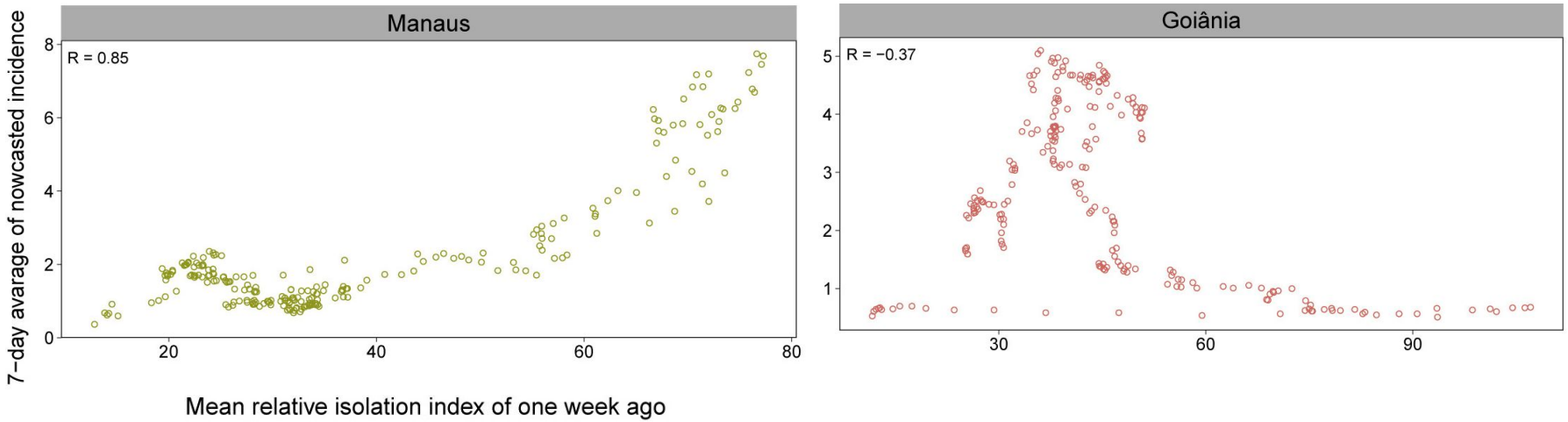
NUNO R. FARIA, THOMAS A. MELLAN, CHARLES WHITTAKER, INGRA M. CLARO, DARLAN DA S. CANDIDO, SWAPNIL MISHRA, MYUKI A. E. CRISPIM

COMMENT | VOLUME 397, ISSUE 10273, P452-455, FEBRUARY 06, 2021 THE LANCET

Resurgence of COVID-19 in Manaus, Brazil, despite high seroprevalence

Ester C Sabino • Lewis F Buss • Maria P S Carvalho • Carlos A Prete Jr • Myuki A E Crispim • Nelson A Fraiji • et al.

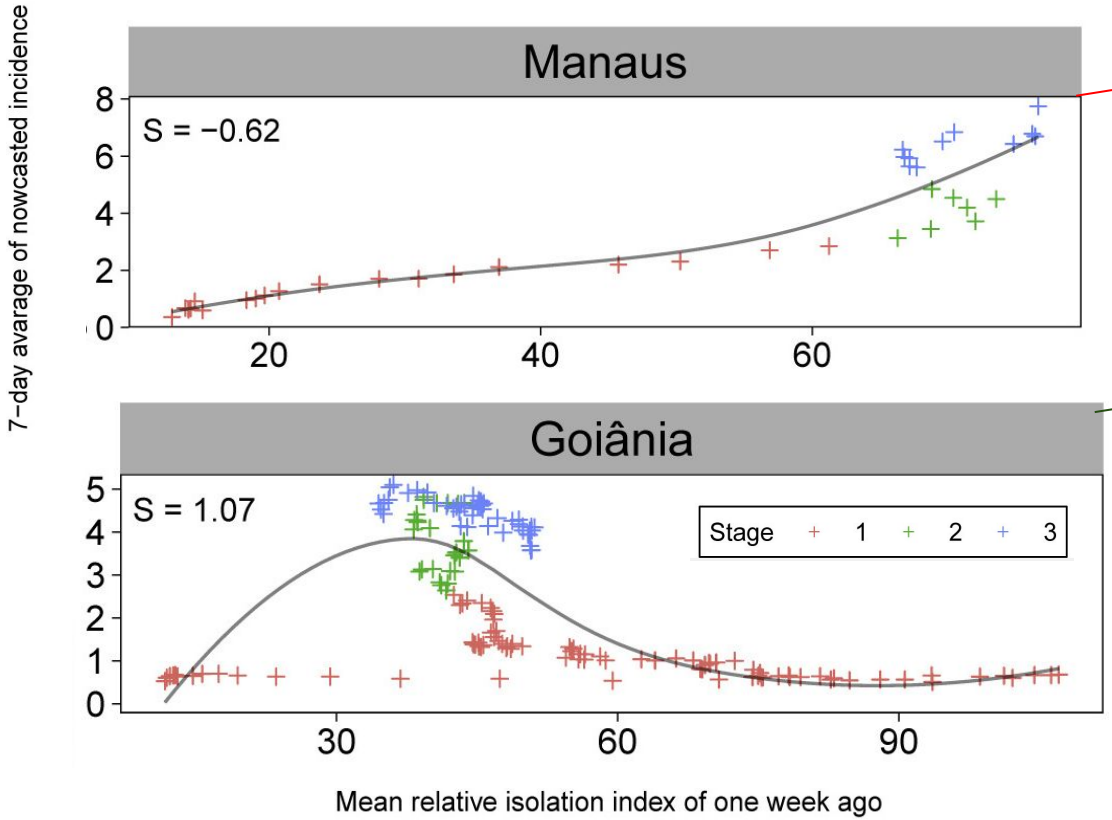
Does social isolation help?



What?!?! The more people isolate, the higher the incidence?!?! Are you crazy?

There is a dynamics behaviour behind the spreading, and the effects are highly dependent on the epidemiological “phase” of dissemination.

Social Isolation



Remedy!

Prevention!

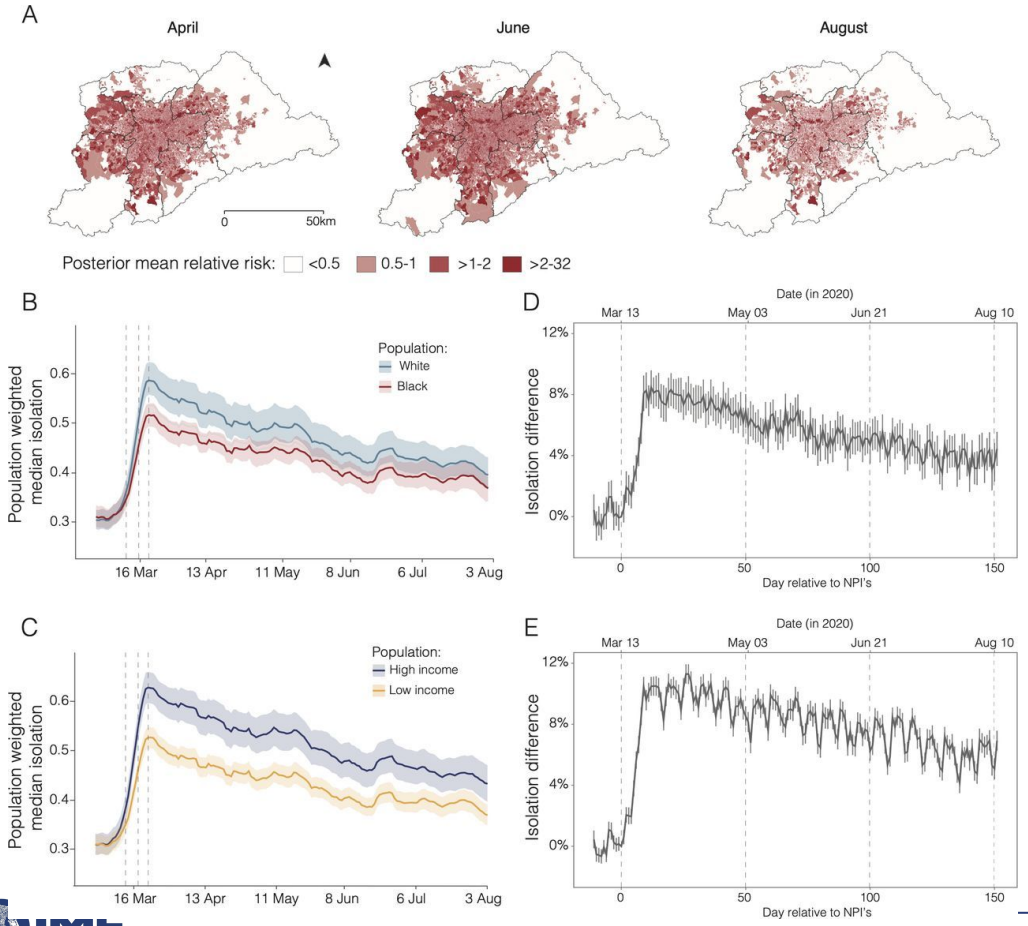
Patterns
Volume 2, Issue 10, 8 October 2021, 100349
CellPress

Article

A snapshot of a pandemic: The interplay between social isolation and COVID-19 dynamics in Brazil

Cláudia P. Ferreira [2], Diego Marcondes [3], Mariana P. Melo [1], Sérgio M. Oliva [3], Cláudia M. Peixoto [3], Pedro S. Peixoto [3, 4]

The social and racial inequality problem



Regions with dominantly black and poor population had difficulty in isolating, and were at higher risks of infection.

BMJ Journals

BMJ Global Health

Higher risk of death from COVID-19 in low-income and non-White populations of São Paulo, Brazil

Sabrina L Li [1], Rafael H M Pereira [2], Carlos A Prete Jr [3], Alexander E Zarebski [4], Lucas Emanuel [2], Pedro Alves [2], Pedro S Peixoto [5], Carlos K V Braga [2], Andreza Aruska de Souza Santos [6], William M de Souza [4, 7], Rogerio J Barbosa [8], Lewis F Buss [9], Alfredo Mendrone [10], Cesar de Almeida-Neto [10, 11], Suzete C Ferreira [10, 12], Nanci A Salles [10, 12], Izabel Marcilio [13], Chieh-Hsi Wu [14], Nelson Gouveia [15], Vitor H Nascimento [3], Ester C Sabino [9], Nuno R Faria [4, 9, 16], Jane P Messina [1, 17]

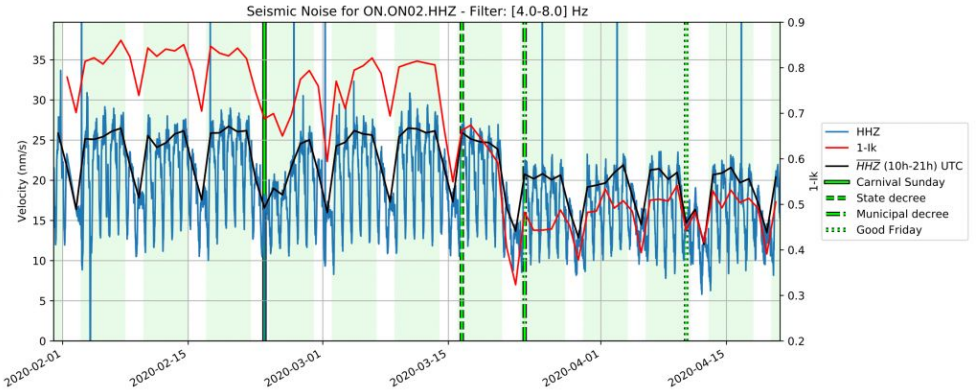
Other studies

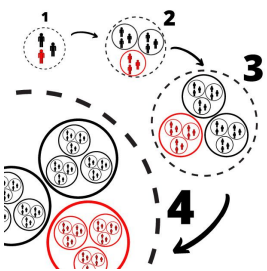
- **Mobility and connections with seismic noise** (Dias, Assumpção, Peixoto, Bianchi, Collaço, Calhau, 2020. Using seismic noise levels to monitor social isolation: An example from Rio de Janeiro, Brazil. Geophysical Research Letters, 47(16))

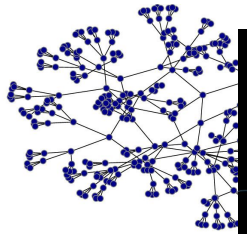
- **Fractal SIR model** (Policarpo, Ramos, Dye, Faria, Leal, Moraes, Parag, Peixoto, Buss, Sabino, Nascimento, 2023. Scale-free dynamics of Covid-19 in a Brazilian city. Applied Mathematical Modelling, 121, pp.166-184.)

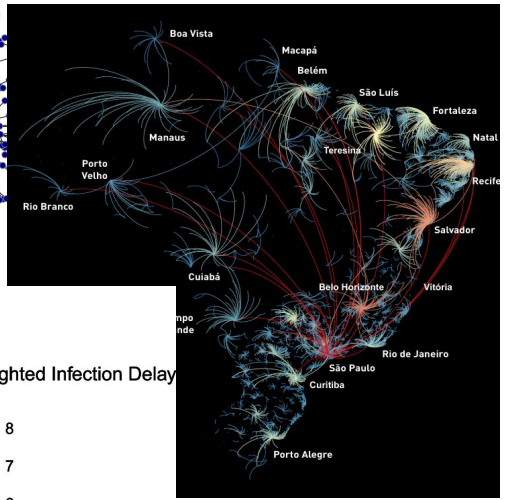
- **Network Centrality** (Shiv , Pereira, Peixoto, Camargo, 2023. Impact of network centrality and income on slowing infection spread after outbreaks. Applied Network Science 8, no. 1, 16.)

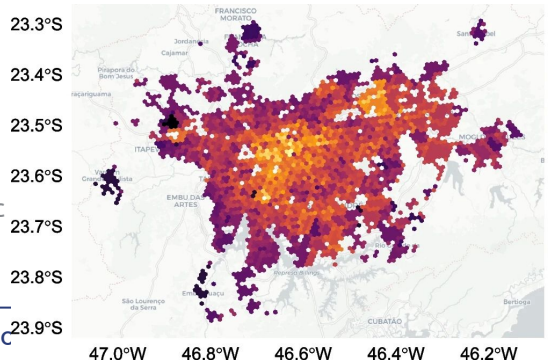
- **Highways and Boomerangs** (Nicolelis, Raimundo, Peixoto, Andreazzi (2021). The impact of super-spreader cities, highways, and intensive care availability in the early stages of the COVID-19 epidemic in Brazil. Scientific Reports.)











https://www.ime.usp.br/~pedrosp/covid19/

What have we learned?

The applied mathematics viewpoint:

- **Mobility data is important** for prevention and understanding...
  ... but has **limitations**!

- Models may provide **useful** insights ...
  ... despite its **limitations**.

- The **spatial-temporal dynamics** and the interplay with human interventions is very **complex**!

- **Applied mathematics** is at the core of epidemiological modelling...
  ... but it requires work in **collaboration**.

Thank you!

"All models are wrong, but some are useful"

— George Box

Check further results and info at:
pedrosp.ime.usp.br

For covid related studies:
https://www.ime.usp.br/~pedrosp/covid19/

Acknowledgements: Many collaborators!

FAPESP FUNDAÇÃO DE AMPARO À PESQUISA DO ESTADO DE SÃO PAULO

CNPq

Propaganda:

- **Concurso!**
  Professor do Departamento de Matemática Aplicada do IME-USP
  https://www.ime.usp.br/concursos/
  Área: **Matemática Aplicada Computacional**

- **Mestrado/Doutorado-Matemática Aplicada**
  (Programa de Excelência CAPES 6)
  Inscrições abertas até *31 de Outubro*.
  www.ime.usp.br/pos-aplicada/

- Curso de **Métodos de Volumes Finitos para Modelos Globais Multiescala**
  https://www.ime.usp.br/~pedrosp/modelagem-numerica-atmosfera/