

Using a metapopulation model to explore measles outbreak risk arising from undervaccination in Virginia

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Background

Measles: a highly infectious childhood disease with an effective vaccine

- Successful vaccination campaigns reduced measles deaths by 73% between 2000-2018 [1]
- Declared eradicated in US in 2000 [2]

Factors contributing to declining vaccination worldwide

- COVID related disruptions, vaccine hesitancy, conflict and instability [3]

Undervaccination has a significant cost

- 5% decline in vax rates → 3x cases [4]
- Outbreak events in recent years with significant public health costs (e.g NY 2018-2019, \$8.4mil) [5]

Goal: Understand & characterize outbreak risk arising from measles undervaccination in Virginia

Methods

Spatial tSIR model

- First described by Xia et al [7]
- A stochastic metapopulation model originally used for analyzing and inferring properties of historical measles case data

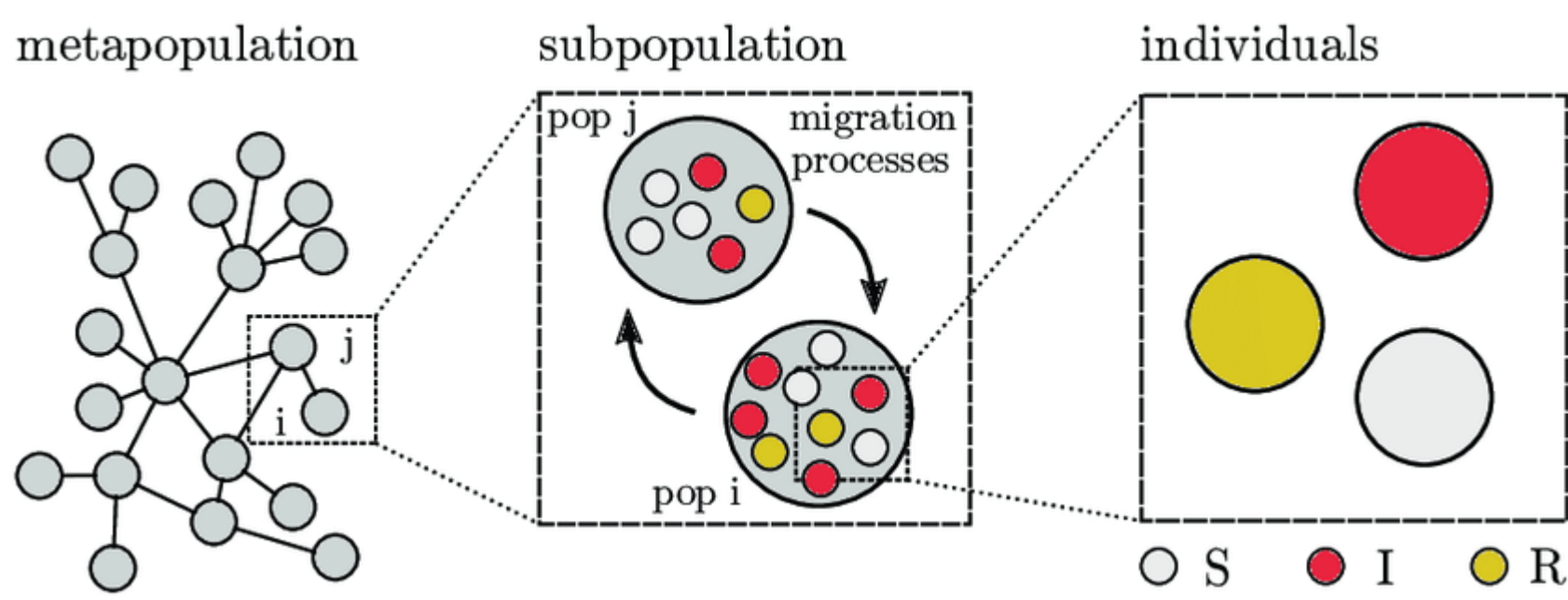


Figure 1. A schematic representation of a metapopulation disease model. [6]

$$\mathbb{E}[I_{k,t+1}] = \frac{\beta_t S_{k,t} (I_{k,t} + \nu_{k,t})^\alpha}{N_{k,t}}$$

Equation 1. The governing equation of the tSIR model. [7]

Gravity model

- Classical empirical model used to model human mobility and economic flows
- Used in the spatial tSIR model to describe spatial diffusion of the disease

$$F_{i,j} = \theta \frac{N_i^{\tau_1} N_j^{\tau_2}}{\text{dist}(i,j)^\rho}$$

Equation 2. The gravity model. [7], [8]

Virginia zipcode data

- Used zipcode-level geospatial data to parameterize the model.
- Latitude and longitude of zipcodes obtained using Nominatim API.
- Straight-line pairwise distances computed using geopy package.
- Zipcode level vaccination data obtained from VA insurance claims data project at BII. Data provided by Sifat Moon.



Figure 2. Heatmap of VA vaccination rates.

References

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- [9] "2011-2015 5-Year ACS Commuting Flows." 2021. Census.gov. US Census Bureau. <https://www.census.gov/data/tables/2015/demo/metro-micro/commuting-flows-2015.html>.
- [10] Silva, JMC Santos, and Silvana Tenreiro. 2006. "The Log of Gravity." *The Review of Economics and Statistics* 88 (4): 641-58.

Calibrating the gravity model

- Obtained 2011-2015 ACS county-level commuting flow data for Virginia from US Census data repository [9].
- Made county-level predictions from zipcode-level model by aggregating flows up to county level.
- Calibrated the gravity model against county-level data by log-transforming input parameters [10] and minimizing prediction MSE using `scipy.minimize`.

$$F_{i,j} = \exp(\theta' + \tau_1' \ln(N_i) + \tau_2' \ln(N_j) - \rho' \ln(\text{dist}(i, j)))$$

where

$$\tau_1' = \ln(\tau_1)$$

$$\tau_2' = \ln(\tau_2)$$

$$\rho' = \ln(\rho)$$

$$\theta' = \ln(\theta)$$

Equation 3. Log-transformed gravity model. [10]

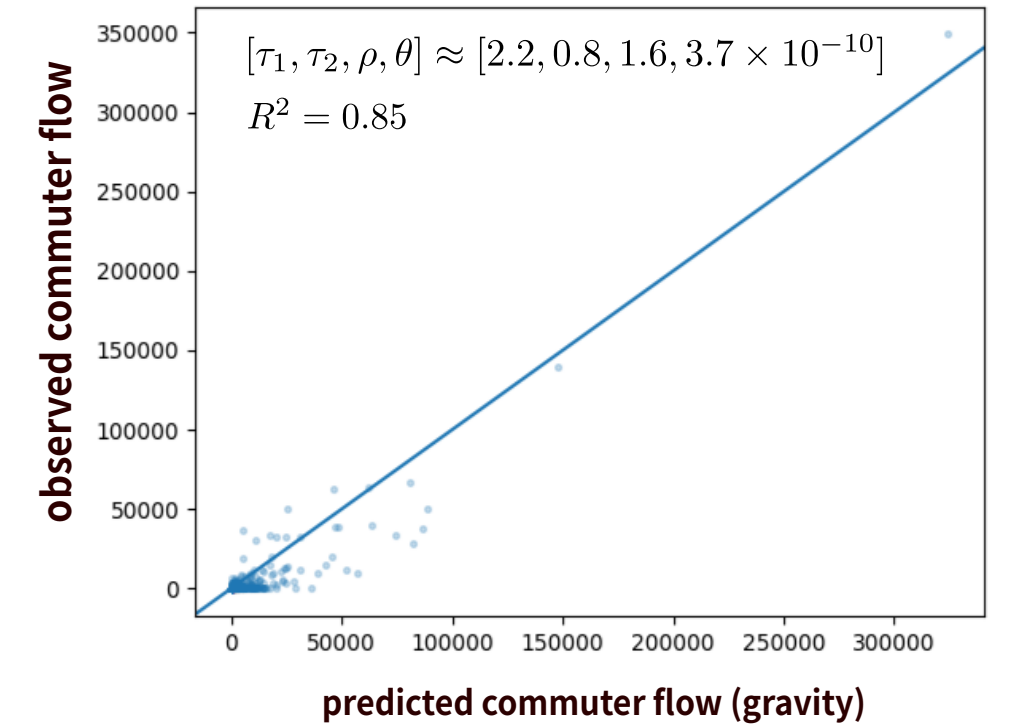


Figure 3. Calibrated gravity model.

Study design

To understand basic properties and behavior of the model, a basic sensitivity analysis was carried out.

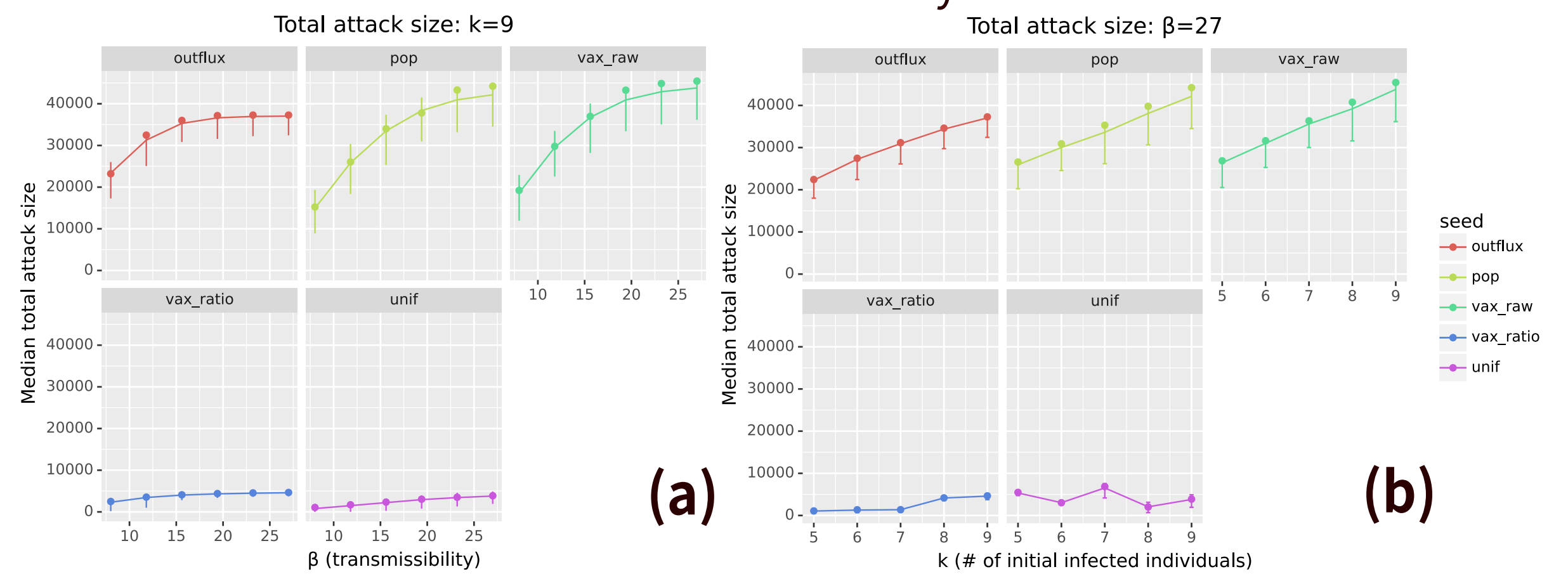
- Performed Monte-Carlo simulation of the model with 8,000 draws per simulation.
- Full factorial design.

Variable	Description	Values
β	Disease transmissibility parameter. In this model, roughly corresponds to R_0 .	8, 11.8, 15.6, 19.4, 23.2, 27
Seeding heuristic	The heuristic used to select the zipcodes to initialize. Each selected zipcode is initialized with one infected individual	'pop' – patches with largest population 'outflux' – patches with largest predicted outflow of individuals to other patches 'vax_ratio' – largest ratio of unvaccinated individuals 'vax_raw' – largest raw counts of unvaccinated individuals 'unif' – select patches uniformly randomly
k	The # of patches matching the heuristic to initialize with an infected individual (e.g top 5 by population if 'pop' selected)	5, 6, 7, 8, 9

Table 1. Parameters of the analysis. All possible combinations were computed.

Results

The total attack size distributions were analyzed.



Seeding heuristic	'pop'	'outflux'	'vax_raw'
Zip codes	22193, 23464, 22191, 23452, 23454	22003, 23452, 23462, 23464, 22042	22193, 23464, 23452, 22030, 22003
County names	Prince William, Virginia Beach	Fairfax County, Virginia Beach, Falls Church	Prince William, Virginia Beach, Fairfax County, Fairfax City

Figure 4.

- Median total attack size of the outbreak simulations with observed 95% interval. Here, k is fixed at $k=9$ while beta varies.
- Median total attack size of the outbreak simulations with observed 95% interval. Here, beta is fixed at $\beta=27$ while k varies.
- Table showing the locations selected by the heuristics 'pop', 'outflux', and 'vax_raw' for $k=5$.

Observations

- When beta low, 'outflux' causes larger outbreaks.
- When beta larger, 'pop' and 'vax_raw' are larger
- Linear scaling with k , nonlinear with beta
- Heavy skew in total attack size distributions.

Next steps

- Model likely overpredicting total outbreak size. Beta parameter likely needs to be tuned more rigorously
- More rigorous analysis:
 - Formal optimization routines for risk analysis
 - Cluster analysis for detection of undervacc. regions

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Sifat Moon for providing VA vaccination data, Srin Venkatraman for advice on using PatchSim and understanding metapopulation models, Bryan Lewis for helpful conversations about doing research