Quantifying pandemic inequality in heterogeneous populations

21 February 2024
CCS Workshop
Evolution of Social Complexity 2024

Sheryl L. Chang

Modelling and Simulation Research Group
School of Computer Science
Faculty of Engineering

Sydney Infectious Diseases Institute

THE UNIVERSITY OF SYDNEY

Overview

- COVID-19 pandemic modelling in Australia
- Comparative analysis
    - Variants of concern
    - Intervention policies
    - Population heterogeneity
- Measuring pandemic inequality across the country
    - Pandemic Lorenz curves

COVID-19 pandemic modelling

- Modelling pandemics with large-scale high-resolution agent-based models (ABM)
  - Demographics: from census based data to agents
  - Mobility: travel patterns including international travels
  - Infection: disease transmission and natural history models
  - AMTraC-19 : Agent-based Model of Transmission and Control of the COVID-19 pandemic in Australia
- COVID-19 pandemic
  - Age-dependent epidemiological characteristics
  - Pandemic trends (peaks, resurgence), and model validation
  - Strategies for mitigation, suppression (or elimination)
  - Tipping points in social distancing for different variants
  - Partial immunity from imperfect vaccines
  - Clinical burden estimation
  - Dynamic NPIs compliance

Our work

#	Date	Strain	NPI	Genome sequencing	Vaccination	Clinical burden	Note
[1]	March 2020	Ancestral	✓				First COVID-19 modelling study
[2]	July 2020	Ancestral		✓			Cross validated with genomic sequencing data
[3]	March 2021	Ancestral	✓		✓		Added vaccination rollout
[4]	July 2021	Delta	✓		✓	✓	Re-calibrated for Delta variant; added clinical burden model
[5]	November 2022	Omicron	✓		✓	✓	Re-calibrated for Omicron variant; added dynamic social distancing assignment and compliance

[1] **S. L. Chang**, N. Harding, C. Zachreson, O. M. Cliff, M. Prokopenko, Modelling transmission and control of the COVID-19 pandemic in Australia, *Nature Communications*, 11, 5710, 2020.

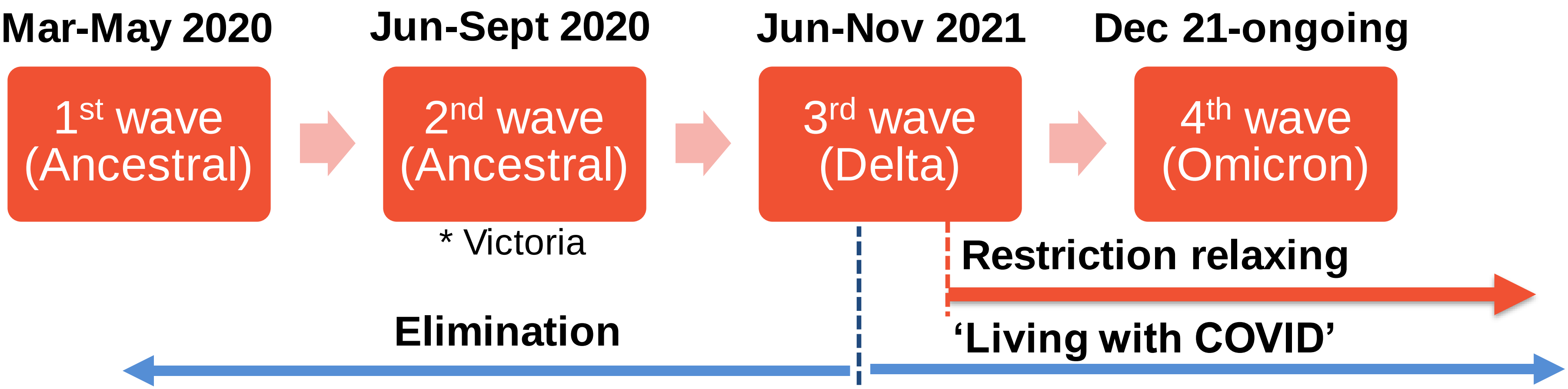
[2] R. J. Rockett, A. Arnott, C. Lam, et al., Revealing COVID-19 transmission by SARS-CoV-2 genome sequencing and agent based modelling, *Nature Medicine*, 26: 1398–1404, 2020.

[3] C. Zachreson, **S. L. Chang**, O. M. Cliff, M. Prokopenko, How will mass-vaccination change COVID-19 lockdown requirements in Australia?, *The Lancet Regional Health – Western Pacific*, 14: 100224, 2021.

[4] **S. L. Chang**, O. M. Cliff, C. Zachreson, M. Prokopenko, Simulating transmission scenarios of the Delta variant of SARS-CoV-2 in Australia, *Frontiers in Public Health*, 10.3389, 2022

[5] **S. L. Chang**, Q. D. Nguyen, A. Martiniuk, V. Sintchenko, T. C. Sorrell, M. Prokopenko, Persistence of the Omicron variant of SARS-CoV-2 in Australia: The impact of fluctuating social distancing, *PLOS Global Public Health*, 3(4):e0001427, 2023

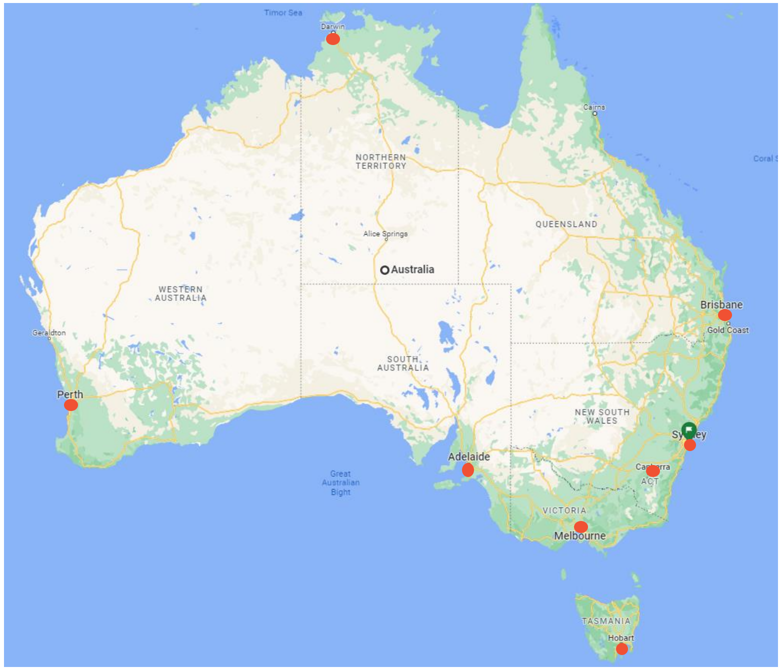
Policy change in Australia



- **Mar 2020:** international and interstate borders closed
- States and territories impose interventions including:
  - Mandatory 14-day quarantine
  - Stay-at-home orders (lockdowns)
  - Travel ban
  - Gathering limit
  - ……
- **Feb 2021:** vaccination rollout (Pfizer, AstraZeneca, and later Moderna)
- **Oct 2021:** 'Freedom day'
- **Feb 2022:** border reopened
- **Mar 2022:** ~95% vaccine coverage in eligible adult population
- **Oct 2022:** national emergency response ended

Comparative analysis

- How does population heterogeneity affect pandemic severity?
  - 2016 v.s. 2021 census
- How are the impacts of policy felt across the country?
  - Capital cities v.s. regional areas
- How does policy effectiveness vary with variants and population heterogeneity?
  - Ancestral, Delta, and Omicron



Our work: pandemic inequality

#	Date	Strain	NPI	Genome sequencing	Vaccination	Clinical burden	Note
[1]	March 2020	Ancestral	✓				First COVID-19 modelling study
[2]	July 2020	Ancestral		✓			Cross validated with genomic sequencing data
[3]	March 2021	Ancestral	✓		✓		Added vaccination rollout
[4]	July 2021	Delta	✓		✓	✓	Re-calibrated for Delta variant; added clinical burden model
[5]	November 2022	Omicron	✓		✓	✓	Re-calibrated for Omicron variant; added dynamic social distancing assignment and compliance
[6]	July 2023	Multiple strains	✓		✓		Pandemic inequality across different statistical areas

[1] **S. L. Chang**, N. Harding, C. Zachreson, O. M. Cliff, M. Prokopenko, Modelling transmission and control of the COVID-19 pandemic in Australia, *Nature Communications*, 11, 5710, 2020.

[2] R. J. Rockett, A. Arnott, C. Lam, et al., Revealing COVID-19 transmission by SARS-CoV-2 genome sequencing and agent based modelling, *Nature Medicine*, 26: 1398–1404, 2020.

[3] C. Zachreson, **S. L. Chang**, O. M. Cliff, M. Prokopenko, How will mass-vaccination change COVID-19 lockdown requirements in Australia?, *The Lancet Regional Health – Western Pacific*, 14: 100224, 2021.

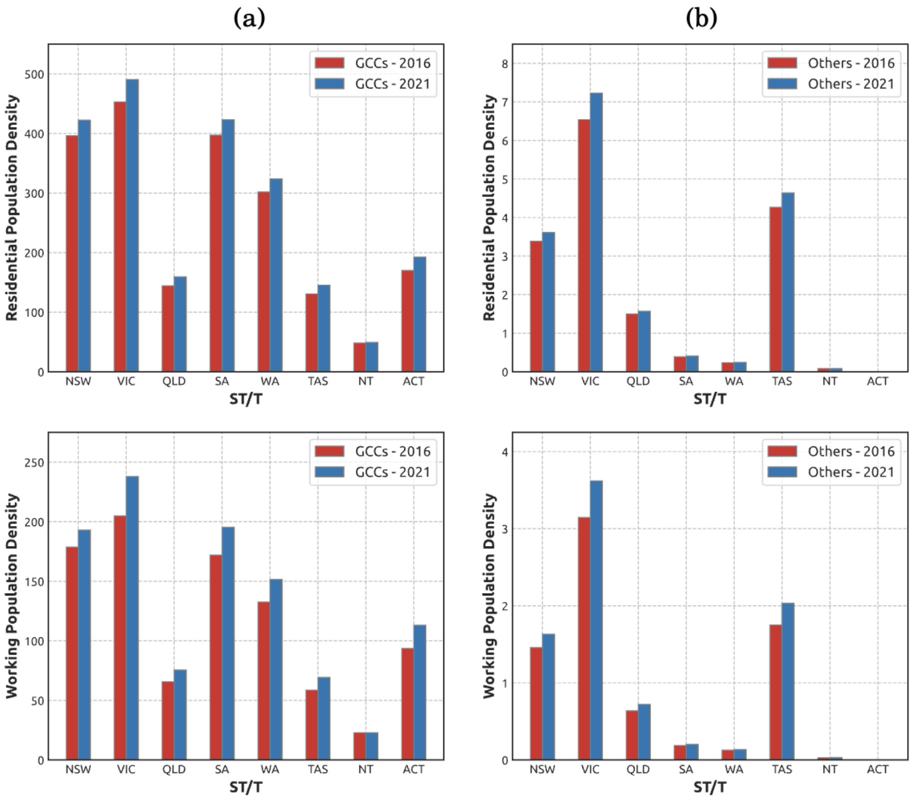
[4] **S. L. Chang**, O. M. Cliff, C. Zachreson, M. Prokopenko, Simulating transmission scenarios of the Delta variant of SARS-CoV-2 in Australia, *Frontiers in Public Health*, 10.3389, 2022

[5] **S. L. Chang**, Q. D. Nguyen, A. Martiniuk, V. Sintchenko, T. C. Sorrell, M. Prokopenko, Persistence of the Omicron variant of SARS-CoV-2 in Australia: The impact of fluctuating social distancing, *PLOS Global Public Health*, 3(4):e0001427, 2023

[6] Q. D. Nguyen, **S. L. Chang**, C. M. Jarmerlan, M. Prokopenko, Measuring unequal distribution of pandemic severity across census years, variants of concern and interventions, *Population Health Metrics* **21,** 17, 2023

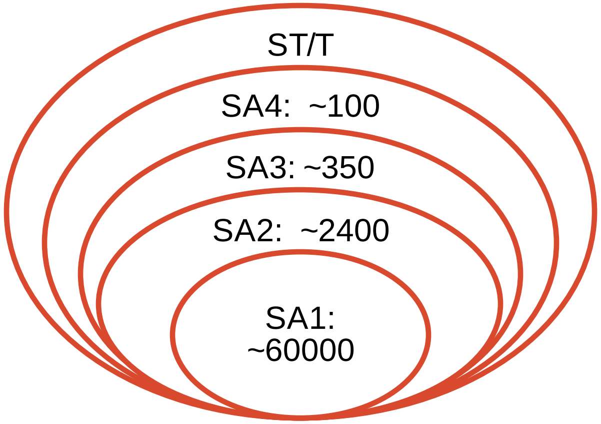
Australian population

- Total population
  - 23.4 million, 2016 Census → 25.4 million, 2021 Census
- High population heterogeneity
  - Greater Capital Cities (GCC) v.s. others



Census-based demographics

- Artificial population constructed from 2016 and 2021 Australian census
  - Residential Statistical Area
  - Destination Zone (i.e., travel to work)
  - Household composition
  - School-aged population and teachers



Statistical area	Population size
SA1	200~800
SA2	3,000~25,000
SA3	30,000~130,000
SA4	100,000~500,000

Q. D. Nguyen, **S. L. Chang**, C. M. Jamerlan, M. Prokopenko, Measuring unequal distribution of pandemic severity across census years, variants of concern and interventions, *Population Health Metrics* **21,** 17, 2023

ABM: population partitions

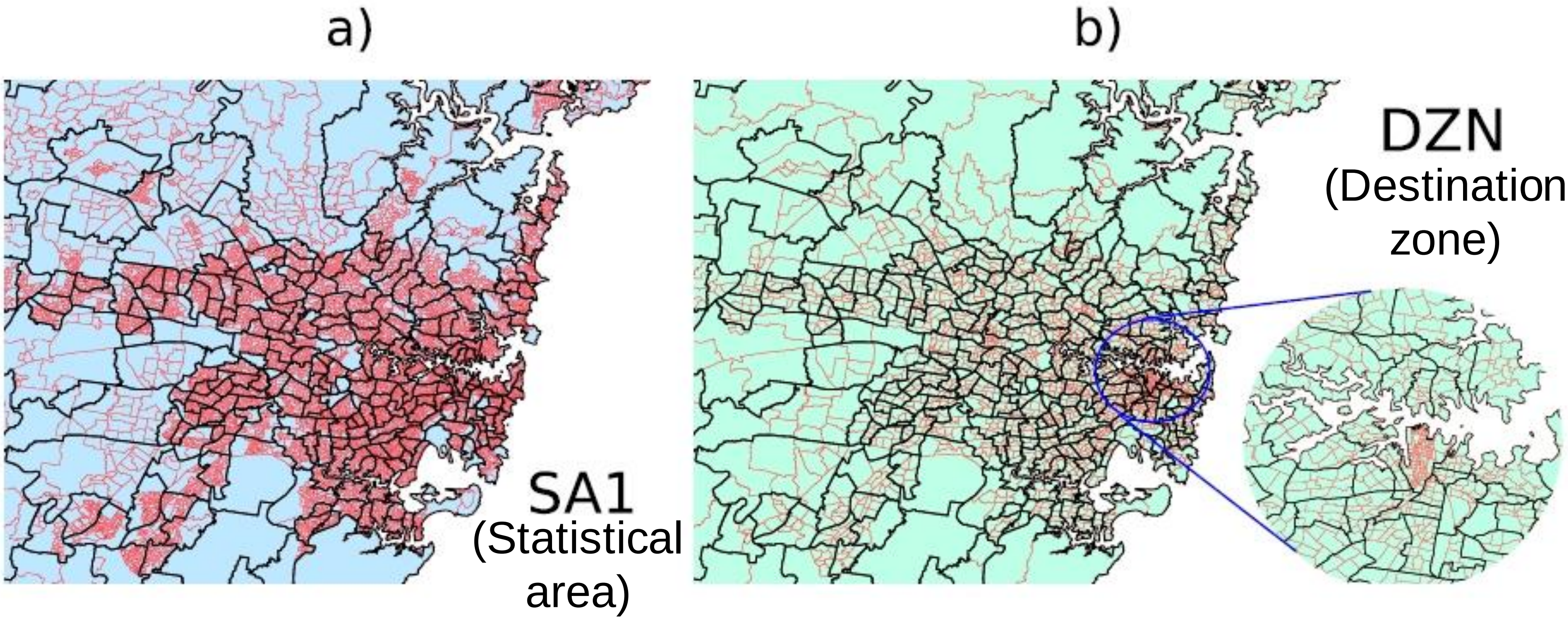
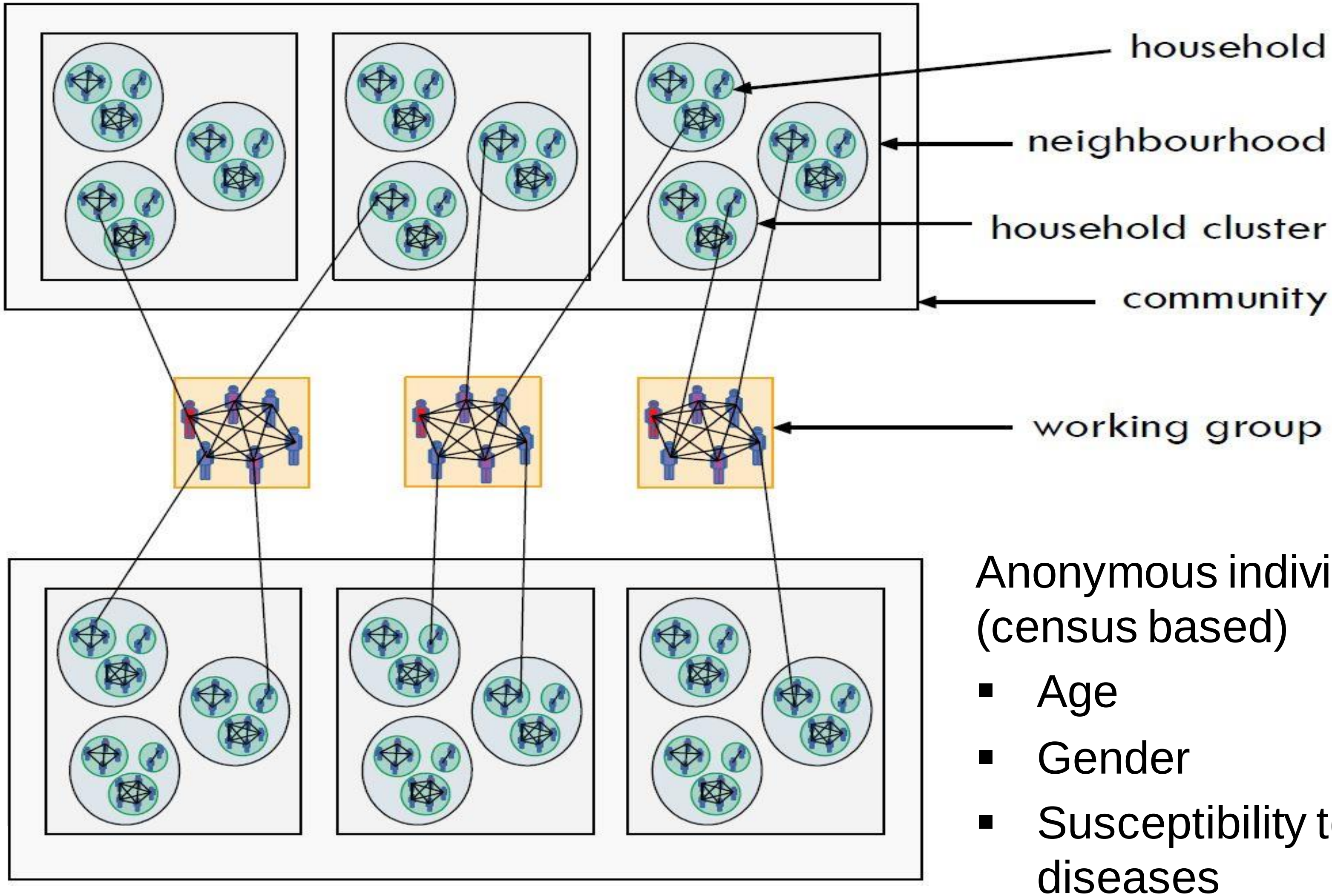


Fig. 1 Maps of the Greater Sydney region illustrating the distribution of population partitions. (**a**) A map of the Greater Sydney region showing SA2 (black) and SA1 (red) population partitions. (**b**) A map of the same area showing SA2 (black) and DZN (red) partitions. The inset in (**b**) zooms in on the Sydney central business district to illustrate the much denser packing of DZN partitions in that area.

K. M. Fair, C. Zachreson, M. Prokopenko, Creating a surrogate commuter network from Australian Bureau of Statistics census data, *Scientific Data*, 6, 150, 2019.

ABM: mixing contexts

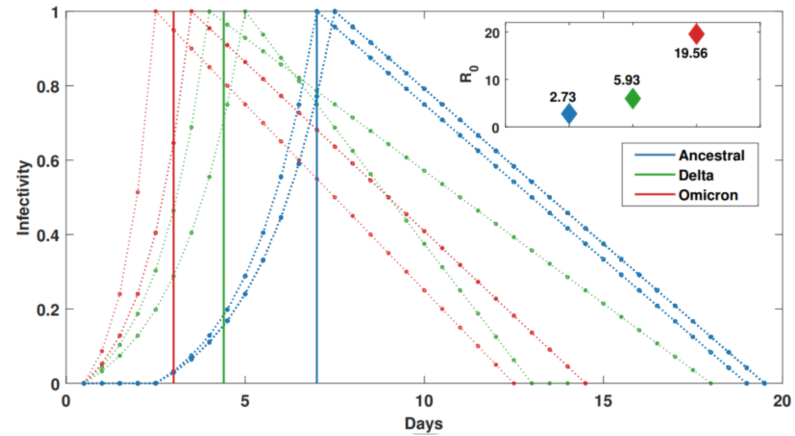


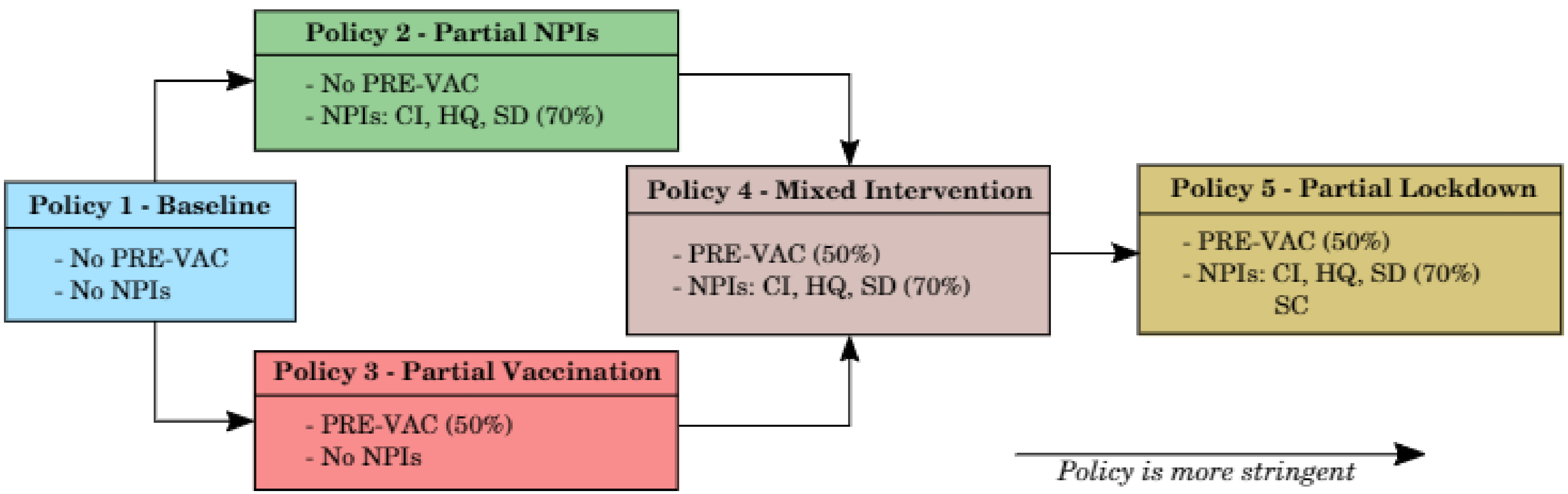
Anonymous individuals (census based)

- Age
- Gender
- Susceptibility to diseases

Simulation scenarios

- Five policies
  - Policy 1 to 5
- Three variants
  - Ancestral, Delta, and Omicron
- Two census years
  - 2016 v.s. 2021

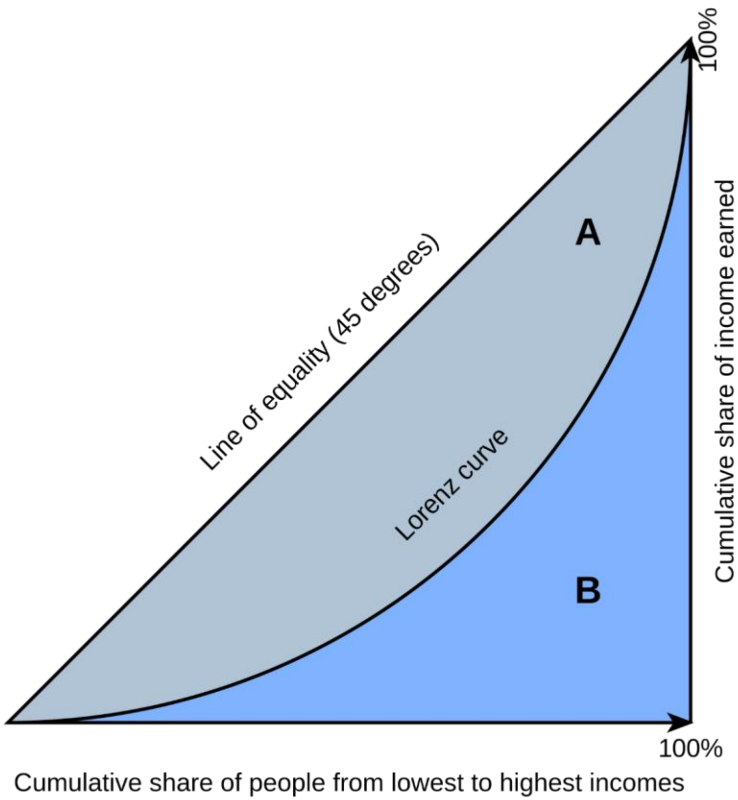




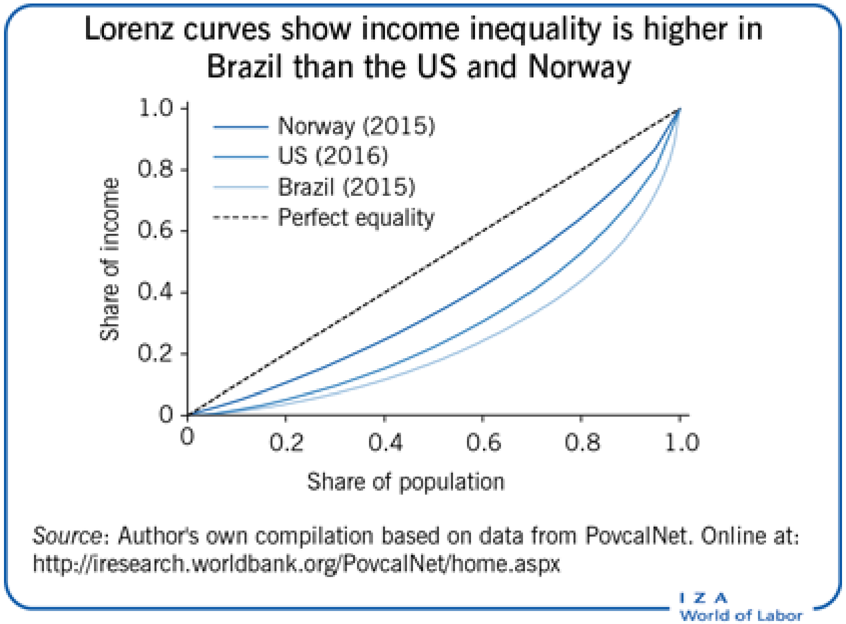
Q. D. Nguyen, **S. L. Chang**, C. M. Jamerlan, M. Prokopenko, Measuring unequal distribution of pandemic severity across census years, variants of concern and interventions, *Population Health Metrics* **21,** 17, 2023

Lorenz Curve

- Inequality of wealth distribution



Credit: https://en.wikipedia.org/wiki/Lorenz_curve



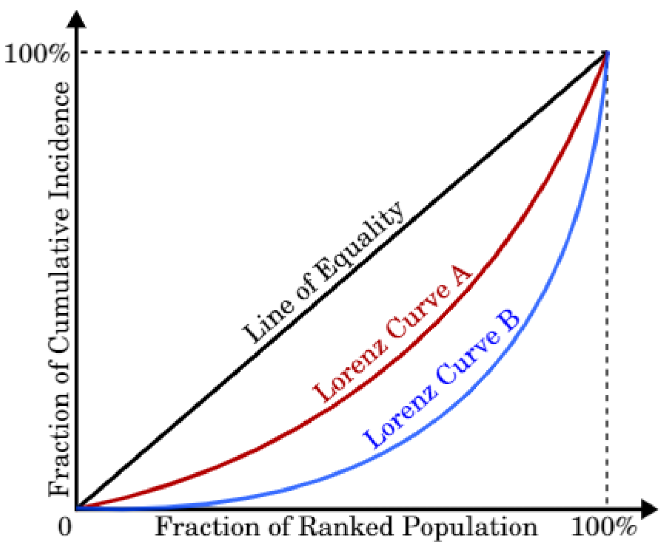
Credit: https://wol.iza.org/articles/measuring-income-inequality/long

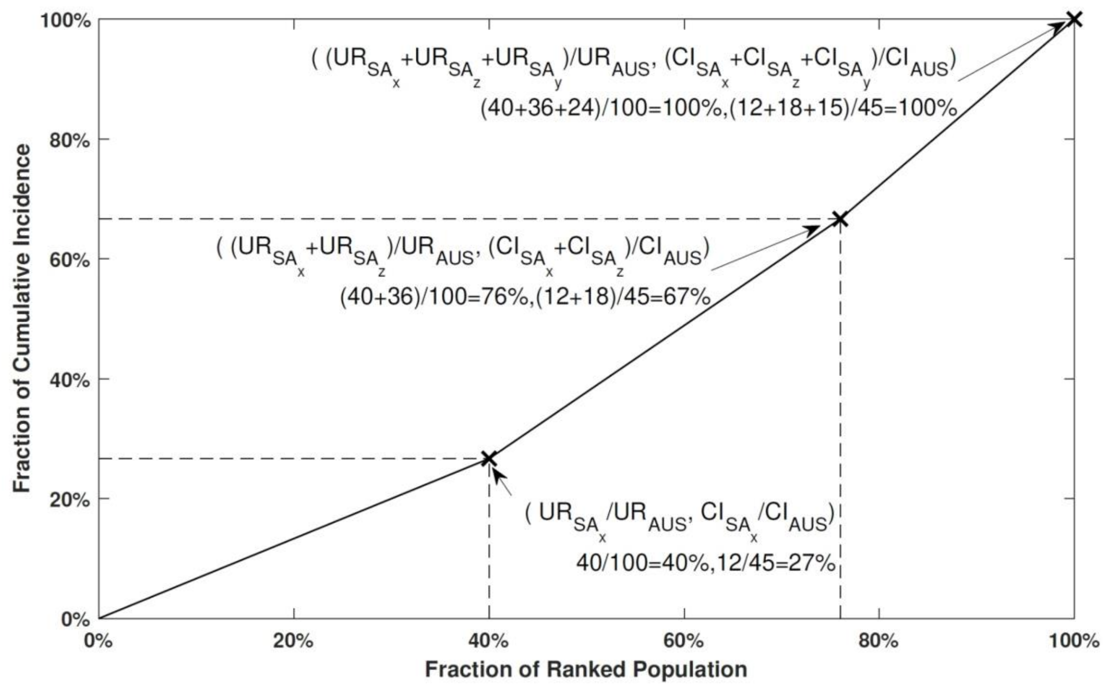
Pandemic Lorenz Curve

- Inequality of pandemic severity
  - Rank SA2s by their local attack rate
  - Add SA2s cumulatively to form:
    - X-axis: residential population (%)
    - Y-axis: cumulative incidence (%)

SA2	CI	UR	AR	AR_{SA2} rank
SA_x	12	40	$12/40 = 0.3$	1
SA_y	15	24	$15/24 = 0.625$	3
SA_z	18	36	$18/36 = 0.5$	2
National total	45	100	$45/100 = 0.45$	NA

Table D.1: Lorenz curves setup: demographic and epidemic characteristics of a simplified example.

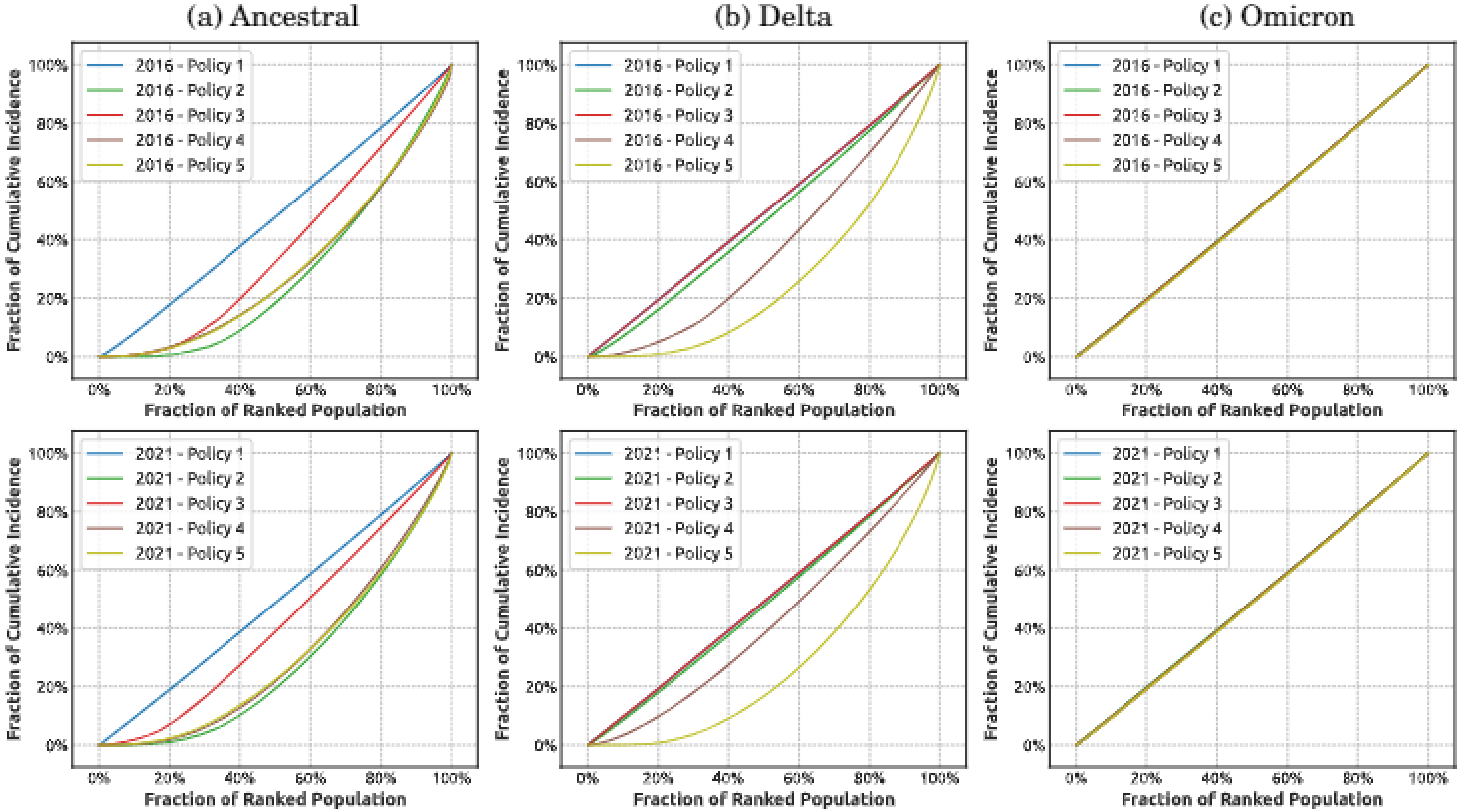




Q. D. Nguyen, S. L. Chang, C. M. Jamerlan, M. Prokopenko, Measuring unequal distribution of pandemic severity across census years, variants of concern and interventions, *Population Health Metrics*, 21, 17, 2023

Key findings: policy comparison

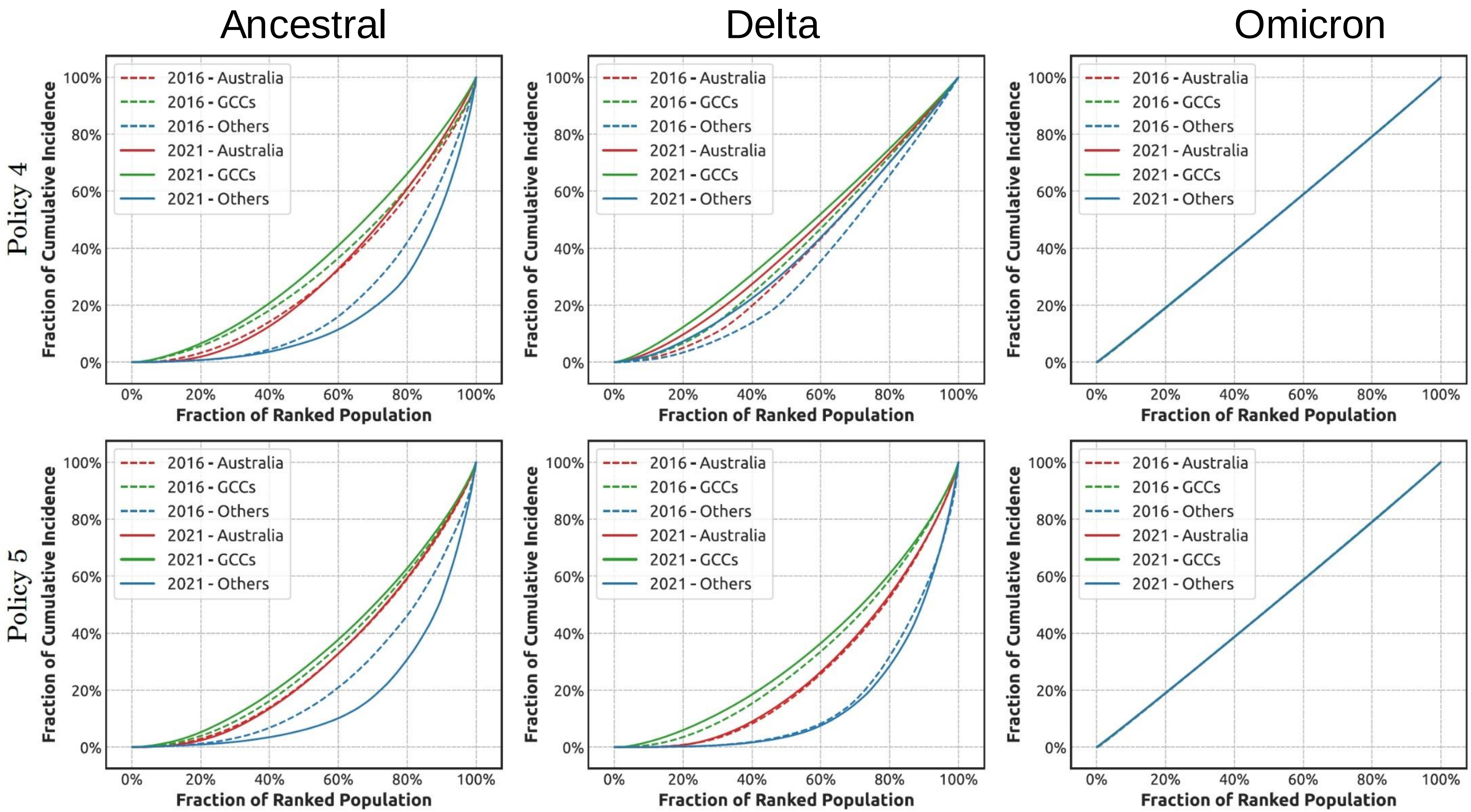
- Unequal distribution of pandemic severity across local areas captured by pandemic Lorenz curves



Q. D. Nguyen, **S. L. Chang**, C. M. Jarmerlan, M. Prokopenko, Measuring unequal distribution of pandemic severity across census years, variants of concern and interventions, *Population Health Metrics* **21,** 17, 2023

Key findings: capital cities vs others

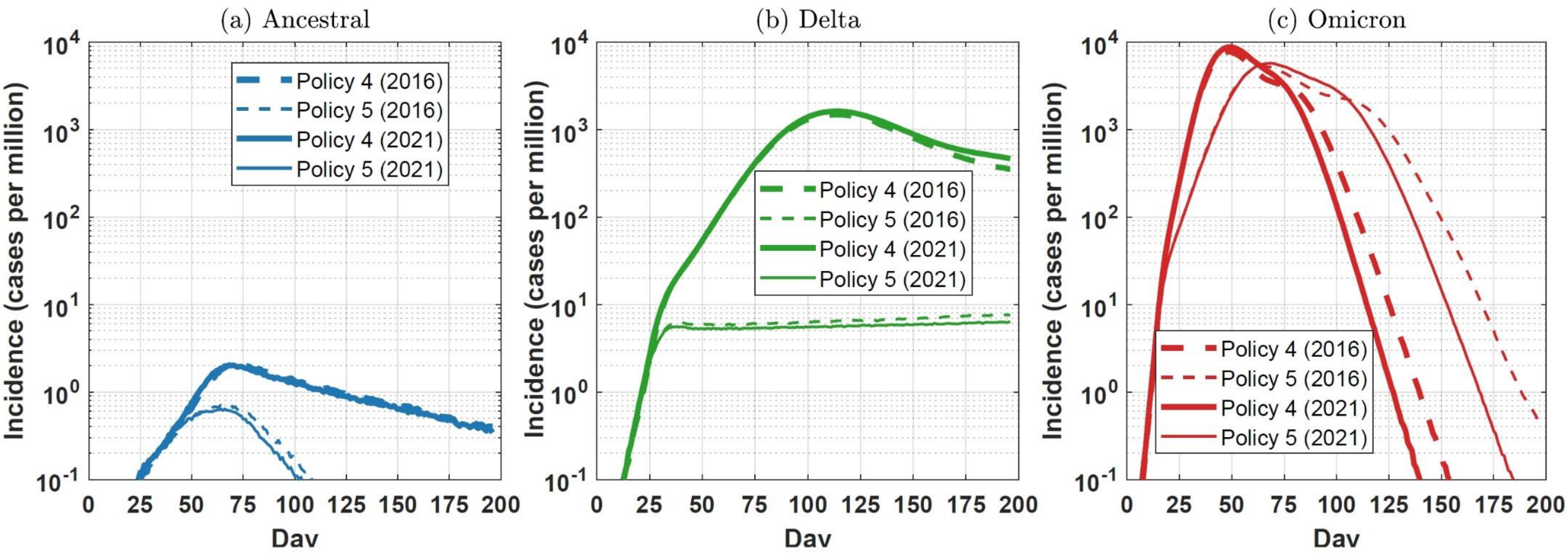
- Unequal distribution of pandemic severity between GCCs and other areas



Q. D. Nguyen, **S. L. Chang**, C. M. Jarmerlan, M. Prokopenko, Measuring unequal distribution of pandemic severity across census years, variants of concern and interventions, *Population Health Metrics* **21,** 17, 2023

Key findings: effect of school closures

- Effects of school closures are most prominent for the Delta variant



Q. D. Nguyen, **S. L. Chang**, C. M. Jarmerlan, M. Prokopenko, Measuring unequal distribution of pandemic severity across census years, variants of concern and interventions, *Population Health Metrics* **21,** 17, 2023

Summary

- We incorporated the latest 2021 Australian census data into our ABM
- Systematic analysis to model comparative scenarios with:
  - Multiple variants of concern
  - Different demographic settings
  - Different intervention policies
- Unequal distribution of pandemic severity affected by:
  - Census years
  - Urbanisation

Looking forward: pandemic inequality

- Other population metrics
  - Occupation
  - Socio-economic factors
- Other severity metrics
  - Health benefits
- More complicated intervention policies
  - Mobility restriction (e.g., 5 km travel radius)
  - Waning compliance to intervention policies

References

- O. M. Cliff, N. Harding, M. Piraveenan, E. Erten, M. Gambhir, M. Prokopenko, Investigating spatiotemporal dynamics and synchrony of infuenza epidemics in Australia: An agent-based modelling approach, *Simulation Modelling Practice and Theory*, 87, 412-431, 2018.
- K. M. Fair, C. Zachreson, M. Prokopenko, Creating a surrogate commuter network from Australian Bureau of Statistics census data, *Scientific data*, 6, 150, 2019.
- **S. L. Chang**, N. Harding, C. Zachreson, O. M. Cliff, M. Prokopenko, Modelling transmission and control of the COVID-19 pandemic in Australia, *Nature Communications,* 11, 5710, 2020.
- R. J. Rockett, et al. Revealing COVID-19 transmission by SARS-CoV-2 genome sequencing and agent based modelling, *Nature Medicine*, 26: 1398–1404, 2020.
- C. Zachreson, **S. L. Chang**, O. M. Cliff, M. Prokopenko, How will mass-vaccination change COVID-19 lockdown requirements in Australia? *The Lancet Regional Health – Western Pacific*, 14: 100224, 2021.
- **S. L. Chang**, O. M. Cliff, C. Zachreson, M. Prokopenko, Simulating transmission scenarios of the Delta variant of SARS-CoV-2 in Australia, *Frontiers in Public Health*, 10.3389, 2022
- **S. L. Chang**, Q. D. Nguyen, A. Martiniuk, V. Sintchenko, T. C. Sorrell, M. Prokopenko, Persistence of the Omicron variant of SARS-CoV-2 in Australia: The impact of fluctuating social distancing, *PLOS Global Public Health*, 3(4):e0001427, 2023
- Q. D. Nguyen, **S. L. Chang**, C. M. Jarmerlan, M. Prokopenko, Measuring unequal distribution of pandemic severity across census years, variants of concern and interventions, *Population Health Metrics* **21,** 17, 2023

ABM: mobility (international air traffic)

- Number of imported infections is proportional to the number of incoming passengers
- 4 large airports take most of the passenger influx

Airport code	State	City	Passengers
SYD	NSW	Sydney	40884
MEL	VIC	Melbourne	25859
BNE	QLD	Brisbane	14250
PER	WA	Perth	11449
OOL	QLD	Gold Coast	3022
ADL	SA	Adelaide	2214
CNS	QLD	Cairns	1874
DRW	NT	Darwin	597
TSV	QLD	Townsville	105

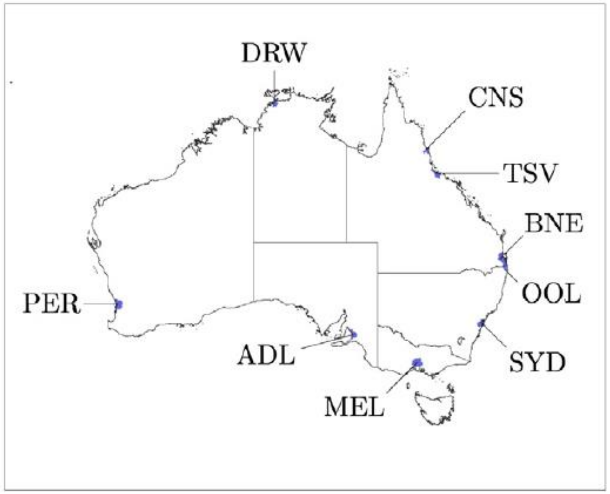


Fig. 3. Daily incoming passengers per Australian international airport obtained from BITRE [30] along with a map detailing the airport locations.

O. M. Cliff, N. Harding, M. Piraveenan, E. Y. Erten, M. Gambhir, M. Prokopenko, Investigating Spatiotemporal Dynamics and Synchrony of Influenza Epidemics in Australia: An Agent-Based Modelling Approach, *Simulation Modelling Practice and Theory*, 87, 412–431, 2018.

ABM: infection (disease transmission)

- Age breakdown:
  - Child
    - Preschool aged children (0-4)
    - Children (5-18)
  - Adult
    - Young adults (19-29)
    - Adults (30-65)
    - Older adults (65+)

- Mixing contexts:
  - Household cluster
  - School
  - Working group
  - Neighbourhood
  - Community

Daily contact probabilities
Daily transmission probabilities

$$p_i(n) = 1 - \prod_{g \in G_i(n)} \left[\prod_{j \in A_g \setminus i} (1 - p^g_{j \to i}(n)) \right]$$

$$p^g_{j \to i}(n) = \kappa \; f(n - n_j \mid j) \; q^g_{j \to i}$$

global scalar (κ)

Calibration:

Ancestral	R_0	T_{gen} (days)	T_{inc} (days)	T_{rec} (days)
Mean	2.77	7.62	5.5	12
95% CI	2.73-2.83	7.53-7.70		

Delta	R_0	T_{gen} (days)	T_{inc} (days)	T_{rec} (days)
Mean	6.2	6.93	4.4	10.5
95% CI	6.16 – 6.23	6.87 – 6.99	Lognormal ($\mu = 1.396; \sigma = 0.413$)	uniform 7 – 14

Omicron	R_0	T_{gen} (days)	T_{inc} (days)	T_{rec} (days)
Mean	19.56	5.42	3	9
95% CI	19.12 -19.65	5.38 -5.44	Lognormal ($\mu = 1.013; \sigma = 0.413$)	uniform7 – 11

We also calibrate against:

- Attack rate in children (lower than adults)
- Initial daily growth rate of cumulative incidence (unmitigated, roughly 0.2 per day)
- Proportion of symptomatic and asymptomatic cases
  - Adult (≥ 19): 67% symptomatic, 33% asymptomatic
  - Child (≤ 18):
    - Ancestral strain: 13.4% symptomatic, 86.6% asymptomatic
    - Delta and Omicron: 26.8% symptomatic, 73.2% asymptomatic
- Reduced asymptomatic infectivity (i.e. 30% of the symptomatic counterpart)

Intervention: NPI

	Population wise ‘Macro parameters’	Context wise ‘Micro parameters’		
NPI	**Compliance**	**Interaction strength**		
		Household	Community	Workplace
Case isolation	0.7 – 0.8	1.0	0.1 – 0.25	0.1 – 0.25
Home quarantine	0.5 – 0.7	2.0	0.1 – 0.25	0.1 – 0.25
School (students)	1.0	1.0	0.1 – 0.5	0.0
School (parents)	0.5	1.0	0.1 – 0.5	0.0
Social distancing	0.0 – 1.0	1.0	0.1 – 0.25	0.1

S. L. Chang, O. M. Cliff, C. Zachreson, M. Prokopenko, Simulating transmission scenarios of the Delta variant of SARS-CoV-2 in Australia, *Frontiers in Public Health*, 10.3389, 2022

Intervention: vaccination rollout

- Age-dependent vaccination strategy
  - Pre-pandemic
  - Progressive rollout (weekly)
- Vaccine type and allocation
  - Priority vaccine
  - General vaccine
  - Immunisation allocation by age (100:10:1 to age >65:18<age<65: age<18)
- Vaccine efficacy
  - Clinical efficacy (VEc)
    - Efficacy for susceptibility (VEs): reduces the probability of becoming infected if exposed
    - Efficacy for disease (Ved): reduces the probability of expressing symptoms if infected)
  - Efficacy for infectiousness (VEi): reduces the force of infection produced by infected individuals who are vaccinated

$$VEc = VEd + VEs - VEs \times VEd \qquad VEi = \sim 0.5$$

for example: $0.92 = 0.8 + 0.6 - 0.8 \times 0.6$ (Priority vaccine)

$0.75 = 0.5 + 0.5 - 0.5 \times 0.5$ (General vaccine)

C. Zachreson, S. L. Chang, O. M. Cliff, M. Prokopenko, How will mass-vaccination change COVID-19 lockdown requirements in Australia? *The Lancet Regional Health – Western Pacific*, 14: 100224, 2021.