A data-driven, model-based approach to infer shifts in social contact patterns during an evolving pandemic

January 27, 2021

Infectious Disease Outbreaks Webinar

Zachary McCarthy
York University

Teams

Collaborators

Zack McCarthy
Yanyu Xiao
Francesca Scarabel
Biao Tang
Nicola Luigi Bragazzi
Kyeongah Nah
Jane Heffernan
Ali Asgary
V. Kumar Murty
Nicholas Ogden
Jianhong Wu

LIAM COVID-19 Reopening and Recovery Modeling Group led by Prof. Jianhong Wu

Prof. Yanyu Xiao
Prof. Ali Asgary
Prof. Michael Chen
Prof. Jianhong Wu
Mahnaz Alavinejad
Nicola Luigi Bragazzi
Christopher Chow
Michael Glazer
Bushra Majeed
Zack McCarthy
Francesca Scarabel

McCarthy, Z., Xiao, Y., Scarabel, F., Tang, B., Bragazzi, N. L., Nah, K., ... & Wu, J. (2020). Quantifying the shift in social contact patterns in response to non-pharmaceutical interventions. *Journal of Mathematics in Industry*, *10*(1), 1-25.

MATHEMATICS OF COVID-19 TASK FORCE

ADERSIM U
ADVANCED DISASTER, EMERGENCY AND RAPID_RESPONSE SIMULATION

LIAM LABORATORY for Industrial & Applied MATHEMATICS

MPH Mathematics for Public Health

University of CINCINNATI

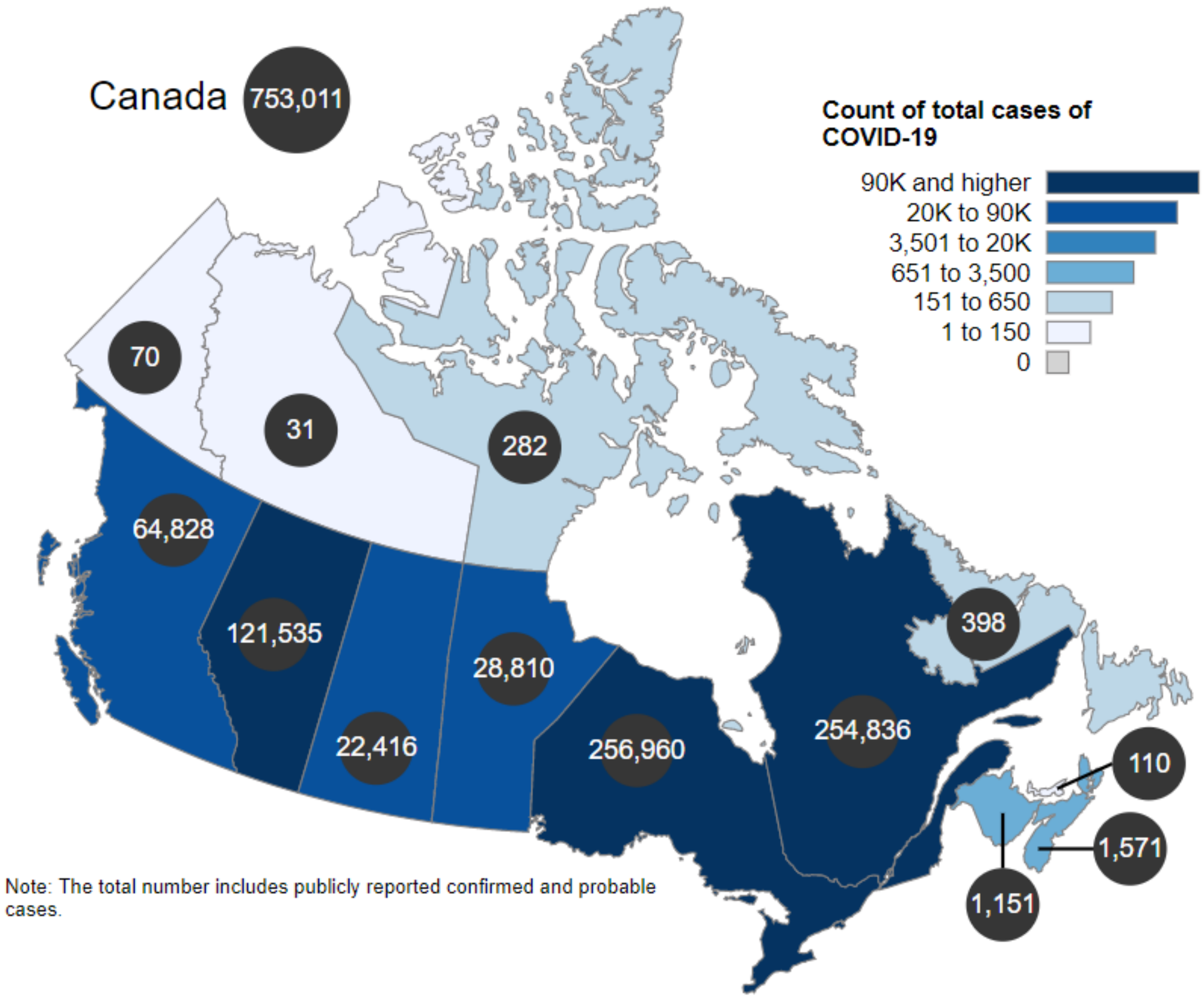
YORK UNIVERSITÉ UNIVERSITY

COVID-19 in Canada

Non-pharmaceutical interventions:

- School closures;
- Workplace closures;
- Establishment closures;
- Limiting the size of gatherings.

- Hygienic measures;
- Respiratory etiquette;
- Face masks.



1. Coronavirus disease (COVID-19): Outbreak update - Canada.ca. https://www.canada.ca/en/public-health/services/diseases/2019-novel-coronavirus-infection.html (accessed Jan 26, 2020).

Outline

- Establish a methodology for modelling impacts of non-pharmaceutical interventions (NPIs) on social contact mixing.

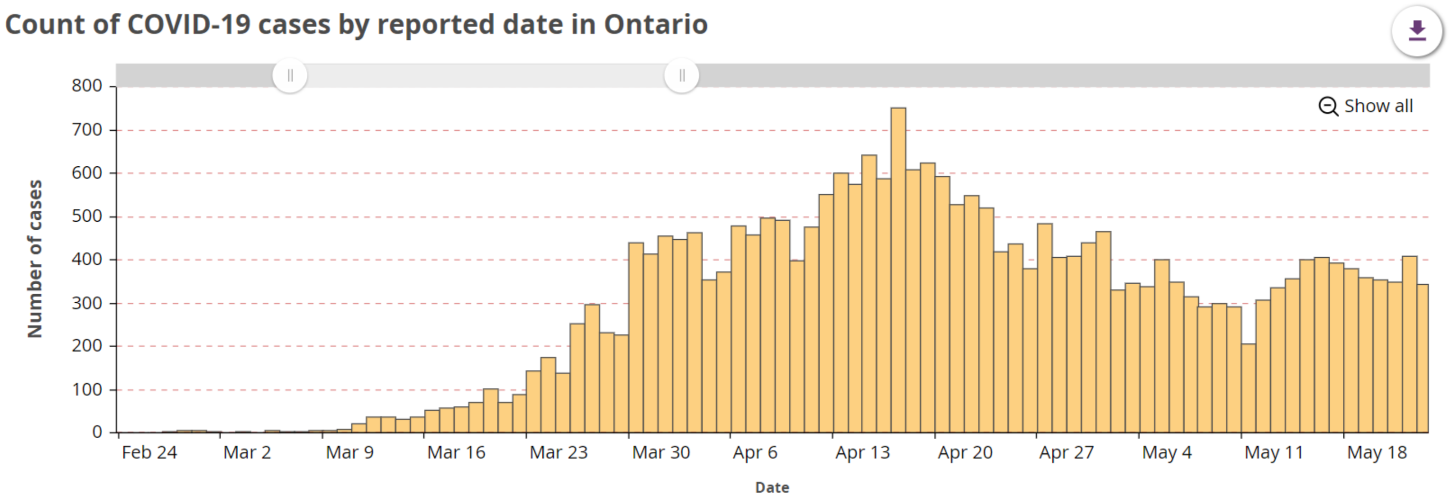
Framework enables us to infer age-specific:

- Susceptibility to infection by SARS-CoV-2;
- Contact mixing in workplace, household, school and leisure settings;
- Transmission acquired in these settings.

Utilize Ontario-specific data to illustrate the methodology.

Escalation phase analysis

- Staged reopening beginning May 19.



2. Ontario COVID-19 Data Tool | Public Health Ontario. https://www.publichealthontario.ca/en/data-and-analysis/infectious-disease/covid-19-data-surveillance/covid-19-data-tool (accessed Nov 10, 2020).

Assessing the impacts of NPIs on contact mixing

In Ontario, we consider four distinct phases:

- February 26 – March 14 (phase 0) **[Monitoring and travel advisories]**
- March 14 – 17 (phase 1) **[Public school closure]**
- March 18 – 23 (phase 2) **[State of emergency and physical distancing]**
- March 24 – May 16 (phase 3) **[Non-essential workplace closure]**

Modelling strategy

1. *Introduce transmission model;*
2. *Identify a social contact matrix representative of mixing in Ontario, Canada;*
3. *Capture the distinct phases of public health interventions taken by the government.*

Transmission model

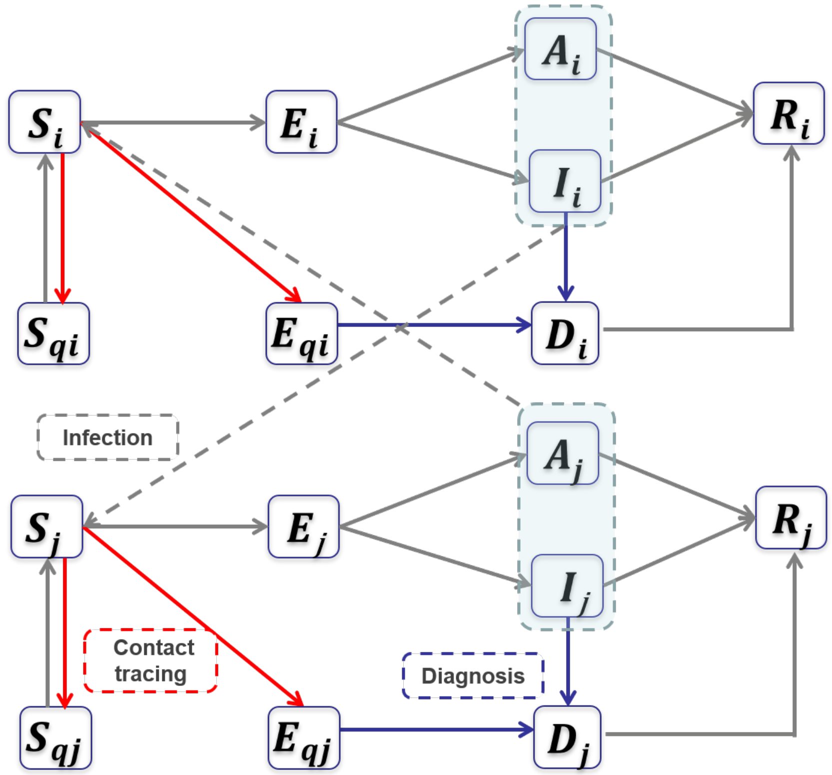
Mechanistic model (ODEs) with discrete age structure.

Age-stratified parameters

- Susceptibility to infection by SARS-CoV-2;
- Diagnosis rates among symptomatic individuals;
- Social contact mixing matrix.

$$S_i{}' = -\sum_{j=1}^{n}(\beta_i C_{ij} + q(1-\beta_i)C_{ij})S_i(I_j + \theta A_j)/N_j + \lambda S_{qi},$$
$$E_i{}' = \sum_{j=1}^{n}\beta_i C_{ij}(1-q)S_i(I_j + \theta A_j)/N_j - \sigma E_i,$$
$$I_i{}' = \sigma\varrho E_i - (\delta_{Ii} + \gamma_I)I_i,$$
$$A_i{}' = \sigma(1-\varrho)E_i - \gamma_A A_i,$$
$$S_{qi}{}' = \sum_{j=1}^{n}(1-\beta_i)C_{ij}qS_i(I_j + \theta A_j)/N_j - \lambda S_{qi},$$
$$E_{qi}{}' = \sum_{j=1}^{n}\beta_i C_{ij}qS_i(I_j + \theta A_j)/N_j - \delta_q E_{qi},$$
$$D_i{}' = \delta_{Ii}I_i + \delta_q E_{qi} - (\alpha + \gamma_D)D_i,$$
$$R_i{}' = \gamma_I I_i + \gamma_A A_i + \gamma_D D_i.$$

for each age group $i = 1, \ldots, n$,

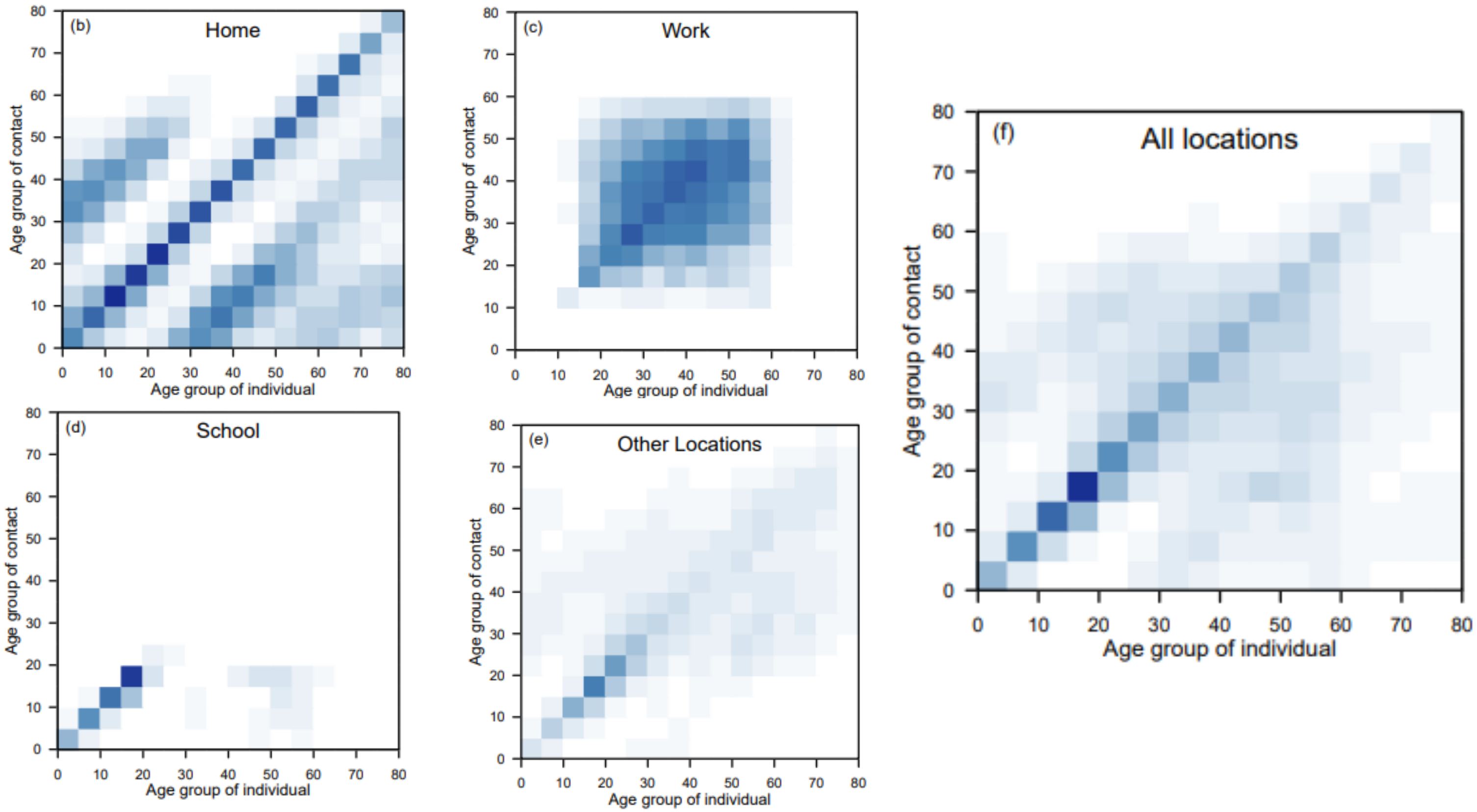


Six age classes:
$\mathbf{0-5, 6-13, 14-17, 18-24, 25-64, 65+.}$

3. Tang, B., Scarabel, F., Bragazzi, N. L., McCarthy, Z., Glazer, M., Xiao, Y., ... & Wu, J. (2020). De-Escalation by Reversing the Escalation with a Stronger Synergistic Package of Contact Tracing, Quarantine, Isolation and Personal Protection: Feasibility of Preventing a COVID-19 Rebound in Ontario, Canada, as a Case Study. *Biology*, 9(5), 100.

Established setting-specific contact matrices

2. Identifying social contact matrices representative of mixing in Ontario, Canada.



4. Mossong, J., Hens, N., Jit, M., Beutels, P., Auranen, K., Mikolajczyk, R., ... & Heijne, J. (2008). Social contacts and mixing patterns relevant to the spread of infectious diseases. *PLoS Medicine*, *5*(3), e74.

5. Prem, K., Cook, A. R., & Jit, M. (2017). Projecting social contact matrices in 152 countries using contact surveys and demographic data. *PLoS Computational Biology*, *13*(9), e1005697.

Baseline contact mixing in Ontario

2. Social contact matrices representative of mixing in Ontario, Canada.

$C_{i,j} \rightarrow C'_{i',j'}$

Original (Canada)→ Target (Ontario)

A suitable contact matrix:

i. Modified age group subdivisions (6 age groups);

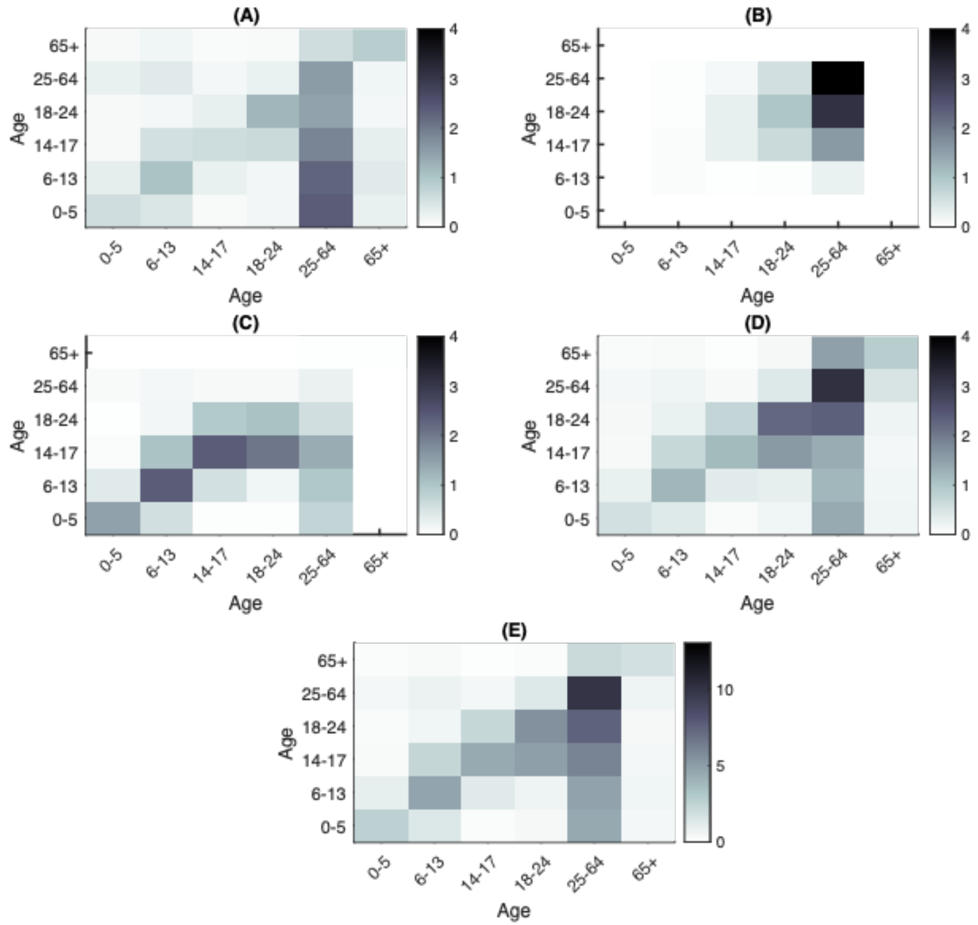
ii. Reciprocity condition is satisfied;

iii. Accounts for the specific age structure of Ontario, Canada, in 2019;

iv. Mean connectivity is representative of individual mean contact rate in Ontario, Canada.

Representative of contact mixing in Ontario, Canada in the absence of physical distancing measures.

6. Arregui, S., Aleta, A., Sanz, J., & Moreno, Y. (2018). Projecting social contact matrices to different demographic structures. *PLoS Computational Biology*, *14*(12), e1006638.



Heatmaps of estimated social contact matrices in Ontario, Canada. A) Households, **B)** Workplaces, **C)** Schools, **D)** Communities and other locations and **E)** contact mixing in all four settings combined.

Shifting mixing patterns in response to public health interventions

3. *Capture the distinct phases of public health interventions taken by the government.*

Ontario's response: A series of public health interventions taken such as school closure, physical distancing advisories, non-essential workplace closure.

We consider four distinct phases:

- February 26 – March 14 (phase 0) **[Monitoring and travel advisories]**
- March 14 – 17 (phase 1) **[Public school closure]**
- March 18 – 23 (phase 2) **[State of emergency and physical distancing]**
- March 24 – May 16 (phase 3) **[Non-essential workplace closure]**

$$C(t) = \begin{cases} C^0, & T_S < t < T_0, \quad \text{(phase 0)}, \\ C^1, & T_0 < t < T_1, \quad \text{(phase 1)}, \\ C^2, & T_1 < t < T_2, \quad \text{(phase 2)}, \\ C^3(t), & T_2 < t < T, \quad \text{(phase 3)}, \end{cases}$$

Shifting mixing patterns in response to public health interventions

Modelling the escalation in terms of setting-specific contact mixing.

Phase 0 (Monitoring and international travel advisories)

$$C^0 = C^H + C^W + C^C + C^S.$$

Phase 1: Public school closure

$$C^1 = (1 + p_1^H)C^H + C^W + (1 + p_1^C)C^C + 0\,C^S.$$

Phase 2: Physical distancing advisories

$$C^2 = (1 + p_2^H)(1 + p_1^H)C^H + C^W + (1 - p_2^C)(1 + p_1^C)C^C.$$

Phase 3: Closure of non-essential workplaces

$$C^3(t) = [(1 + p_3^H) - e^{-r_H(t-T_2)}p_3^H]\,(1 + p_2^H)(1 + p_1^H)C^H$$

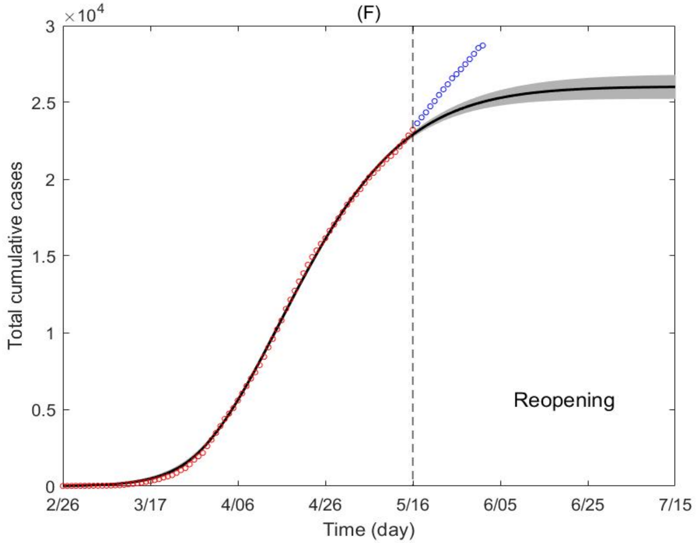
$$+ [p_3^W\, e^{-r_W(t-T_2)} + (1 - p_3^W)]C^W + [p_3^C e^{-r_C(t-T_2)} + (1 - p_3^C)](1 - p_2^C)(1 + p_1^C)C^C$$

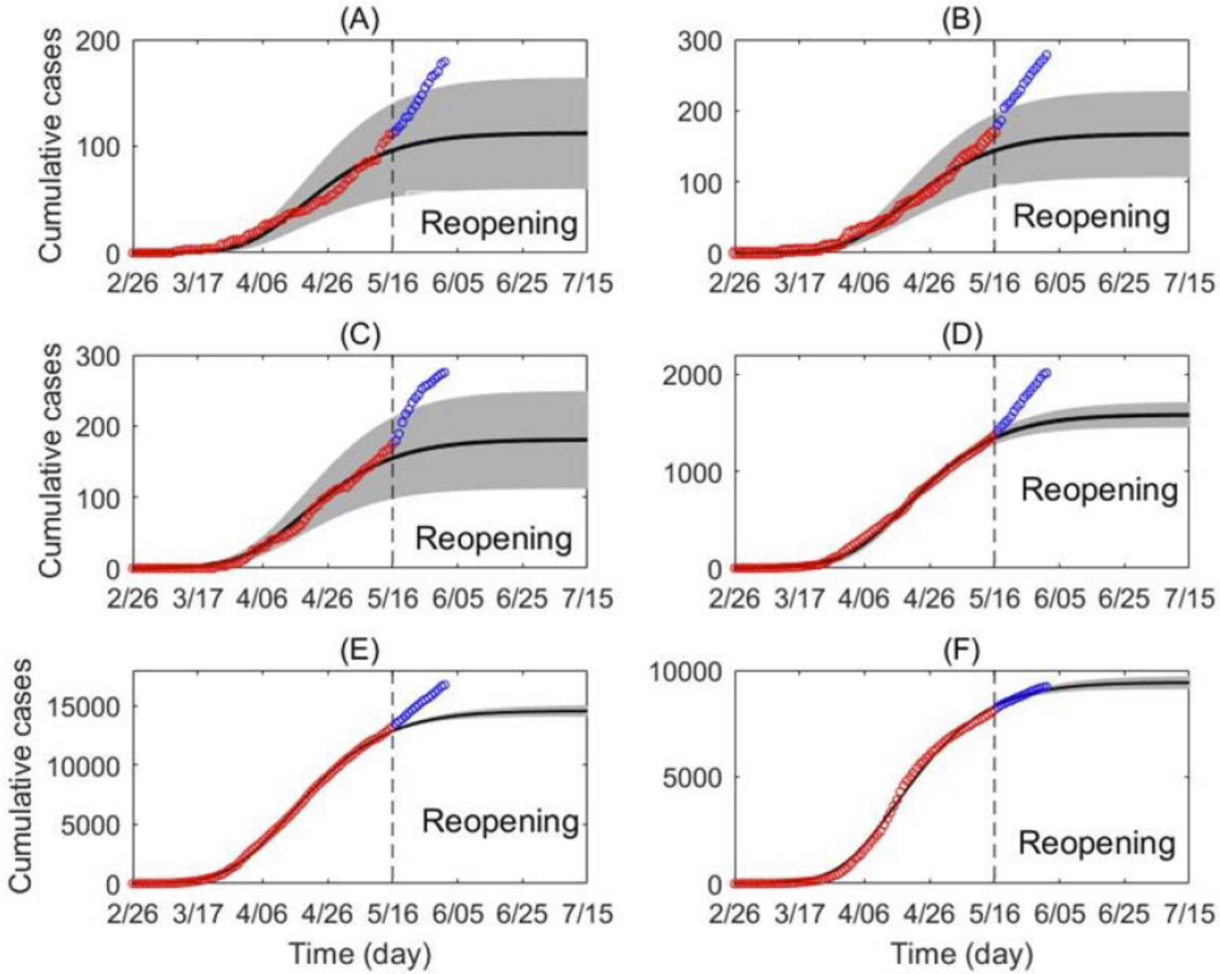
Model fitting

Fit to age-stratified incidence:

- Six lists of time series;
- Feb 26 2020 – May 16 2020;
- Single fitting procedure to estimate all age-dependent and age-independent model parameters.

Parameter uncertainty quantification

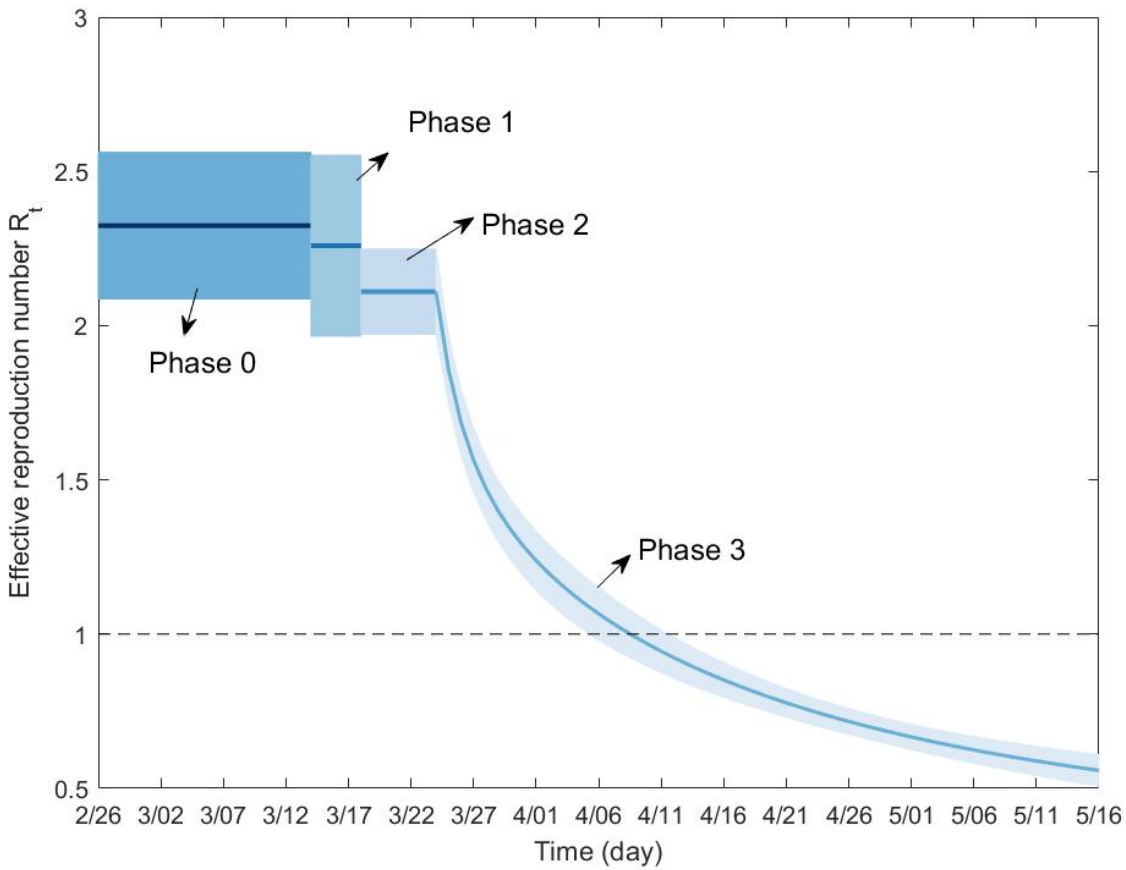




Cumulative incidence according to age class.
A) ages 0-5; **B)** ages 6-13; **C)** ages 14-17;
D) ages 18-24; **E)** ages 25-64 and **F)** ages 65+.

Effective reproduction number in Ontario

R_t declines below 1 between April 5 and April 12 following the implementation of a package of non-pharmaceutical interventions.

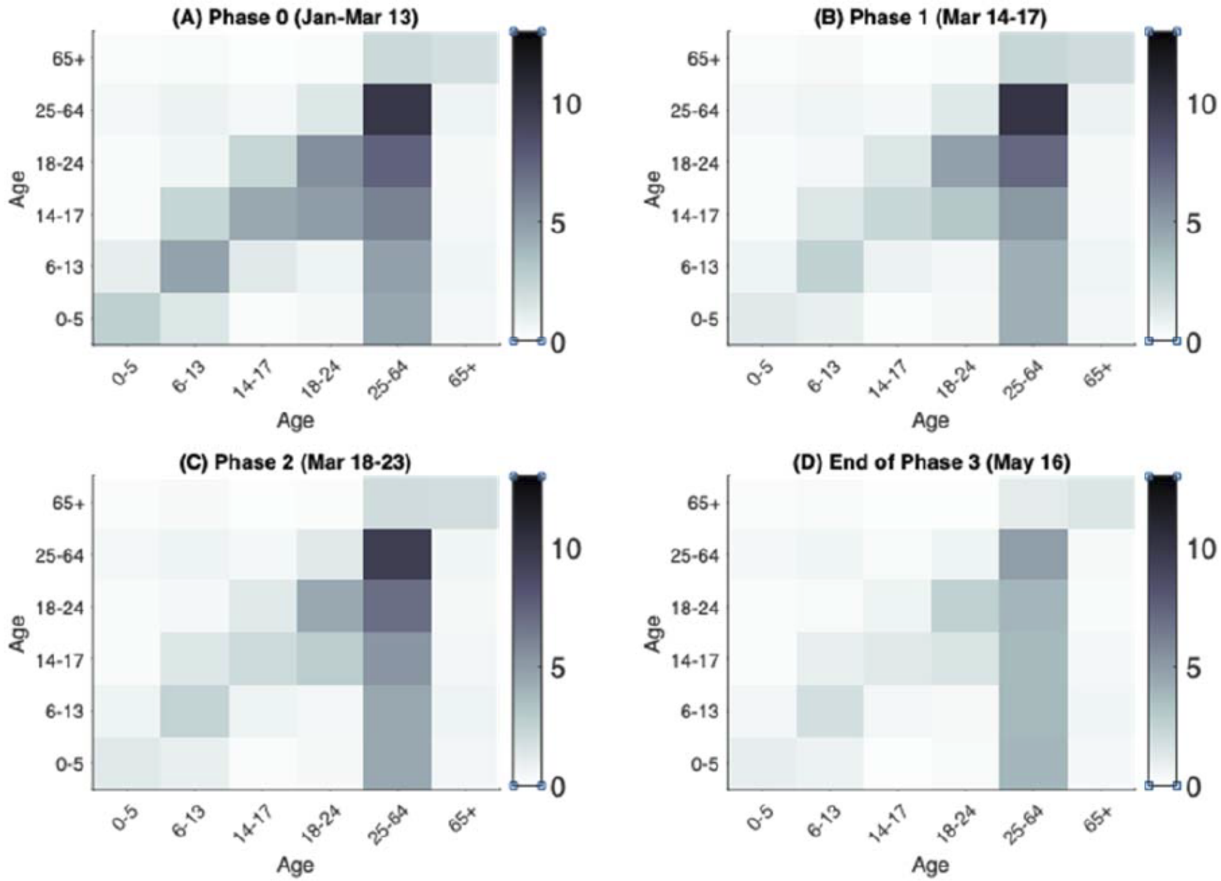


Estimated effective reproduction number R_t.

Contact mixing pattern estimated for each escalation phase

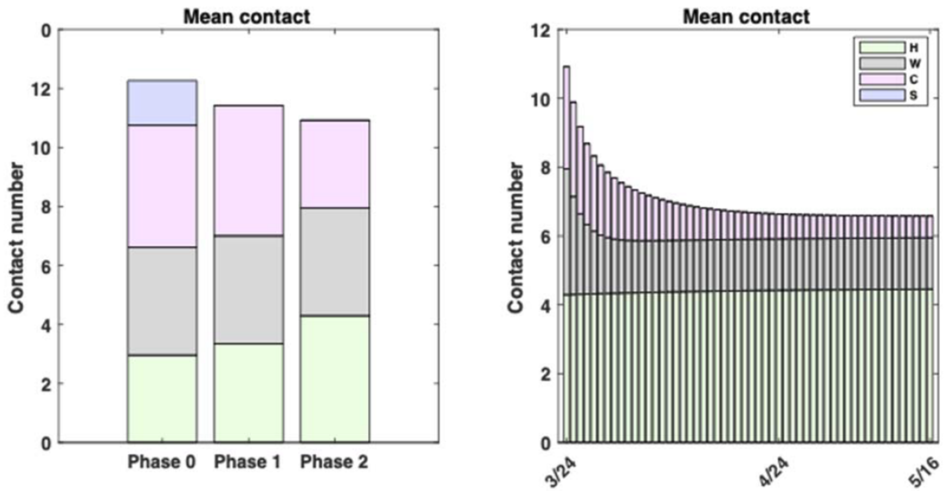
Household contact pattern emerges following the implementation of public health measures.

Consistent with results from contact survey-based studies.



February 26 – March 14 (phase 0) **[Monitoring and travel advisories]**
March 14 – 17 (phase 1) **[Public school closure]**
March 18 – 23 (phase 2) **[State of emergency and physical distancing]**
March 24 – May 16 (phase 3) **[Non-essential workplace closure]**

Mean contact rate by escalation phase



February 26 – March 14 (phase 0) **[Monitoring and travel advisories]**
March 14 – 17 (phase 1) **[Public school closure]**
March 18 – 23 (phase 2) **[State of emergency and physical distancing]**
March 24 – May 16 (phase 3) **[Non-essential workplace closure]**

$$< k > = \frac{1}{N}\sum_{i,j} C_{ij}N_i.$$

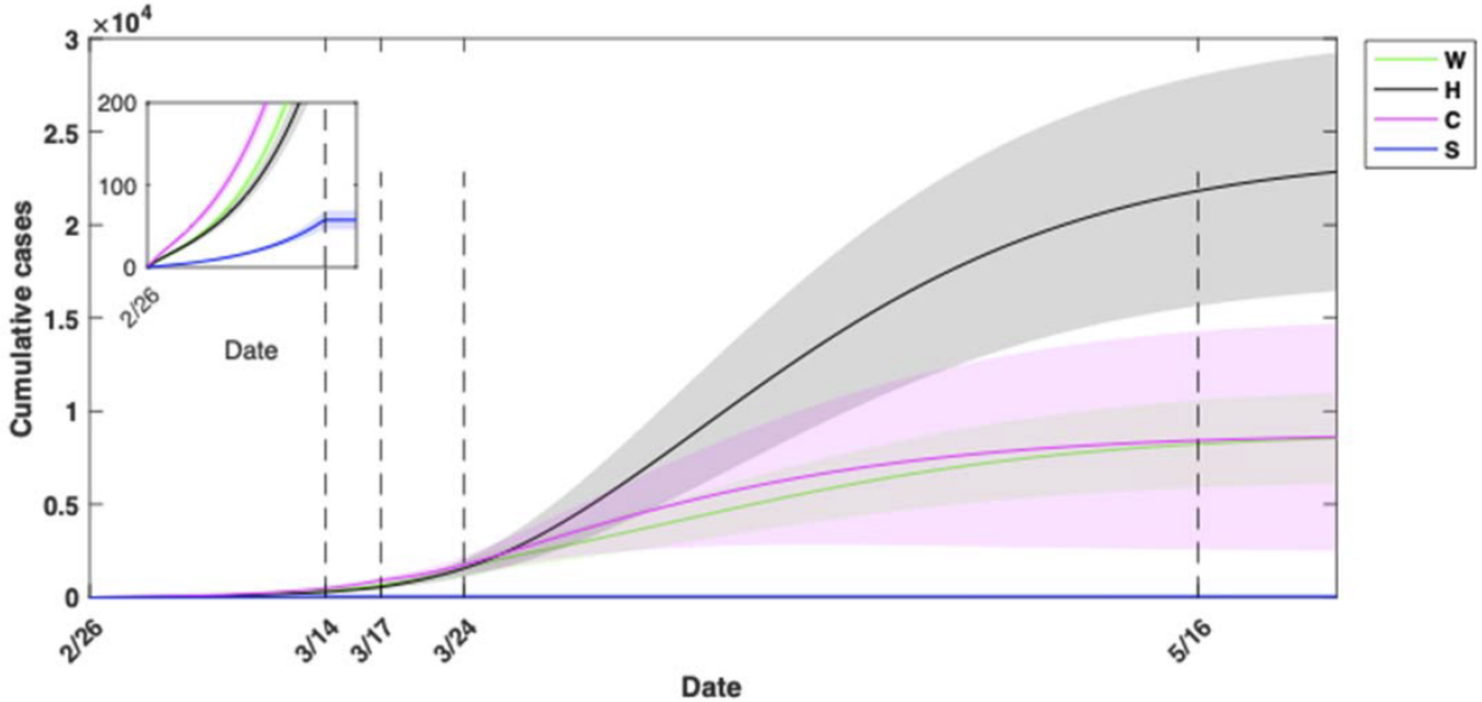
Fig. 1 | Mean contact during four escalation phases of physical distancing measures.

Shift to household contact observed, by magnitude of contacts.

Table 1 | Estimated mean daily contact rate by setting escalation phase

Setting	Daily contact rate pre-interventions (contacts/day)	Running daily contact rate (Change relative to pre-intervention)		
		Phase 1	Phase 2	Phase 3 (May 16)
School	1.52	0 (-100%)	0 (-100%)	0 (-100%)
Workplace	3.66	3.66 (0%)	3.66 (0%)	1.49 (-59%)
Community	4.14	4.42 (+7%)	2.97 (-28%)	0.64 (-85%)
Household	2.95	3.34 (+13%)	4.29 (+45%)	4.45 (+51%)
Total	12.27	11.42 (-7%)	10.92 (-11%)	6.58 (-46%)

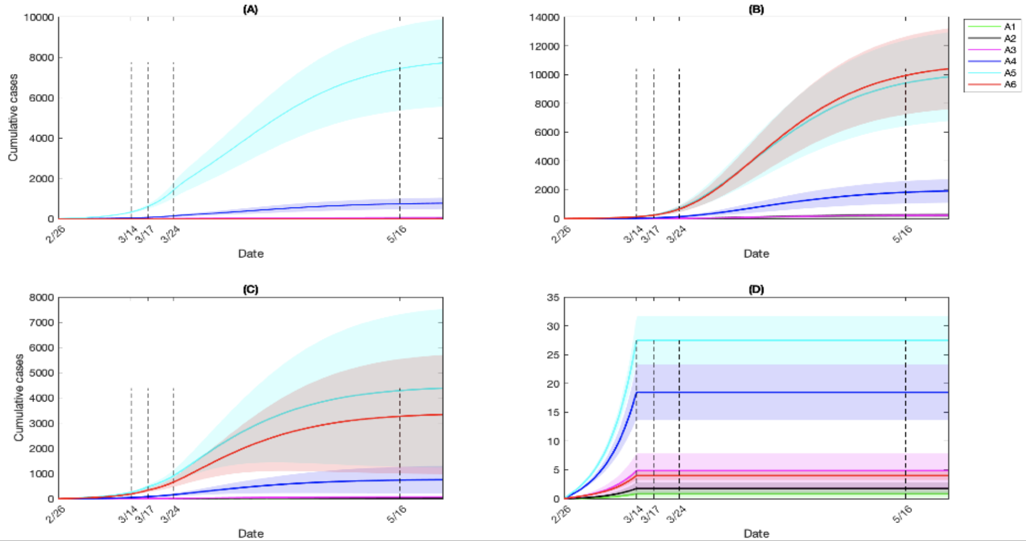
Estimated infections acquired in Ontario according to setting

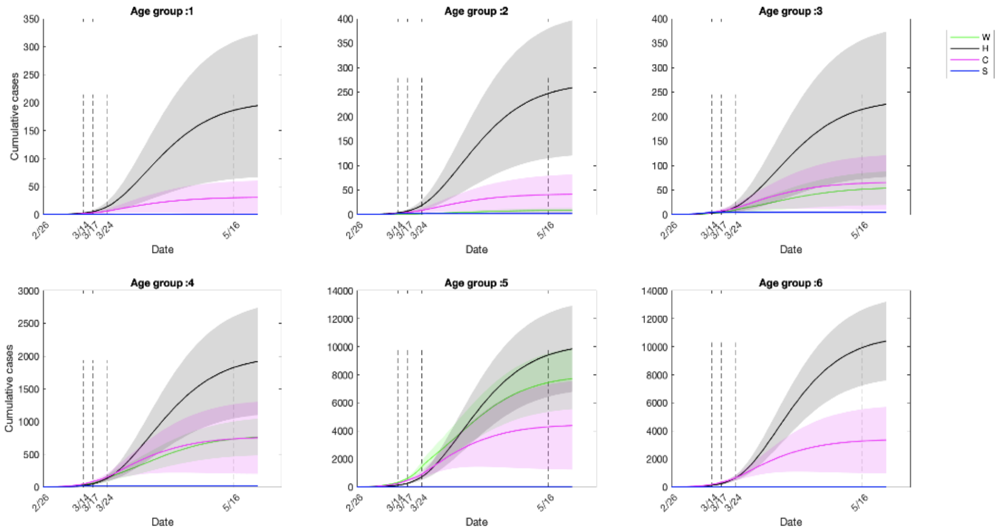


Community contacts initially contributed to more infections than contacts from remaining three locations, while household contacts played the primary role in contributing new infections after the closure of non-essential workplaces on March 24.

Estimated infections by setting acquired and age class

Cumulative infections by setting (and age class). Model-estimated cumulative infections acquired in **A)** Workplaces, **B)** Household, **C)** Community and other locations and **D)** Schools.





Cumulative infections by age class (and setting).
A) ages 0-5; **B)** ages 6-13; **C)** ages 14-17;
D) ages 18-24; **E)** ages 25-64 and **F)** ages 65+.

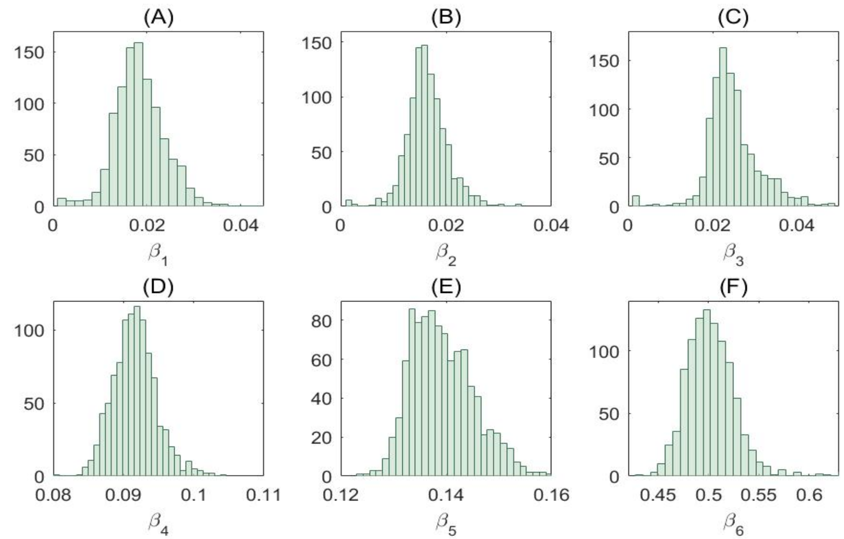
Age-dependent model parameters

Parameter	Age class					
	0-5	6-13	14-17	18-24	25-64	65+
Percentage of symptomatic individuals diagnosed	31%	38%	37%	20%	64%	67%
Susceptibility to infection	1.9%	1.6%	2.5%	9.2%	13.9%	50.2%

Percentage of symptomatic diagnosed individuals and susceptibility (i.e., probability of infection upon contact, β_i). The reported values are obtained from the mean of the fitting results of 1000 bootstrap realizations. The fraction of symptomatic diagnosed individuals is calculated from $\frac{\delta_{I,i}}{\delta_{I,i}+\gamma_I}$, where $\delta_{I,i}$ and γ_I denote the diagnosis and recovery rate, respectively.

We estimated that the susceptibility to SARS-CoV-2 infection increases with age.

Estimated an overall increasing trend with age in the percentage of symptomatic individuals diagnosed.



Empirical distributions of the age-specific susceptibility to infection.

Caveats to consider

Reported case data subject to error.

Testing protocols have been variable in Ontario.

Heterogeneities in geographical location.

Health care workers and long-term care homes were disproportionately affected.

Conclusions

Retrospective analysis:

Framework for intervention evaluation.

Proactive analysis:

Framework for evaluating reopening measures and vaccine distribution strategies.

Data-driven approach can provide insights and infer contact mixing in a timely manner, without the usage of participant-based surveys.

Methodology can be applied in many regions worldwide.

Projects in progress

1. Comparative analysis of contact shifts between Toronto and the rest of Ontario: insights for more region specific intervention strategies;

2. Age-specific immunization program optimization integrating with economic recovery;

3. Assess the impacts of relaxation and reopening measures in terms of contact mixing.

Acknowledgments

This project has been partially supported by the Canadian Institute of Health Research (CIHR) 2019 Novel Coronavirus (COVID-19) rapid research program.

Jianhong Wu is a member of the Ontario COVID-19 Modelling Consensus Table, and a member of the Expert Panel of the Public Health Agency of Canada (PHAC) Modeling group.

References

1. Coronavirus disease (COVID-19): Outbreak update - Canada.ca. https://www.canada.ca/en/public-health/services/diseases/2019-novel-coronavirus-infection.html (accessed Nov 10, 2020).
2. Ontario COVID-19 Data Tool | Public Health Ontario. https://www.publichealthontario.ca/en/data-and-analysis/infectious-disease/covid-19-data-surveillance/covid-19-data-tool (accessed Nov 10, 2020).
3. Tang, B., Scarabel, F., Bragazzi, N. L., McCarthy, Z., Glazer, M., Xiao, Y., ... & Wu, J. (2020). De-Escalation by Reversing the Escalation with a Stronger Synergistic Package of Contact Tracing, Quarantine, Isolation and Personal Protection: Feasibility of Preventing a COVID-19 Rebound in Ontario, Canada, as a Case Study. *Biology*, 9(5), 100
4. Mossong, J., Hens, N., Jit, M., Beutels, P., Auranen, K., Mikolajczyk, R., ... & Heijne, J. (2008). Social contacts and mixing patterns relevant to the spread of infectious diseases. *PLoS Medicine*, *5*(3), e74.
5. Prem, K., Cook, A. R., & Jit, M. (2017). Projecting social contact matrices in 152 countries using contact surveys and demographic data. *PLoS Computational Biology*, *13*(9), e1005697.
6. Arregui, S., Aleta, A., Sanz, J., & Moreno, Y. (2018). Projecting social contact matrices to different demographic structures. *PLoS Computational Biology*, *14*(12), e1006638.