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RESEARCH

The mobility gap: estimating mobility thresholds required to control SARS-CoV-2 in Canada

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ABSTRACT

BACKGROUND: Nonpharmaceutical interventions remain the primary means of controlling severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) until vaccination coverage is sufficient to achieve herd immunity. We used anonymized smartphone mobility measures to quantify the mobility level needed to control SARS-CoV-2 (i.e., mobility threshold), and the difference relative to the observed mobility level (i.e., mobility gap).

METHODS: We conducted a time-series study of the weekly incidence of SARS-CoV-2 in Canada from Mar. 15, 2020, to Mar. 6, 2021. The outcome was weekly growth rate, defined as the ratio of cases in a given week versus the previous week. We evaluated the effects of average time spent outside the home in the previous 3 weeks using a log-normal regression model, accounting for province, week and mean temperature. We calculated the SARS-CoV-2 mobility threshold and gap.

RESULTS: Across the 51-week study period, a total of 888 751 people were infected with SARS-CoV-2. Each 10% increase in the mobility gap was associated with a 25% increase in the SARS-COV-2 weekly case growth rate (ratio 1.25, 95% confidence interval 1.20–1.29). Compared to the prepandemic baseline mobility of 100%, the mobility threshold was highest in the summer (69%; interquartile range [IQR] 67%–70%), and dropped to 54% in winter 2021 (IQR 52%–55%); a mobility gap was present in Canada from July 2020 until the last week of December 2020.

INTERPRETATION: Mobility strongly and consistently predicts weekly case growth, and low levels of mobility are needed to control SARS-CoV-2 through spring 2021. Mobility measures from anonymized smartphone data can be used to guide provincial and regional loosening and tightening of physical distancing measures.

The global toll of coronavirus disease 2019 (COVID-19) continues to grow, despite the promise of recently approved vaccines. A surge is occurring in many countries in the Northern Hemisphere, including Canada, that may take a considerable toll before vaccination is sufficiently widespread to achieve herd immunity. Nonpharmaceutical public health interventions, including physical distancing, remain the primary population-based means of controlling COVID-19.[1] Since early in the second wave, which started in September 2020, polling has suggested that most people in Canada have supported and adhered to government-directed restrictions,[2] and many favour strengthened measures to control community transmission of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the causative viral agent of COVID-19.[3]

SARS-CoV-2 is spread primarily through close contact with people who are infected.[4] As with any infectious disease, contact rates are a primary driver of SARS-CoV-2 transmission.[5] Mobility measures capturing human activity through anonymized tracking of smartphones are believed to be reasonable proxies of contact rates outside of one's own home; these measures can provide more timely and reliable sources of information on contact rates compared with time-use surveys or contact tracing.[6–8]

Aggregated smartphone mobility data are provided by a number of software developers and have been used to quantify the impact of policy on mobility in Canada,[9] the effectiveness of lockdowns aiming to reduce the spread of SARS-CoV-2[10–12] and loopholes from excessively localized measures.[13] Mobility metrics are helpful for gauging the effect of restrictions on behaviour, but do not, on their own, show decision-makers whether restrictions in place at the time are sufficient to curtail the spread of SARS-CoV-2. In this study, we evaluated the association between smartphone mobility measures and the spread of SARS-CoV-2 in Canada, both nationally and provincially, between March 2020 and March 2021. We also sought to quantify the mobility level needed to control COVID-19 (i.e., the mobility threshold), and the difference between observed mobility levels and the threshold (i.e., the mobility gap). We hypothesized that lower mobility levels may be needed in provinces with larger urban populations in the winter compared with more rural provinces in the summer.[14]

Methods

Study design

We conducted a time-series study of the impact of mobility on weekly SARS-CoV-2 incidence in Canada between Mar. 15, 2020, and Mar. 6, 2021. The study was conducted at both the national and provincial levels. For analyses at the provincial level, only weeks with an incidence greater than 20 cases in the previous week were included, because incidence rates during weeks with small case counts are likely to be considerably affected by importation and sporadic outbreaks. Based on visual inspection of model fit, we included only provinces or territories for which at least 50% of weeks were eligible for inclusion in the province-level analyses, to ensure that province-specific estimates were accurate. When several disjoint segments of eligible weeks from the same province were eligible, we included the longest segment.

Outcome

We measured the weekly case counts and test positivity for SARS-CoV-2 in each province using data from the COVID-19 Canada Open Data Working Group[15] in the 51-week period from Mar. 15, 2020, to Mar. 6, 2021. Outcomes were aggregated by week in order to control for daily patterns evident in Canadian case reporting data.[16] The Open Data Working Group obtains and compiles daily case counts reported across the country by provincial public health agencies, accredited news media and official social media accounts. Weeks were defined as starting on Sunday and ending on Saturday.

Because we hypothesized that mobility would impact SARS-CoV-2 dynamics in terms of changes in rates, rather than absolute levels of infection, our outcome was the weekly growth rate, measured as the ratio of SARS-CoV-2 cases in a given week divided by the number of SARS-CoV-2 cases in the previous week. A weekly growth rate equal to 1 meant that incidence was stable relative to the previous week, and a weekly growth rate greater than 1 meant that cases increased. Because surveillance data are subject to time-varying underdetection, we developed a corrected growth rate, equal to the weekly growth rate of cases multiplied by the weekly growth rate of test positivity.

Mobility measures

Province-level smartphone mobility data were drawn from open-source Google Community Mobility Reports,[17] which are updated daily. These data are collected from select users of Google Maps who have enabled the location history setting, which is turned off by default. The primary exposure of interest was the average time spent outside of home in the previous 3-week period, which has been validated and is a strong indicator of the introduction and lifting of nonpharmaceutical public health interventions.[18] This lag period was chosen based on a 10-day buffer around the known peak correlation between mobility and case growth rate at 11 days.[12]

We defined the baseline level of the mobility measure as its median value during the 5-week period from Jan. 3 to Feb. 6, 2020, namely the 1-month period before the first confirmed case of community transmission in Canada (Mar. 5 in British Columbia) and before the first school closures in Canada (Mar. 15 in Ontario). We rescaled the Google residential mobility values (formula: $100 \times [1 - X/30]$; estimating that, in winter, Canadians spend 30% of time outside the home) so that levels in the baseline period represented 100%, with a range from 0% (no out-of-home mobility) to values greater than 100%.[8,9] For the purposes of plotting out-of-home mobility, we smoothed the index values using a penalized spline with a knot for each 2-week period,[19] and also superimposed a 7-day rolling average.

Covariates

In addition to mobility, we controlled for week and average temperature (degrees centigrade) in a 3-week lag period of the most populous city of each province, based on Environment Canada data.[20] For descriptive purposes, we grouped weeks in the same quarter together: March 2020, April–June 2020, July–September 2020, October–December 2020 and January–March 2021.

Analysis

We described the weekly case growth rates, positivity and nonresidential mobility levels across provinces and quarters with the median and interquartile range (IQR). We modelled the logarithm of weekly SARS-CoV-2 growth using a Gaussian regression model. Covariate coefficients from this model were exponentiated and represented growth rate ratios (GRRs). Factors with GRR values greater than 1 were associated with accelerating growth; factors with GRR values less than 1 were associated with decelerating growth. For the primary (uncorrected for test positivity) and secondary (corrected for test positivity) outcomes, we developed 2 regression models: an unadjusted model that included out-of-home mobility in the previous 3-week period and penalized spline for the week (with a knot for every 2-month period), and an adjusted model that also accounted for mean temperature in the previous 3 weeks as a linear covariate. All models were fit using the mgcv package in R (model details in Appendix 1, available at www.cmaj.ca/lookup/doi/10.1503/cmaj.210132/tab-related-content).[19,21]

Using the adjusted model of the association between SARS-CoV-2 growth rate and mobility, we estimated the mobility threshold at which SARS-CoV-2 growth would cease to occur. The calculation of the mobility threshold is detailed in Appendix 1. We defined the mobility gap as the difference between the observed mobility and the mobility threshold. The mobility gap can be interpreted as the estimated incremental reduction in mobility that would have been needed to achieve control of SARS-CoV-2 growth rate in a given province in a given week.

Table 1: Weekly SARS-CoV-2 test positivity, case growth rates and mobility in Canada, Mar. 15, 2020, to Mar. 6, 2021

Level of analysis	No. of weeks	No. of cases	Median (IQR) Test positivity, %*	Case growth rate	Positivity-corrected growth rate	Out-of-home mobility, % of baseline
Canada	51	888 751	3.7 (1.2–6.1)	1.0 (0.9–1.2)	1.1 (0.7–1.5)	61 (48–73)
Period						
March 2020	3	14 149	4.1 (2.7–5.6)	4.0 (3.0–4.7)	8.7 (6.1–11.3)	82 (71–89)
April–June 2020	13	92 650	3.9 (1.4–6.0)	1.0 (0.8–1.1)	0.8 (0.5–1.1)	40 (31–52)
July–September 2020	13	59 643	0.9 (0.8–1.1)	1.2 (1.0–1.3)	1.3 (1.0–1.7)	75 (73–77)
October–December 2020	13	423 081	5.9 (4.0–6.3)	1.1 (1.0–1.2)	1.3 (1.1–1.4)	65 (60–67)
January–March 2021	9	299 228	4.5 (3.7–6.2)	0.9 (0.8–1.0)	0.8 (0.7–0.9)	48 (45–50)
Provinces						
Alberta	51	135 498	2.1 (1.1–4.6)	1.1 (0.9–1.4)	1.0 (0.7–1.9)	63 (52–78)
British Columbia	51	83 034	2.3 (1.2–5.6)	1.0 (0.9–1.3)	1.0 (0.9–1.5)	62 (56–73)
Manitoba	32	31 785	5.7 (2.1–9.4)	1.0 (0.8–1.4)	1.1 (0.7–1.8)	64 (52–82)
Ontario	51	311 810	2.3 (0.9–3.8)	1.1 (0.9–1.2)	1.1 (0.7–1.4)	57 (40–66)
Quebec	50	289 583	9.1 (2.3–14.7)	1.0 (0.8–1.2)	1.0 (0.6–1.6)	60 (45–73)

Note: IQR = interquartile range, SARS-CoV-2 = severe acute respiratory syndrome coronavirus 2.
*Two missing weeks for test positivity at the national level (n = 49) and 10 missing weeks at the provincial level (n = 269).

To enable model comparison, we measured several model diagnostics, including the Pearson residual autocorrelation at 1 week of lag, the model R^2 (1 – deviance$_{model}$/deviance$_{null}$), the estimated model degrees of freedom (taking penalties into consideration) and the model Akaikes' Information Criterion (AIC; equal to the sum of the model deviance plus the model degrees of freedom), a measure of model fit where smaller values indicate more parsimonious and better-fitting models.

Ethics approval

All data used in this study were in the public domain; therefore the study was exempt from review by the University of Toronto Research Ethics Board.

Results

Across the 51-week period (Mar. 15, 2020, to Mar. 6, 2021), there were 888 751 cases of SARS-CoV-2 in Canada (Table 1). All cases were included in the national analysis, and 881 009 (99.1%) were included in the province-level analyses, which included 279 eligible province-weeks. Ontario (n = 311 810) and Quebec (n = 289 583) had the highest number of eligible SARS-CoV-2 cases.

Across Canada, out-of-home mobility dropped rapidly in March 2020 to reach a low of 23% in the week of April 5 (Figure 1). Mobility increased through the summer of 2020 and reached levels approaching baseline in the week of August 23 (78%), and then decreased slowly through the fall months and rapidly in December 2020. Manitoba was unique, with mobility levels dropping comparatively more than other provinces during the fall of 2020.

Mobility and SARS-CoV-2 growth rate

In the national model, adjusting for both date and temperature effects, each 10% increase in mobility was associated with a 25% increase in the weekly growth rate (adjusted GRR 1.25 per 10% increase in mobility, 95% confidence interval [CI] 1.20–1.29) (Table 2 and Figure 2). Increases in mean weekly temperature were significantly associated with decreased SARS-CoV-2 growth rates (GRR 0.83 per 5°C increase, 95% CI 0.75–0.93). Model diagnostics indicated low levels of residual autocorrelation (Pearson correlation, adjusted model = 0.15), and that model fit was strong (R^2, adjusted model = 81.6%). The positivity-corrected outcome was missing for 2 weeks, leaving 49 weeks in the analysis. Results were similar with this outcome (adjusted GRR 1.35 per 10% increase in mobility, 95% CI 1.17–1.55), though overall model fit was worse (R^2 = 56.2%)

In provincial-level analyses, adjusting for both date and temperature effects, each 10% increase in mobility was associated with a 20% increase in the weekly growth rate (adjusted GRR 1.20, 95% CI 1.16–1.24), and increasing temperature was associated with lower growth rates (GRR 0.88 per 5°C increase in temperature, 95% CI 0.86–0.91). Model fit for the provincial level models was weaker (R^2, adjusted model = 38.2%). The positivity-corrected outcome was missing for 10 weeks, leaving 269 province-weeks in the analysis. A strong association between mobility and the positivity-corrected growth rate was also apparent (adjusted GRR 1.29 per 10% increase in mobility, 95% CI 1.21–1.38).

Mobility threshold and mobility gap

We used the adjusted national and provincial models to measure the mobility threshold (Figure 3). The national mobility threshold

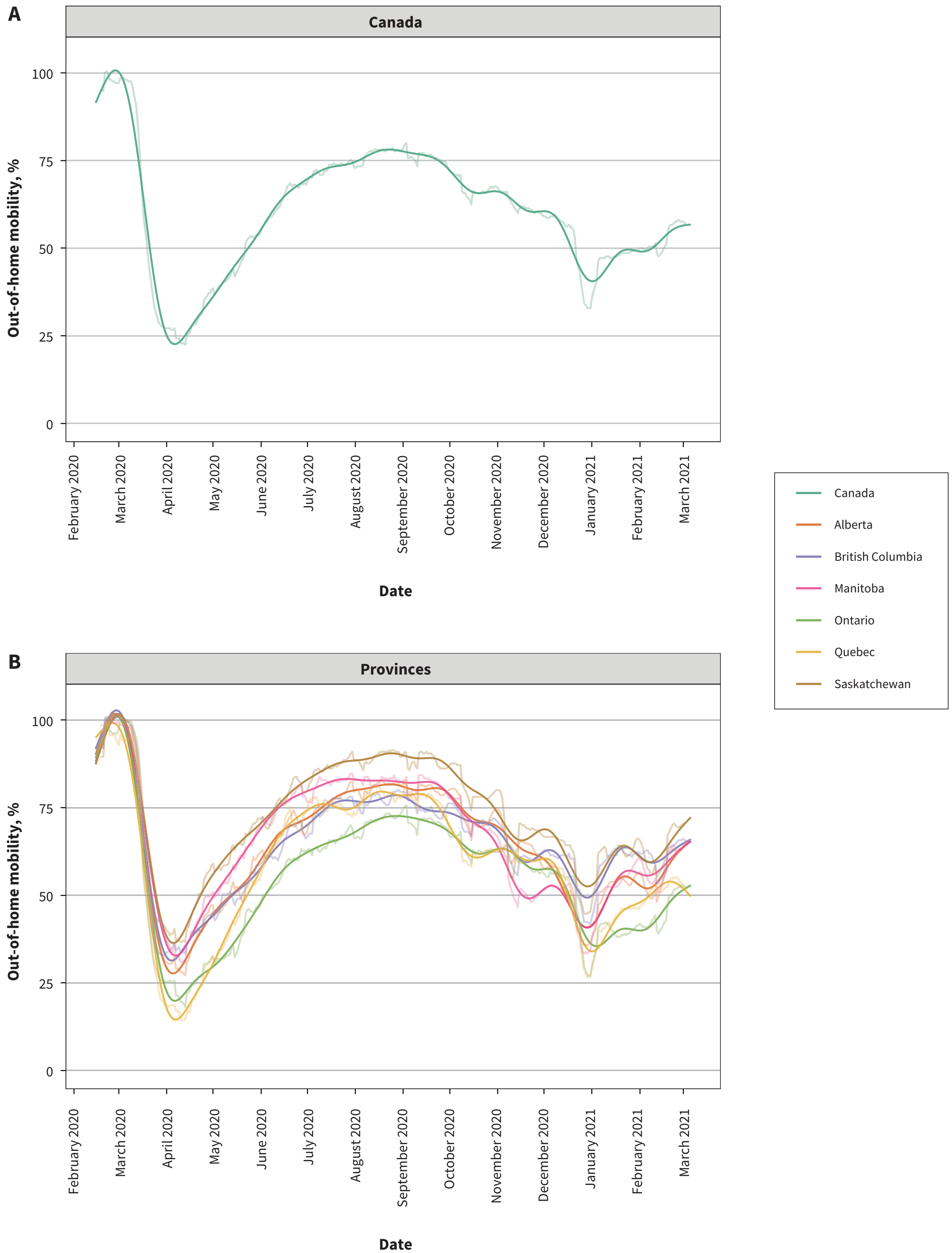

Figure 1: Out-of-home mobility (A) across Canada and (B) in 6 Canadian provinces, Feb. 5, 2020, to Mar. 6, 2021. Note: The out-of-home mobility index is a measure of the average amount of time spent outside the home, based on smartphone mobility data (the index is scaled so that levels in the baseline period from Jan. 3 to Feb. 6, 2020, represent 100%). The index values are smoothed using a penalized spline with a knot for each 2-week period (bold line) and are superposed with a 7-day rolling average (pale line).

Table 2: Factors influencing SARS-CoV-2 weekly growth rates and positivity-corrected growth-rates, across Canada, Mar. 15, 2020, to Mar. 6, 2021

	National level* *n* = 51		Provincial level* *n* = 279	
Variable	**Unadjusted†**	**Adjusted‡**	**Unadjusted†**	**Adjusted‡**
Weekly growth rate				
Coefficients, GRR (95% CI)				
Mean out-of-home mobility in previous 3-week period, per 10% increase	1.19 (1.13–1.24)	1.25 (1.20–1.29)	1.16 (1.12–1.20)	1.20 (1.16–1.24)
Temperature, per 5°C increase		0.83 (0.75–0.93)		0.88 (0.86–0.91)
Model characteristics				
Residual autocorrelation	0.14	0.15	0.20	0.09
Model complexity (degrees of freedom)	7.8	7.5	23.9	15.6
Goodness-of-fit, R^2 (%)	81.8	81.6	33.3	38.2
Model fit criterion (AIC)	–28.8	–28.9	242.1	204.1
Positivity-corrected weekly growth rate				
Coefficients, GRR (95% CI)				
Mean out-of-home mobility in previous 3-week period, per 10% increase	1.27 (1.10–1.47)	1.35 (1.17–1.55)	1.13 (1.08–1.19)	1.29 (1.21–1.38)
Temperature, per 5°C increase		0.73 (0.56–0.94)		0.89 (0.84–0.94)
Model characteristics				
Residual autocorrelation	0.04	0.03	0.15	0.10
Model complexity (degrees of freedom)	7.8	8.2	3.0	15.0
Goodness-of-fit, R^2 (%)	54.4	56.2	9.7	15.6
Model fit criterion (AIC)	34.6	33.3	509.0	490.5

Note: AIC = Akaike's Information Criterion (lower is better), CI = confidence interval, GRR = growth rate ratio, SARS-CoV-2 = severe acute respiratory syndrome coronavirus 2.
*Positivity-corrected weekly growth models are missing 2 weeks for test positivity at the national level (*n* = 49) and missing 10 weeks at the provincial level (*n* = 269).
†The unadjusted model included out-of-home mobility in the previous 3 weeks and a penalized spline for the week.
‡The adjusted model included out-of-home mobility in the previous 3 weeks, a penalized spline for the week and mean temperature in the previous 3 weeks.

varied markedly through the pandemic period and was highest in the summer (median 71%, IQR 69%–72%), and dropped throughout the fall to 54% (IQR 52%–55%) in the winter. Variations across provinces in the estimated mobility threshold were also apparent; Ontario (50%, IQR 46%–59%) and Quebec (54%, IQR 52%–63%) had the lowest thresholds.

The mobility gap in Canadian provinces passed through distinct phases over the course of the pandemic (Figure 3). At the onset of the pandemic in March 2020, out-of-home mobility was in excess of the mobility threshold. Strict lockdown measures led to rapid declines in mobility below the threshold and control of the SARS-CoV-2 growth rate (April–May). Easing of lockdown measures in the late spring coincided with increasing mobility thresholds, but mobility soon increased to exceed the threshold needed to control SARS-CoV-2 in the summer of 2020. Mobility thresholds decreased throughout the fall and mobility remained above the threshold, coinciding with surging case counts. In November 2020, Manitoba markedly reduced mobility to levels below the mobility threshold, but mobility in Canada dropped below the threshold only in the last week of December.

Interpretation

Our evaluation of predictors of weekly SARS-CoV-2 growth rates across Canada shows that reductions in mobility strongly predict future control of SARS-CoV-2 growth rates in the subsequent 3-week period, and suggests that more substantial reductions in mobility were required to control transmission of SARS-CoV-2 through the fall of 2020. We developed measures of the estimated mobility level required to achieve SARS-CoV-2 control in Canada (the mobility threshold), and the estimated mobility reduction required to control SARS-CoV-2 growth (the mobility gap).

This study builds on work showing strong associations between physical distancing measures and the incidence of SARS-CoV-2.[11,22,23] Studies using smartphone mobility measures show that changes in mobility specifically predict SARS-CoV-2 incidence in the subsequent 1–3 weeks.[12] More detailed mobility data suggest that dine-in restaurants, take-out services (likely representing risk for workers more than customers), gyms and cafés are particularly important drivers of SARS-CoV-2 incidence in the United States.[24] A mobility threshold necessary to control

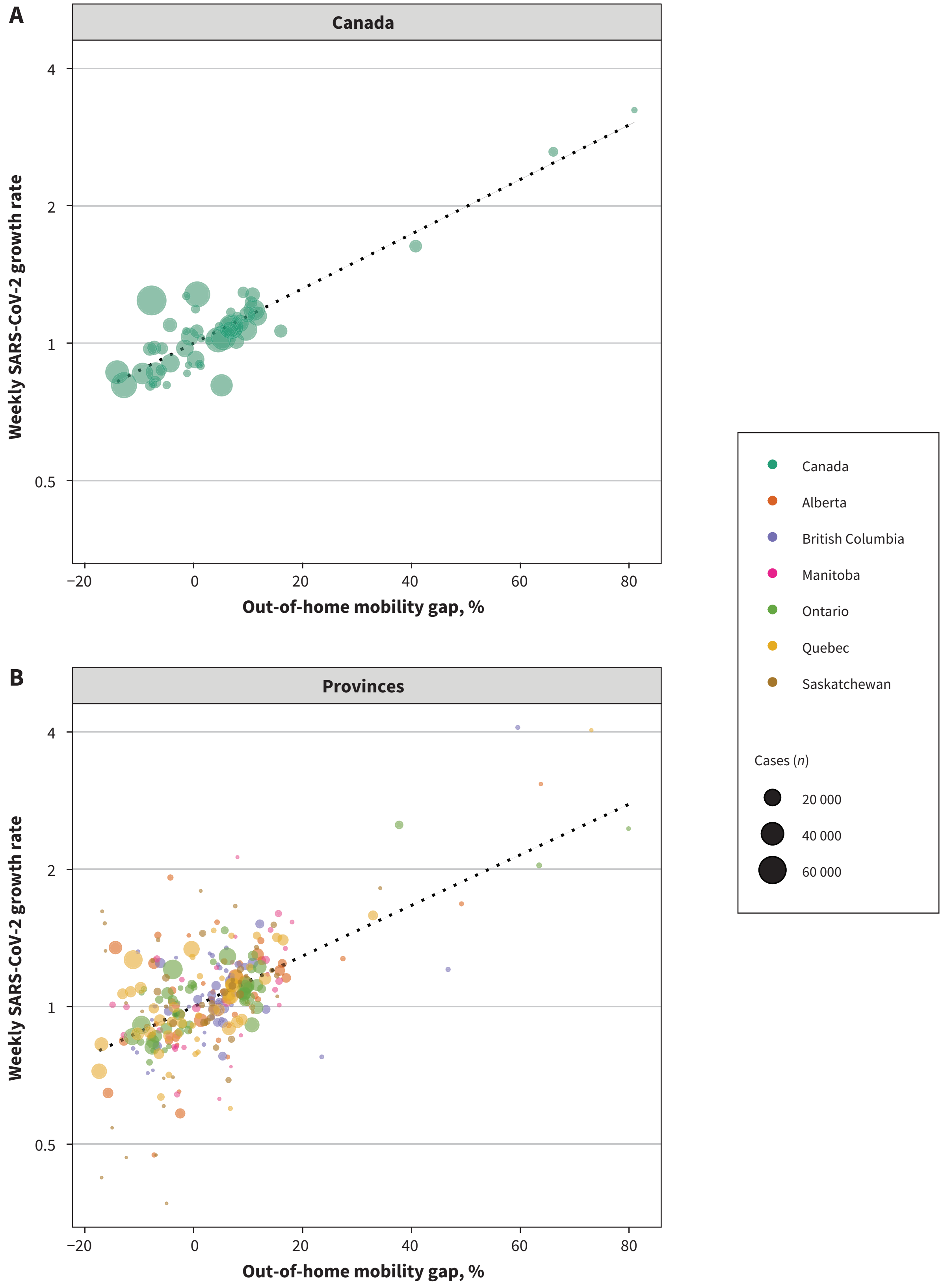

Figure 2: Adjusted-association between out-of-home mobility and severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) growth rate across 6 Canadian provinces, Mar. 15, 2020, to Mar. 6, 2021. Weekly SARS-CoV-2 growth rate (cases in given week/cases in previous week) is strongly associated with the out-of-home mobility in the prior 3-week period. In the adjusted Canada-level analysis, each 10% increase in out-of-home mobility was associated with a 25% increase in the growth rate (growth rate ratio [GRR] 1.25, 95% confidence interval [CI] 1.20–1.29). In the adjusted province-level analysis, each 10% increase in mobility was associated with a 20% increase in the growth rate ratio (GRR 1.20, 95% CI 1.16–1.24). These associations are represented by the dotted lines.

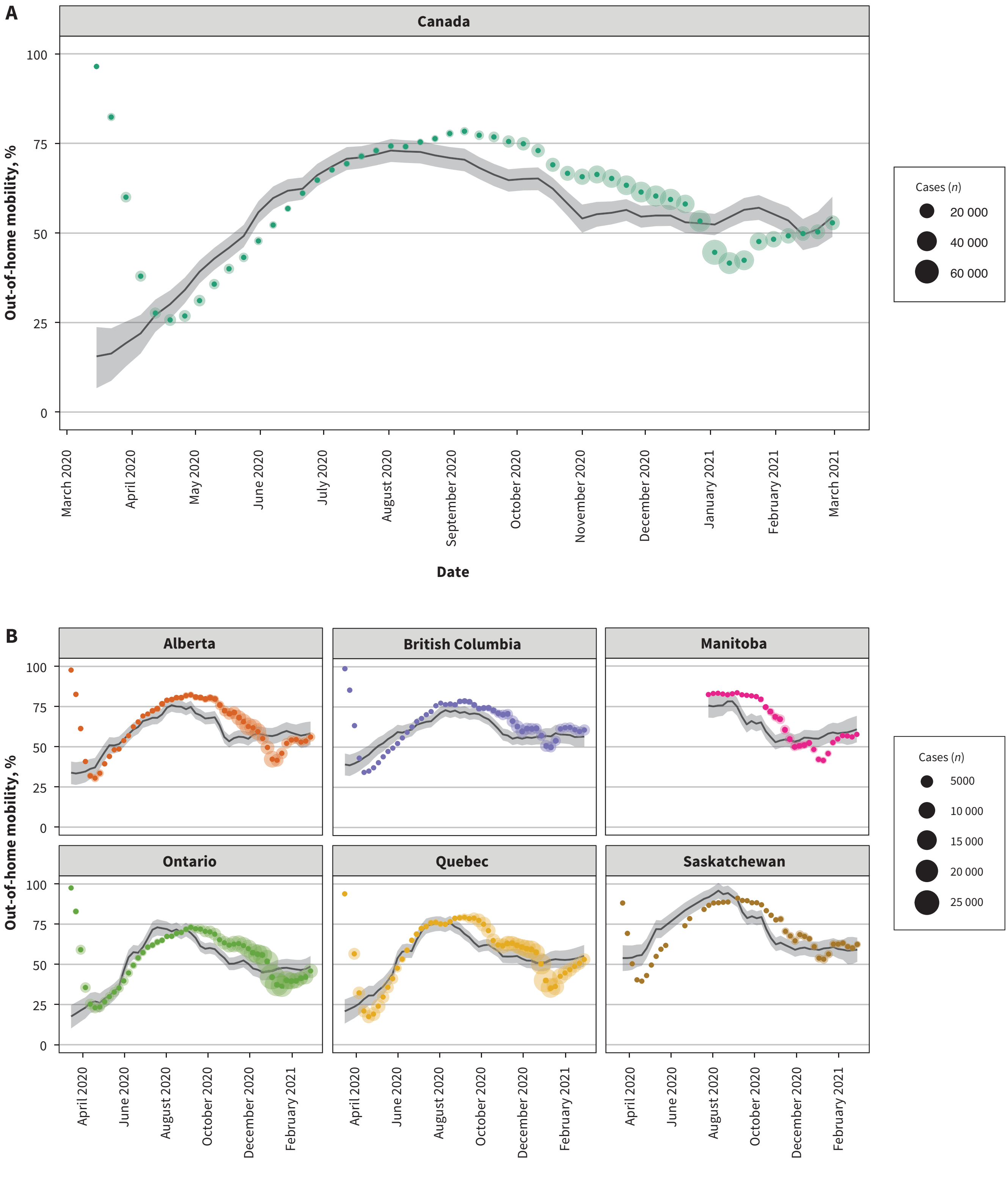

Figure 3: Variation in 3-week rolling average of mobility (coloured points) and the estimated mobility threshold (black line) and 80% confidence intervals (shaded region) for (A) Canada and (B) 6 Canadian provinces. Size of circles is proportional to the number of cases in a given week. Note: The mobility threshold is the estimated level of mobility needed to control severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) case growth. This threshold is highest in summer and is lowest in the most populated provinces, particularly in Ontario (median 50%) and Quebec (median 54%). When mobility decreased below the mobility threshold in spring 2020 and winter 2021, weekly SARS-CoV-2 case counts decreased. In late November 2020, Manitoba was the only province that successfully crossed the mobility threshold, which led to reductions in SARS-CoV-2 case growth. Other provinces attained this only in late December 2020 or early January 2021.

SARS-CoV-2 spread can be measured.[25] We have shown that the mobility reductions required are seasonally dependent — relatively small reductions were required to control SARS-CoV-2 in the summer of 2020, but larger mobility reductions have been needed since the fall.

As with several respiratory pathogens,[26,27] we observed substantial seasonal variation in the risk of SARS-CoV-2 infection. Substantial controversy remains as to the underlying drivers of the increased incidence in the winter. Hypotheses include human behavioural factors, particularly the increased time spent in poorly ventilated indoor environments, increased virus survival in winter climatic conditions (in particular, decreased absolute humidity)[28] and factors related to the immune system.[26]

Our work suggests that if governments and public health agencies wish to suppress community transmission of SARS-CoV-2 through the spring of 2021, before vaccination is widespread, stringent nonpharmaceutical interventions may be necessary. Manitoba, which lowered mobility sufficiently to achieve control of SARS-CoV-2 in the fall, did so by moving the entire province into the most stringent lockdown level on Nov. 12, 2020. Measures included restricting private gatherings to 5 persons, closing nonessential businesses and in-restaurant dining[29] and increasing enforcement (almost $1 million in fines given out by early January 2021).[30,31]

Limitations

We did not examine granular patterns of mobility within provinces, limiting potential insights into the effectiveness of the regional approaches pursued in some provinces. We used comparative measures of mobility relative to levels in January 2020 rather than absolute counts, which added to the complexity of interprovincial comparisons. Further, the Google Community Mobility Reports may not be representative of the Ontario population as a whole, and the data compiled by the Canadian Open Data Working Group have not been formally validated. The SARS-CoV-2 growth rates that we observed may be temporally dependent, which could lead to underestimation of coefficient standard errors; model diagnostics suggested that autocorrelation was weak. Weather was crudely measured based on the most populous city of the province. We considered only a limited number of potential confounding variables and did not control for SARS-CoV-2 vaccination levels. Vaccines were first administered in Canada on Dec. 14, 2020, and remain well below herd immunity levels as of March 2021. As vaccination rates increase, this could be embedded into models of the predicted mobility threshold. Meanwhile, the rapidly spreading variants arising from the United Kingdom and South Africa[32] may need a lower mobility threshold to control the spread of SARS-CoV-2.

Conclusion

This study shows that mobility strongly predicts the growth rate of SARS-CoV-2 up to 3 weeks in the future, and that stringent measures will continue to be necessary through spring 2021 in Canada. The mobility threshold and mobility gap can be used by public health officials and governments to estimate the level of restrictions needed to control the spread of SARS-CoV-2 and guide, in real-time, the implementation and intensity of nonpharmaceutical public health interventions to control the COVID-19 pandemic.

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