Supplementary Materials for

Drivers and forecasts of multiple waves of the coronavirus disease 2019 pandemic: a systematic analysis based on an interpretable machine learning framework

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Materials and Methods

Policy score

The original values of the policies are classification variables, which are more graphically represented by scoring the intensity of policy implementation. For this purpose, the following formula is used to convert classification variables into a policy score.

$$I_{j,t} = 100 \times \frac{v_{j,t} - 0.5 \times (F_j - f_{j,t})}{N_j}$$

where each sub-policy score (I) for given indicator (j) on day (t). Among them, N_j is maximum value of the indicator (j), and j has a flag (F_j), if $F_j = 1$, j has a flag variable, or 0 if j does not have a flag variable. $v_{j,t}$, $f_{j,t}$ are expressed as the recorded policy value on the ordinal scale and the recorded binary flag for j respectively.

Conversion of the different classification variables produces a sub-policy score between 0 and 100 where each full point on the ordinal scale is equally spaced.

Time lag effect

Since there are potential time-lag effects for policy implementation, it is necessary to consider it. Discrete week lags were tested and selected based on model testing. For this purpose, R_t models were built using XGBoost based on data from 39 countries in the pre-vaccine era using factors with lags: 1 week, 2 weeks, 4 weeks, and 8 weeks. The root mean square error, R^2, and mean square error were used as the indicators of fitting goodness and the lag with the minor error was selected (Table S3).

Table S1: Description of policy-related factors.

Non-pharmaceutical intervention policy	Scale	Score	Description
School closing (Record closings of schools and universities.)	0	0.00	No measures
	1	16.67, 33.33	Recommend closing
	2	50.00, 66.67	Required closing (only some levels or categories, e.g. just high school, or just public schools)
	3	83.33, 100.00	Required closing all levels
Workplace closing (Record closings of workplaces.)	0	0.00	No measures
	1	16.67, 33.33	Recommend closing (or recommend work from home)
	2	50.00, 66.67	Required closing (or work from home) for some sectors or categories of workers
	3	83.33, 100.00	Required closing (or work from home) for all but essential workplaces (e.g. grocery stores, doctors)
Cancel public events (Record cancelling public	0	0.00	No measures

events.)	1	25.00, 50.00	Recommend cancelling
	2	75.00, 100.00	Required cancelling
Restrictions on gatherings (Record limits on private gatherings.)	0	0.00	No measures
	1	25.00	Restrictions on very large gatherings (the limit is above 1000 people)
	2	37.50, 50.00	Restrictions on gatherings between 101-1000 people
	3	62.50, 75.00	Restrictions on gatherings between 11-100 people
	4	87.50, 100.00	Restrictions on gatherings of 10 people or less
Close public transport (Record closing of public transport.)	0	0.00	No measures
	1	25.00, 50.00	Recommend closing or significantly reduce volume, route and means of transport available.
	2	75.00, 100.00	Required closing or prohibit most citizens from using it.
Stay at home requirements (Record orders to "shelter-in-place" and otherwise confine to the home.)	0	0.00	No measures
	1	16.67, 33.33	Recommend not leaving house
	2	50.00, 66.67	Required not leaving house with exceptions for daily exercise, grocery shopping, and 'essential' trips.
	3	83.33	Required not leaving house with minimal exceptions (e.g. allowed to leave once a week, or only one person can leave at a time, etc.)
Restrictions on internal movement (Record restrictions on internal movement between cities or regions.)	0	0.00	No measures
	1	25.00, 50.00	Recommend not to travel between regions or cities
	2	75.00, 100.00	Internal movement restrictions in place
International travel controls (Record restrictions on international travel.)	0	0.00	No measures
	1	25.00	Screening arrivals
	2	50.00	Quarantine arrivals from some or all regions
	3	75.00	Ban arrivals from some regions
	4	100.00	Ban on all regions or total border closure
Income support (Record if the government is providing direct cash payments to people who lose their jobs or cannot work. This policy only includes payments to firms if explicitly linked to payroll and salaries.)	0	0.00	No income support
	1	25.00, 50.00	Government is replacing less than 50% of lost salary or if a flat sum, it is less than 50% median salary.
	2	75.00, 100.00	Government is replacing 50% or more of lost salary or if a flat sum, it is greater than 50% median salary.
Debt or contract relief (Record if the government is freezing financial obligations for households.)	0	0.00	No debt or contract relief
	1	50.00	Narrow relief, specific to one kind of contract
	2	100.00	Broad debt or contract relief
Public information campaigns (Record presence of public info campaigns.)	0	0.00	No Covid-19 public information campaign
	1	50.00	Public officials urging caution about COVID-19
	2	75.00, 100.00	Coordinated public information campaign (e.g. across traditional and social media)
Testing policy (Record government policy on who has access to testing. This records policies about testing for current infection (PCR tests) not testing for immunity, such as antibody test.)	0	0.00	No testing policy
	1	33.33	Only those who both (a) have symptoms and (b) meet Specific criteria (e.g. key workers, admitted to hospital, encountered a known case, returned from overseas)
	2	66.67	Testing of anyone showing COVID-19 symptoms
	3	100.00	Open public testing (e.g. "drive through" testing available to asymptomatic people)
Contact tracing (Record government policy on contact tracing after a positive diagnosis.)	0	0.00	No contact tracing
	1	50.00	Limited contact tracing; not done for all cases
	2	100.00	Comprehensive contact tracing; done for all identified cases

Table S2: Fitting performance of three models on the training sets.

Stage	Method	Root Mean Square Error	R^2	Mean Square Error
Pre-vaccine era	SVM	0.280	0.560	0.078
	RF	0.230	0.702	0.053
	XGBoost	0.221	0.725	0.049
Post-vaccine era	SVM	0.099	0.725	0.010
	RF	0.132	0.519	0.017
	XGBoost	0.047	0.938	0.002

Note: SVM, RF, XGBoost represent support vector machine, random forest, and extreme gradient boosting respectively.

Table S3: Lag effects based on the training set in the pre-vaccine era.

Lag week	Root Mean Square Error	R^2	Mean Square Error
1 week	0.290	0.574	0.084
2 weeks	0.298	0.547	0.089
4 weeks	0.305	0.527	0.093
8 weeks	0.369	0.306	0.136

Table S4: Contribution percentages (%) for different group of factors to the effective reproductive number of COVID-19 for 39 countries.

	Pre-vaccine era					Post-vaccine era						
Country	Policy	Travel	Socioeconomic	Medical	Environmental	Policy	Travel	Socioeconomic	Medical	Environmental	Vaccine	Mutants
Afghanistan	66.85	14.70	6.21	7.45	4.79	50.14	10.76	16.66	5.04	7.13	3.75	6.52
Algeria	51.79	22.99	8.05	11.27	5.90	33.91	26.04	5.36	4.00	11.36	6.77	12.55
Argentina	46.13	19.40	14.60	4.12	15.76	35.73	14.96	5.65	7.38	7.09	7.54	21.66
Australia	59.25	15.60	10.66	6.47	8.02	21.06	26.00	5.32	8.93	13.40	4.54	20.75
Austria	75.05	9.37	7.98	3.54	4.05	28.09	24.87	8.77	8.40	10.77	9.16	9.93
Bangladesh	67.44	9.84	10.71	5.14	6.87	18.01	11.11	10.98	1.57	10.64	15.03	32.67
Bolivia	49.89	22.52	13.21	3.25	11.13	31.80	17.84	16.28	4.41	7.04	11.18	11.45
Bulgaria	76.36	4.71	8.61	3.93	6.39	29.77	40.48	7.54	5.45	8.19	5.31	3.26
Cameroon	59.53	32.70	3.69	2.12	1.97	13.41	9.38	4.09	65.60	3.94	1.37	2.21
Canada	56.43	19.38	11.19	9.89	3.11	10.93	16.90	6.85	8.30	18.56	12.54	25.92
Chile	54.96	18.63	14.64	4.26	7.51	25.72	22.87	5.47	5.66	9.46	6.26	24.57
China	59.71	23.63	4.12	6.81	5.73	13.55	21.59	6.20	10.87	11.22	4.17	32.40
Colombia	52.52	14.33	16.17	3.77	13.21	18.63	22.10	4.69	6.07	6.00	16.08	26.44
Denmark	59.56	22.04	7.74	6.21	4.45	37.66	22.70	10.43	4.44	8.41	6.93	9.41
Ecuador	55.63	15.70	12.39	2.68	13.60	31.43	21.29	5.85	7.20	7.68	7.17	19.36
Finland	62.28	15.11	6.24	6.27	10.11	16.84	23.81	9.10	6.03	12.71	10.33	21.19
France	57.19	28.49	6.71	3.74	3.88	28.34	20.88	7.71	6.16	9.12	5.82	21.97
Germany	49.69	31.19	8.39	3.50	7.24	33.43	18.61	7.22	5.27	9.19	5.54	20.75
Greece	76.19	11.49	5.77	3.53	3.02	32.96	25.11	6.46	10.44	6.89	8.93	9.20
Iceland	60.27	22.94	4.89	3.31	8.59	27.56	28.02	14.52	7.72	8.36	7.78	6.05
India	57.02	12.46	14.27	4.58	11.67	19.66	22.15	12.75	6.71	18.00	5.55	15.19
Indonesia	72.57	9.72	8.65	2.66	6.40	21.32	27.32	2.49	5.02	16.84	5.12	21.88
Ireland	67.14	11.73	10.42	4.14	6.57	36.60	19.83	11.66	7.80	6.58	6.20	11.33
Italy	53.87	24.80	13.40	4.11	3.82	22.18	21.29	5.51	9.90	8.00	8.68	24.45
Japan	64.87	14.34	13.27	3.14	4.39	37.35	20.99	5.17	9.93	5.01	8.84	12.71
Kenya	51.15	16.71	14.89	4.15	13.10	33.42	14.71	8.88	3.64	8.64	5.05	25.66
Mexico	79.83	9.11	5.14	3.78	2.13	38.54	21.00	3.71	12.01	7.45	5.13	12.16

New Zealand	56.72	28.84	8.04	1.72	4.69	35.04	21.97	8.11	4.37	8.47	6.22	15.82
Norway	65.65	12.43	7.08	3.63	11.21	23.26	23.40	10.83	8.64	12.61	8.22	13.03
Pakistan	73.27	6.94	8.42	4.23	7.14	32.06	19.16	16.53	2.34	11.10	4.80	14.01
Panama	55.85	19.62	11.37	3.11	10.05	26.86	28.50	12.16	5.31	8.81	5.97	12.38
Philippines	72.47	7.65	11.79	2.65	5.44	26.56	7.53	12.68	3.07	8.51	5.80	35.86
Portugal	66.61	12.36	13.46	4.73	2.85	39.19	20.43	3.28	15.44	5.80	3.07	12.79
Romania	71.41	6.51	10.96	4.21	6.91	29.60	26.39	4.53	10.08	12.02	4.24	13.14
South Africa	57.11	13.25	12.69	5.15	11.80	31.54	11.93	4.11	6.47	7.12	10.66	28.16
South Korea	61.86	18.21	10.32	6.23	3.38	28.37	24.91	6.60	4.52	9.37	8.52	17.70
Spain	44.04	44.26	4.61	4.62	2.48	25.08	31.35	3.72	8.64	8.82	4.89	17.50
Sweden	81.87	6.89	5.92	3.69	1.64	23.36	17.62	7.32	6.65	15.92	7.52	21.61
United States	50.22	32.90	7.26	4.99	4.63	20.84	24.84	9.17	13.11	9.40	5.23	17.40

Table S5: The fitting performance of three phases on the training set.

Situation	Root Mean Square Error	R^2	Mean Square Error
Single-peak	0.634	0.824	0.4020
Double-peak	0.298	0.712	0.0889
Multi-peak	0.021	0.988	0.0004

Table S6: Evaluations for the rebound forecast model on the training and testing sets.

Stage	Data Set	Accuracy	Precision	Recall	F1-Score	AUC
Pre-vaccine era	Training Set	0.9597	0.9597	0.9624	0.9648	0.96
	Testing Set	0.7817	0.7817	0.8307	0.8506	0.77
Post-vaccine era	Training Set	0.9465	0.9466	0.9457	0.9463	0.94
	Testing Set	0.8148	0.8150	0.7791	0.8034	0.82

Note: Two training sets are pre-vaccine era (up to October 31st, 2020) and post-vaccine era (January 2021 to May 31st, 2021). Testing sets are pre-vaccine era (November 1st to 30th, 2020) and post-vaccine era (June 1st to 30th, 2021) respectively.

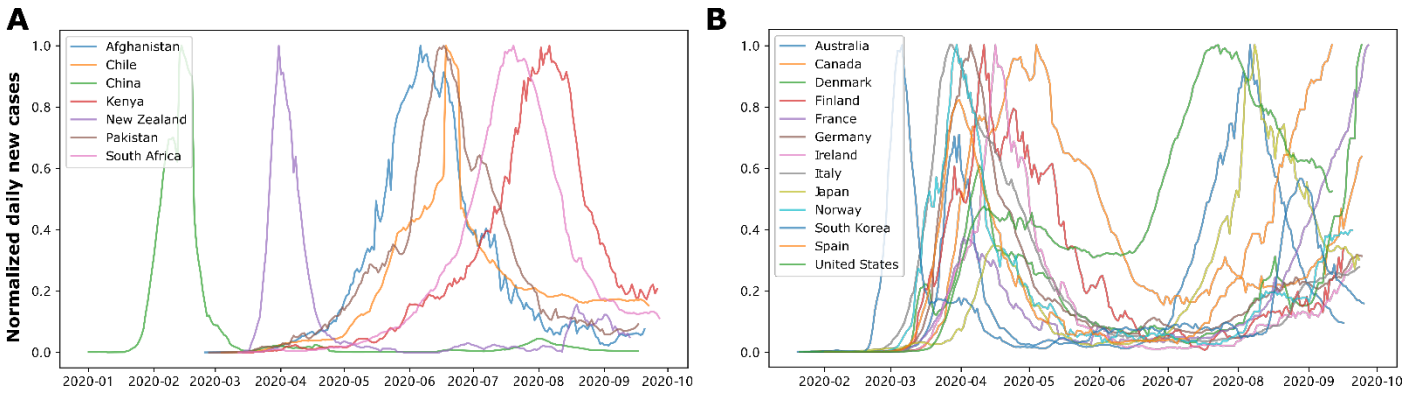

Figure S1: Normalized daily new cases of COVID-19 for single-peak (A) and double-peak (B) countries. The highest number of cases normalized the cases during the study period for all the countries.

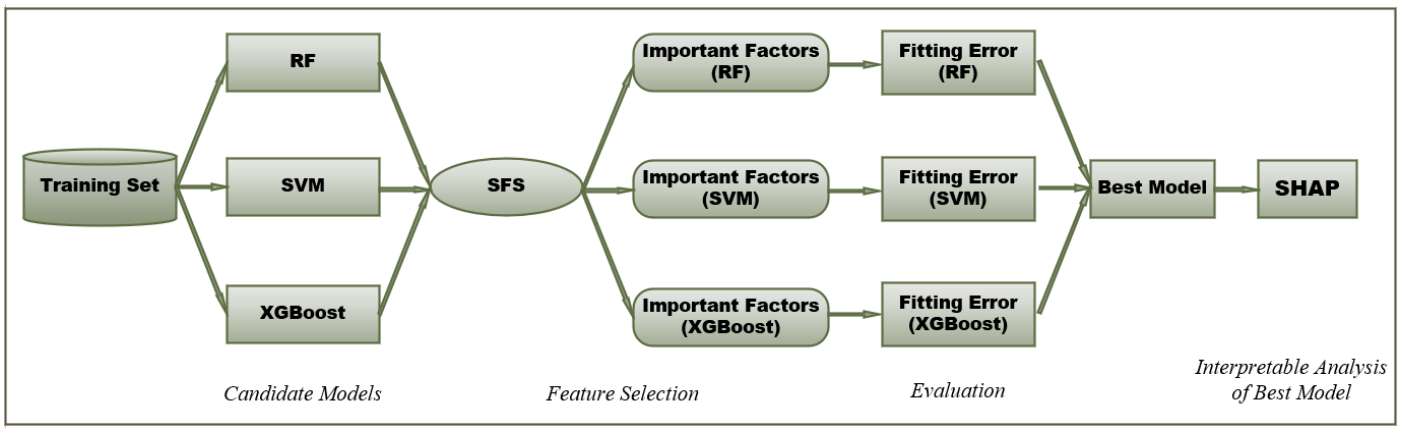

Figure S2: Model framework.

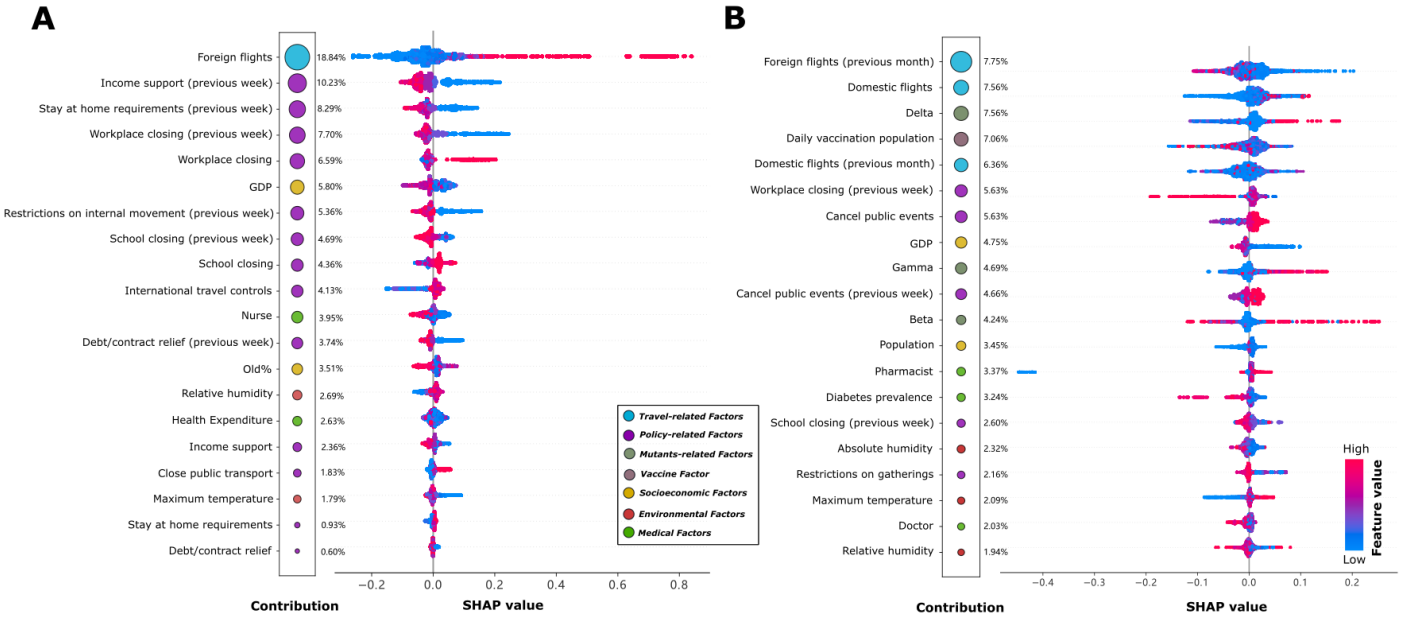

Figure S3: Top 20 contributors to R_t with their SHAP value based on data from 39 countries. (A) Pre-vaccine era. (B) Post-vaccine era. Feature value is the true value of the factor, redder it is the larger the true value of the current factor, on the contrary, bluer the true value is smaller the true value. The SHAP value is the vector contribution of the current factor to R_t. The contribution is calculated based on the SHAP value (see Materials and Methods for details), the size of the circle indicates the amount of contribution, and the different colors represent the factor group to which the factor belongs.

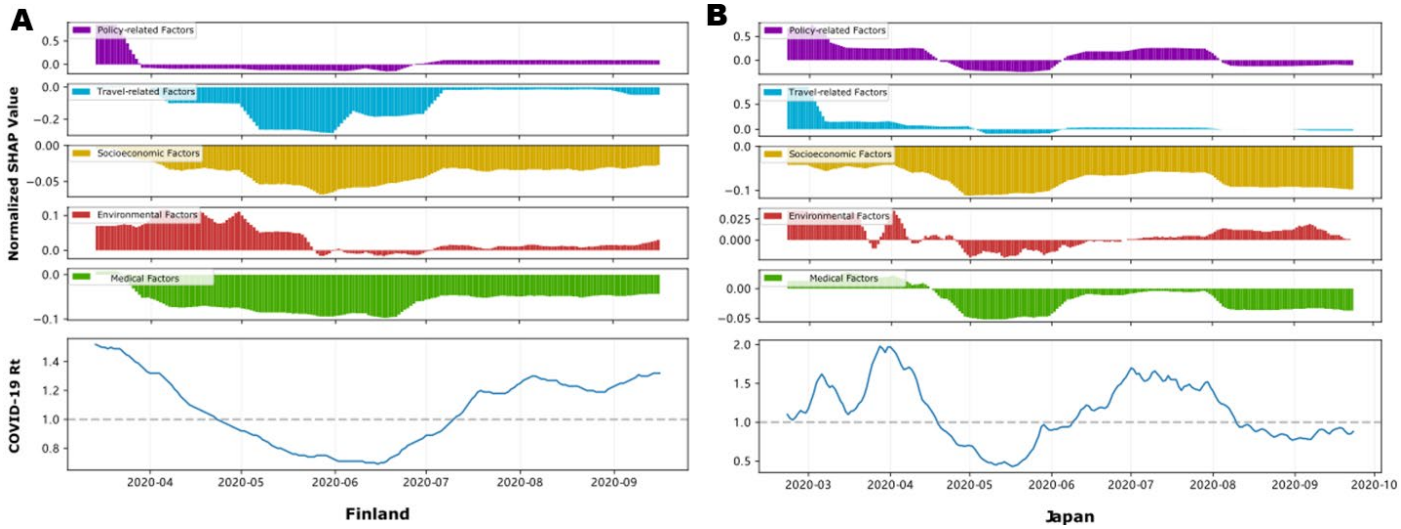

Figure S4: Normalized SHAP values for each group of factors and the daily new cases rate of COVID-19 for Finland (A) and Japan (B) The highest value normalizes SHAP values among countries for each group of factors. For more information

on the dynamic contribution of 39 countries factor group, please see *https://github.com/caozicheng/AI-exploration-multiple-waves-of-COVID-19-*.