

Results

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We evaluated a total 181851 forecast predictions from 47 forecasting models, contributed by 37 separate modelling teams to the European COVID-19 Forecast Hub. 5 teams contributed more than one model. Models varied over time as forecasting teams joined or left the Hub and contributed predictions for varying combinations of forecast targets. Between 7 and 33 models contributed in any one week, forecasting for any combination of 256 possible weekly forecast targets (32 countries, 4 horizons, and 2 target outcomes). On average each model contributed 3869 forecasts, with the median model contributing 764 forecasts.

We categorised 12 models as statistical, 12 as semi-mechanistic, 17 as mechanistic, 3 as agent-based and 3 models that used human judgement forecasting as “other” (Supplementary Table). For 17 (36%) models, investigators disagreed on model classification. The majority of 2/3 was used as the final classification, with additional manual review which in all cases retained the majority decision. In the volume of forecasts provided, mechanistic, semi-mechanistic, and statistical models each contributed similar numbers of forecasts with approximately one-third each. Agent-based and “other” models provided fewer forecasts, representing only 1-2% of forecasts.

On average we observed similar performance of the interval score between mechanistic and semi-mechanistic models. These performed relatively better than statistical models and worse than agent-based and “other” models, although in all these cases with largely overlapping variation in performance. Relative performance among modelling methods also appeared to vary over time (Figure 1). For example, over summer 2021 all model types saw worsening performance coinciding with the introduction of the Delta variant across Europe, but this decline was most marked among statistical models of death outcomes compared to any other model type.

We considered models forecasting for only one, or multiple countries. We collated 19 single-country models and 28 multi-country models. Single-country models targeted Germany (7 models), Poland (5), Spain (3), Italy (2), Czechia (2) and Slovenia (1). The average multi-country model forecast for a median number of 23 locations. Models classified as targeting multiple countries could vary from week to week in how many locations they forecast. Only 2 models consistently forecast for the same number of locations throughout the entire study period.

Multi-country models typically under-performed relative to single-country models. This relative under-performance was stable over time, although with overlapping range of variation. Multi-country models saw a more sustained period of relative poorer performance in forecasting deaths over spring-summer 2022, although we did not observe this difference among case forecasts.

Apart from differences between models, we also observed differences based on the epidemiological situation and predictive horizon. Average performance decreased from 1 to 4 weeks of predictive horizon, and was best when the epidemiological situation was stable, with little observed difference between decreasing and increasing situations.

We further used a generalised additive mixed model to characterise the association between different factors and predictive performance. The interval score was highly right-skewed with respect to all explanatory variables (see Supplementary Figure 1), which we accounted for by using a log-link. We found no clear evidence that any one type of method structure consistently outperformed others when predicting cases, but we saw some small differences (with overlapping confidence intervals) indicating that statistical and agent-based models performed better and semi-mechanistic models worse than the average when predicting

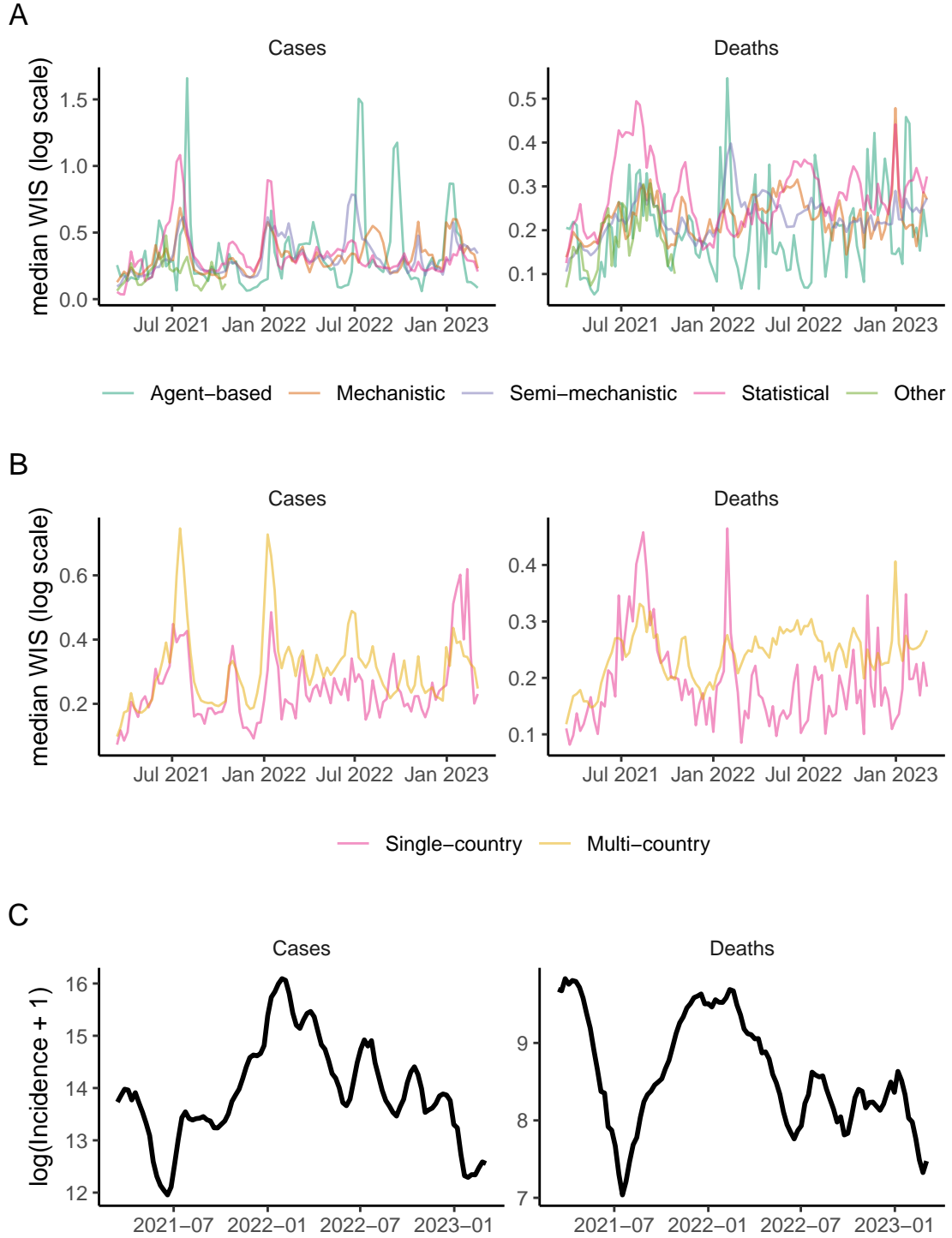


Figure 1: Predictive accuracy of multiple models' forecasts for COVID-19 cases and deaths across 32 European countries. Forecast performance is shown as the median weighted interval score (WIS), where a lower score indicates better performance. Forecast performance is summarised across 32 target locations and 1 through 4 week forecast horizons, with varying numbers of forecasters participating over time. Shown for (A) the method structure used by each model; (B) the number of countries each model targeted (one or multiple); with (C) the total count of observed incidence across all 32 countries, shown on the log scale.

Table 1: Characteristics of forecast performance (interval score) contributed to the European COVID-19 Forecast Hub, March 2021-2023.

Variable	Cases			Deaths		
	Models	Forecasts	Median WIS (IQR)	Models	Forecasts	Median WIS (IQR)
Overall	42 (100%)	91966 (100%)	0.28 (0.14-0.63)	38 (100%)	89885 (100%)	0.23 (0.12-0.63)
Method						
Agent-based	3 (7.1%)	814 (0.9%)	0.23 (0.11-0.51)	2 (5.3%)	720 (0.8%)	0.17 (0.09-0.31)
Mechanistic	16 (38.1%)	27987 (30.4%)	0.28 (0.12-0.64)	16 (42.1%)	33449 (37.2%)	0.22 (0.11-0.64)
Semi-mechanistic	9 (21.4%)	28742 (31.3%)	0.27 (0.14-0.62)	10 (26.3%)	28494 (31.7%)	0.22 (0.13-0.64)
Statistical	11 (26.2%)	32680 (35.5%)	0.3 (0.15-0.65)	7 (18.4%)	25478 (28.3%)	0.27 (0.14-0.65)
Other	3 (7.1%)	1743 (1.9%)	0.18 (0.08-0.42)	3 (7.9%)	1744 (1.9%)	0.15 (0.08-0.42)
Number of country targets						
Single-country	19 (45.2%)	3680 (4%)	0.23 (0.1-0.5)	14 (36.8%)	2821 (3.1%)	0.19 (0.09-0.5)
Multi-country	23 (54.8%)	88286 (96%)	0.29 (0.14-0.63)	24 (63.2%)	87064 (96.9%)	0.23 (0.13-0.63)
Week ahead horizon						
1	42 (100%)	24900 (27.1%)	0.14 (0.07-0.28)	38 (100%)	25417 (28.3%)	0.17 (0.09-0.28)
2	40 (95.2%)	22839 (24.8%)	0.25 (0.13-0.5)	33 (86.8%)	21710 (24.2%)	0.21 (0.12-0.5)
3	38 (90.5%)	22247 (24.2%)	0.38 (0.2-0.77)	32 (84.2%)	21498 (23.9%)	0.27 (0.15-0.77)
4	37 (88.1%)	21980 (23.9%)	0.52 (0.26-1.05)	31 (81.6%)	21260 (23.7%)	0.34 (0.19-1.05)
3-week trend in incidence						
Stable	38 (90.5%)	12682 (13.8%)	0.2 (0.11-0.41)	37 (97.4%)	16793 (18.7%)	0.18 (0.09-0.41)
Increasing	41 (97.6%)	36673 (39.9%)	0.31 (0.14-0.74)	37 (97.4%)	32402 (36%)	0.25 (0.13-0.74)
Decreasing	42 (100%)	42611 (46.3%)	0.29 (0.15-0.62)	38 (100%)	40690 (45.3%)	0.24 (0.14-0.62)

deaths (Figure 2). We further saw some indication that models focusing on a single country outperformed those modelling multiple countries when forecasting cases (again with overlapping confidence intervals) but not when forecasting deaths.

Lastly, both when forecasting cases and deaths the estimated effects supported our observation that WIS values were substantially lower during stable periods of each country’s outbreak curve, compared to increasing or decreasing trends in incidence, indicating improved predictive performance during those periods. Using the estimated partial random effect for each model as a proxy of its performance whilst correcting for missingness and common factors we found substantial variation beyond the factors we modelled, indicating that these factors were not sufficient for explaining variation in performance (Figure 3).

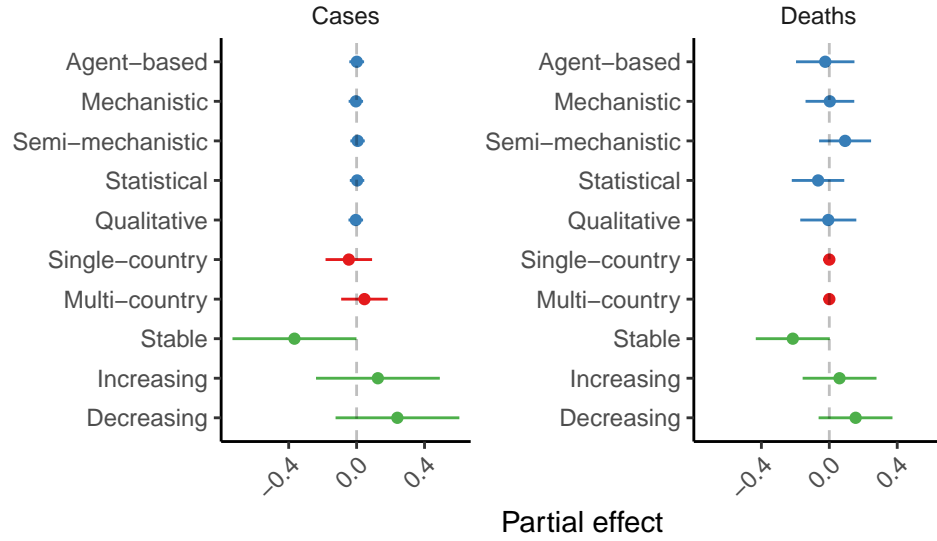


Figure 2: Partial effect size (95% CI) by explanatory variable.

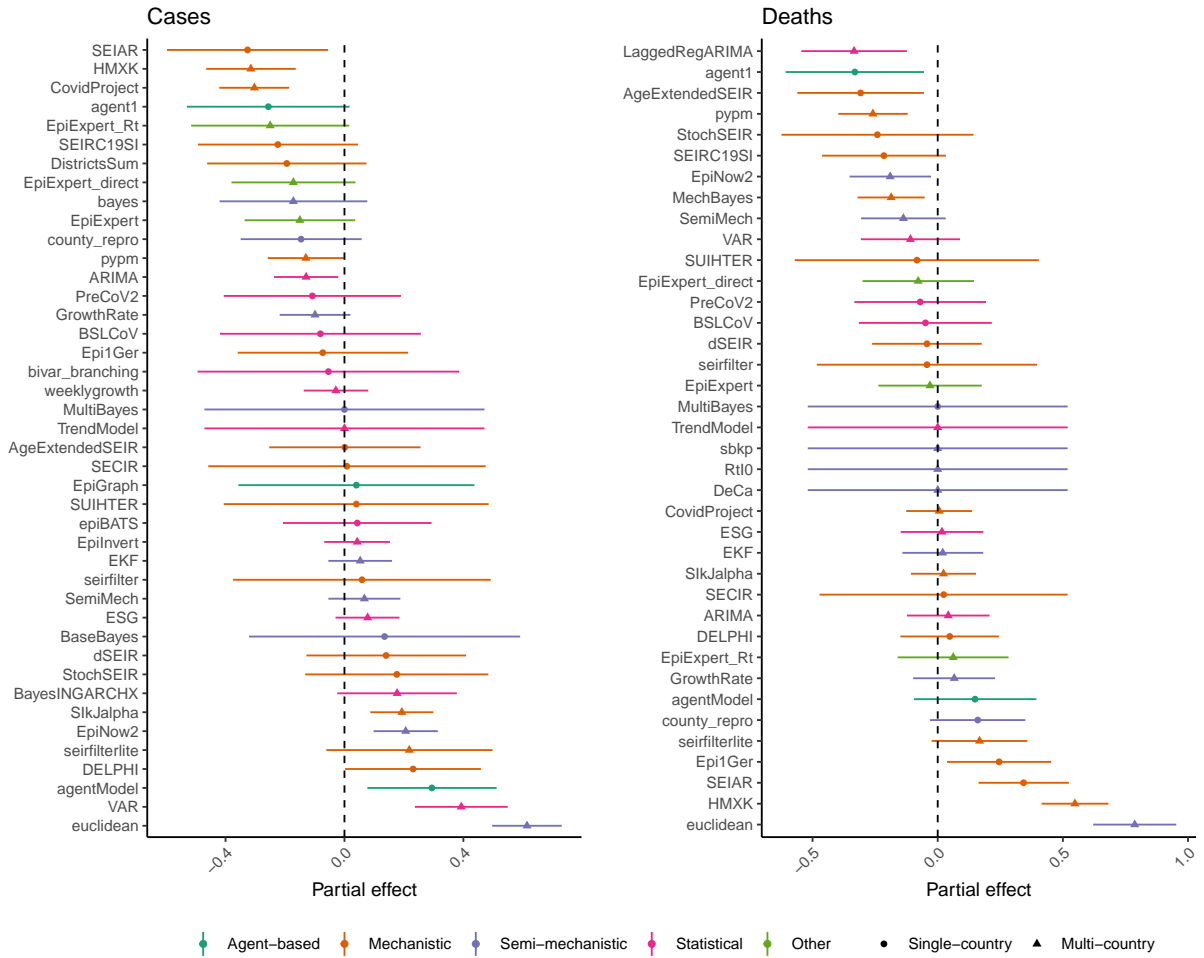


Figure 3: Partial effect size (95% CI) by model.