Response to question 1: A brief overview of qualifications, career history, professional expertise and major publications

FULL NAME AND TITLE: Dr Edward Mervyn Hill
DEPARTMENT: Mathematics Institute
CURRENT APPOINTMENT: Warwick Zeeman Lecturer, Warwick Mathematics Institute, University of Warwick.

I am a Warwick Zeeman Lecturer at the University of Warwick. I have worked in the field of mathematical epidemiology and the modelling of infectious disease dynamics since 2013. My research to date may be grouped under three broad categories: (i) Public health policy; (ii) Social contagion and impact of behaviour on infectious disease dynamics; (iii) Zoonotic transmission and One Health. Current research interests involve addressing interdisciplinary problems in epidemiology that involve the dynamics of behaviour.

I am also a member of JUNIPER (Joint UNIversities Pandemic and Epidemiological Research), a consortium of epidemiological modelling groups from seven universities: Bristol, Cambridge, Exeter, Lancaster, Manchester, Oxford and Warwick.

PREVIOUS APPOINTMENTS

2017-2022. Postdoctoral Research Fellow, University of Warwick

EDUCATION/QUALIFICATIONS

2008-2012. First class honours degree in Mathematics (MMath), University of Warwick.
2012-2013. Distinction grade for MSc in Complexity Science, University of Warwick.
2013-2017. Postgraduate Certificate in Transferable Skills in Science, University of Warwick.
2013-2017. PhD in Interdisciplinary Mathematics and Complexity Science, University of Warwick.

SELECTED PEER-REVIEWED PUBLICATIONS (~30 in total; * denotes joint first authors)

1. MJ Keeling, L Dyson, MJ Tildesley, **EM Hill**, S Moore. (2022) Comparison of the 2021 COVID-19 roadmap projections against public health data in England. *Nature Communications*, 13: 4924. doi:10.1038/s41467-022-31991-0.
2. MJ Keeling, L Dyson, G Guyver-Fletcher, A Holmes, MG Semple, ISARIC4C Investigators, MJ Tildesley, **EM Hill**. (2022) Fitting to the UK COVID-19 outbreak, short-term forecasts and estimating the reproductive number. *Statistical Methods in Medical Research,* 31(9): 1716-1737. doi: 10.1177/09622802211070257.
3. MJ Tildesley, A Vassall, S Riley, M Jit, F Sandmann, **EM Hill**, RN Thompson, BD Atkins, J Edmunds, L Dyson, MJ Keeling. (2022) Optimal health and economic impact of non-pharmaceutical intervention measures prior and post vaccination in England: a mathematical modelling study. *Royal Society Open Science*, 9(8): 211746. doi:10.1098/rsos.211746.
4. L Dyson*, **EM Hill*** ***et al.*** (2021) Possible future waves of SARS-CoV-2 infection generated by variants of concern with a range of characteristics. *Nature Communications*, 12: 5730. doi: 10.1038/s41467-021-25915-7.
5. **EM Hill**, MJ Keeling. (2021) Comparison between one and two dose SARS-CoV-2 vaccine prioritization for a fixed number of vaccine doses. *Interface*, 18(182): 20210214. doi: 10.1098/rsif.2021.0214.
6. J Enright*, **EM Hill***, HB Stage, KJ Bolton, EJ Nixon, EM Fairbanks, ML Tang, E Brooks-Pollock, L Dyson, CJ Budd, RB Hoyle, L Schewe, JR Gog, MJ Tildesley. (2021) SARS-CoV-2 infection in UK university students: Lessons from September-December 2020 and modelling insights for future student return. *Royal Society Open Science*, 8(8): 210310. doi:10.1098/rsos.210310.

7. **EM Hill**, BD Atkins, MJ Keeling, MJ Tildesley, L Dyson. (2021) Modelling SARS-CoV-2 transmission in a UK university setting. *Epidemics*, 36: 100476. doi: 10.1016/j.epidem.2021.100476.
8. **EM Hill***, BD Atkins*, MJ Keeling, L Dyson, MJ Tildesley. (2021) A network modelling approach to assess non-pharmaceutical diseases controls in a worker population: An application to SARS-CoV-2. *PLoS Computational Biology,* 17(6): e1009058. doi: 10.1371/journal.pcbi.1009058.
9. RN Thompson, **EM Hill**, JR Gog. (2021) SARS-CoV-2 incidence and vaccine escape. *Lancet Infectious Diseases,* 21(7): 913-914. doi: 10.1016/S1473-3099(21)00202-4.
10. S Moore, **EM Hill**, MJ Tildesley, L Dyson, MJ Keeling. (2021) Vaccination and Non-Pharmaceutical Interventions: a mathematical modelling study. *Lancet Infectious Diseases,* 21(6): 793-802. doi: 10.1016/S1473-3099(21)00143-2.
11. S Stanizewska, **EM Hill**, R Grant, P Grove, J Porter, T Shiri, S Tulip, J Whitehurst, C Wright, S Datta, S Petrou, MJ Keeling. (2021) Developing a Framework for Public Involvement in Mathematical and Economic Modelling: Bringing New Dynamism to Vaccination Policy Recommendations. *Patient*, 14(4): 435-445. doi:10.1007/s40271-020-00476-x.
12. **EM Hill**, S Petrou, H Forster, S de Lusignan, I Yonova, MJ Keeling. (2020) Optimising age coverage of seasonal influenza vaccination in England: A mathematical and health economic evaluation. *PLoS Computational Biology*, 16(10): e1007096. doi: 10.1371/journal.pcbi.1008278.
13. **EM Hill**, S Petrou, S de Lusignan, I Yonova, MJ Keeling. (2019) Seasonal influenza: Modelling approaches to capture immunity propagation. *PLoS Computational Biology*, 15(10): e1007096. doi: 10.1371/journal.pcbi.1007096.
14. **EM Hill** *et al.* (2018) The impact of surveillance and control on highly pathogenic avian influenza outbreaks in poultry in Dhaka division, Bangladesh. *PLoS Computational Biology*, 14(9): e1006439. doi: 10.1371/journal.pcbi.1006439.
15. **EM Hill** *et al.* (2017) Modelling H5N1 in Bangladesh across spatial scales: Model complexity and zoonotic transmission risk. *Epidemics*, 20C: 37-55. doi:10.1016/j.epidem.2017.02.007.
16. **EM Hill**, MJ Tildesley and T House. (2017) Evidence for history-dependence of influenza pandemic emergence. *Scientific Reports*, 7: 43623. doi:10.1038/srep43623.
17. **EM Hill**, FE Griffiths and T House. (2015) Spreading of healthy mood in adolescent social networks. *Proceedings of the Royal Society B*, 282(1813): 20151180. doi:10.1098/rspb.2015.1180.

SELECTED PREPRINTS (~10 in total; * denotes joint first authors)

1. **EM Hill**. (2022) Modelling the epidemiological implications for SARS-CoV-2 of Christmas household bubbles in England. *medRxiv*. doi: 10.1101/2022.07.04.22277231.
2. S Moore, **EM Hill**, MJ Tildesley, L Dyson, MJ Keeling. (2022) The impacts of increased global vaccine sharing on the COVID-19 pandemic; a retrospective modelling study. *medRxiv*. doi: 10.1101/2022.01.26.22269877.
3. MJ Keeling, B Penman, **EM Hill**, S Moore. (2022) The Impact of SARS-CoV-2 Vaccine Dose Separation and Dose Targeting on Hospital Admissions and Deaths from COVID-19 in England. *medRxiv*. doi: 10.1101/2022.08.22.22278973
4. LM Guzman-Rincon, **EM Hill**, L Dyson, MJ Tildesley, MJ Keeling. (2022) Bayesian Estimation of real-time Epidemic Growth Rates using Gaussian Processes: local dynamics of SARS-CoV-2 in England. *medRxiv*. doi: 10.1101/2022.01.01.21268131.
5. R Challen, … , **EM Hill**, … *et al.* (2021) Early epidemiological signatures of novel SARS-CoV-2 variants: establishment of B.1.617.2 in England. *medRxiv*. doi: 10.1101/2021.06.05.21258365.

Response to questions 2&3: Summary of participation in SPI-M-O

I was a participant of the Scientific Pandemic Influenza Group on Modelling, Operational sub-group (SPI-M-O).

I began attending meetings relating to SPI-M-O on 27 March 2020. My participation was suggested to Graham Medley by Matt Keeling; Matt Keeling was, prior to this, the only participant of SPI-M-O from the University of Warwick. I attended 85 main meetings of SPI-M-O from 6 April 2020 to its last meeting on 23 March 2022.

My contributions in these meetings and in email discussions was to provide scientific advice and insight with my expertise on mathematical epidemiology and modelling of infectious disease dynamics. These contributions included: presenting research undertaken by myself and others; reading, listening to and critically reviewing others' contributions; contributing to group discussions which were then represented by the SPI-M-O secretariat in consensus statements (summaries of the work provided to SPI-M-O are provided in response to question 4).

In general, SPI-M-O participants responded to commissions communicated to us via the SPI-M-O secretariat. These commissions provided a structure for the committee to submit work relevant to policy decisions in a timely manner. Participants were also encouraged to submit other non-commissioned work that we felt to be important.

Response to question 4: Summary of documents for the purpose of advising SAGE and/or its related subgroups

Documents are grouped into the following categories (alphabetically ordered): Christmas Bubbles, Early dynamics, Exiting the First Wave, Higher Education, Impact on Seasonal Influenza, Omicron, Precautionary Breaks, Roadmap Out of Lockdown, School Closures and Reopening, Vaccination, Variants (pre-Omicron), Workplaces and Worker Patterns.

This response concludes with "Other Documents" that were on topics outside those previously listed.

If there are multiple documents contained in a category, they are listed in chronological order.

Christmas Bubbles

02 Dec 2020	**Household bubbles over 23rd-27th December** Hill	SPI-M-O
16 Dec 2020	**Household Secondary Attack Rate plots: Household bubble model extension** Hill	SPI-M-O
Summary. In November 2020, plans were published to allow individuals to socialise within "Christmas bubbles" with friends and family. This policy involved a planned easing of restrictions in England between 23-27 December 2020, with Christmas bubbles allowing people from up to three households to meet throughout the holiday period. This document reports on a stochastic individual-based model for a synthetic population of 100,000 households, used to estimate the epidemiological impact of both this and alternative bubble strategies that allowed extending contacts beyond the immediate household. The findings indicated that visiting family and friends over the holiday period for a shorter duration and in smaller groups was less risky than spending the entire five days together. Furthermore, the increases in infection from greater amounts of social mixing disproportionately impacted the eldest. This work is available online as a preprint: Edward M. Hill. (2022) "Modelling the epidemiological implications for SARS-CoV-2 of Christmas household bubbles in England" *medRxiv*. https://doi.org/10.1101/2022.06.13.22276316		

Early Dynamics

27 Apr 2020	**Assessment of Changes to Lock-Down and Other Controls.** Keeling, Tildesley, Dyson, Hill, Gorsich, Penman, Tamborrina, Hutton, McKimm, Leng, Guyver-Fletcher, Holmes.	SPI-M-O SAGE 29
Summary. This work examined (i) targeting lockdown at the elderly, (ii) controls that were responsive to local ICU burden, and (iii) the impact of waning compliance in the population. We state: "Of the strategies investigated here, very few do not lead to a sizeable second or third wave" and "If we knew when a vaccine would be available, this would completely change the perspective on many of these calculations, as one option becomes containing the infection until mass immunisation is possible." **SAGE link**: https://www.gov.uk/government/publications/university-of-warwick-assessment-of-changes-to-lockdown-and-other-controls-26-april-2020		

Exiting the First Wave

04 May 2020	**Simulations of Potential Exit Strategies.**	SPI-M-O

	Keeling, Tildesley, Dyson, Hill, Gorsich, Penman, Tamborrina, Hutton, McKimm, Leng, Guyver-Fletcher, Holmes	SAGE 33
Summary. This work examined the relaxation of the first lockdown over four phases (from 11th May to 15th August). It assumed that some measures would remain in place and that high levels of contact tracing would be in operation. We also considered sensitivity to compliance, looking at compliance declining over time. We stated that "In general the proposal of gradually opening schools, workplaces and leisure activities, together with contact tracing limits the chance of a second wave"; however, we caveat this by noting that with poor tracing we projected a notable epidemic peak in Nov/Dec 2020. **SAGE link**: https://www.gov.uk/government/publications/university-of-warwick-simulations-of-potential-exit-strategies-3-may-2020		

13 May 2020	**Reasonable Worse Case Scenarios.** Keeling, Dyson, Hill, Tildesley & the Warwick Team.	SPI-M-O SAGE 37
Summary. Performed a set of scenarios in which (i) *R* increases for a short period before settling to *R*=1 - this generates an increase in cases, which is then maintained until herd immunity is reached; and (ii) *R* is increased for a period, it then is reduced to 0.7 before settling at 1 - this generates a spike in cases before plateauing at a low level. These were used as part of SPI-M-O: COVID-19 short-term forecasts to SAGE 37.		

20 Jul 2020	**Reasonable worst case scenario (RWCS) for July 2020** Dyson, Hill	SPI-M-O

Summary. Assorted documents summarising the use of the Warwick COVID-19 model to perform a set of scenarios described below:
• Incidence remained low throughout July 2020
• Incidence doubled once by the end of August 2020
• Incidence doubled during the first two weeks of September 2020, after which policy measures reduce R to around 1 until the end of October 2020
• Return to a two week doubling time during November 2020
• At the end of November:
  ○ SCENARIO A: Reduce all non-household contacts to 25% of their normal (pre-lockdown) level
  ○ SCENARIO B: Reduce all non-household contacts to 35% of their normal level
  ○ SCENARIO C: Reduce all non-household contacts to 50% of their normal level
• This is sustained until the end of March 2021
A version of Scenarios A,B & C was also considered where school contacts were not reduced. These RWCS were considered with and without the application of dexamethasone from 1st July 2020.		

28 Jul 2020	**Warwick Reasonable Worst Case (RWC) Narrative.** Keeling, Hill, Tildesley, Dyson & the Warwick Team	SPI-M-O
Summary. This document discussed five RWC (reasonable worse case) scenarios for the immediate future: importations from tourists returning to UK; increase in R in the approach to winter; increased mixing over Christmas & New Year (particularly the movement of students); general apathy towards control measures; lack of protection against infection by the vaccine and reduced efficacy in the elderly.		

Higher Education

13 Jan 2021	**COVID-19 and Universities: Report from the Higher Education working group at the Isaac Newton Institute.**	SPI-M-O SAGE 76

	Isaac Newton Institute Higher Education working group (included Hill, Dyson, Keeling & Tildesley as authors)	
Summary. This was a report submitted to SPI-M-O in January 2021 from the Isaac Newton Institute Higher Education (INI HE) working group. The INI HE group was comprised of academics from nine universities around the UK (Bath, Bristol, Cambridge, Edinburgh, Glasgow, Manchester, Nottingham, Southampton, Warwick) who were tasked with analysing the impact of SARS-CoV-2 in higher education settings. This report summarised their findings and covered a number of areas including (i) the potential influence of a staggered return of students to universities in January 2021, (ii) the potential for spillover transmission from HE settings to the community, (iii) the impact of the emergence of more transmissible variants on HE settings and (iv) the effectiveness of mass testing and the impact of adherence to intervention measures upon transmission. This report found that adherence to measures would have a much more significant impact upon transmission than any marginal gains from staggered student returns, that spillover from students to the community was observed in some, but not all settings and that the emergence of a more transmissible variant may result in impaired effectiveness of mass testing of students. **SAGE link**: https://www.gov.uk/government/publications/isaac-newton-institute-covid-19-and-universities-13-january-2021		

21 Apr 2021	**Higher Education - return of Face to Face Teaching, Lateral Flow Testing and potential impact on the Road Map** INI Higher Education working group (including Hill, Tildesley, Dyson)	SPI-M-O
Summary. Discusses the impact of a return to face-to-face teaching and lateral flow testing (LFT) upon transmission both within universities and in the wider community. There were four main conclusions: (i) The impact of a return to face-to-face teaching on R was highly uncertain and may vary from region to region, potentially amplifying geographic variability in transmission; (ii) The background community prevalence may influence the effect that any campus outbreaks may have on R; (iii) A potential return of international students from 17th May 2021 may increase the risk of importation of variants of concern; (iv) We did not expect a direct relationship between re-opening of university campuses and an increase in R. However, we may expect an increased potential for spillover events to occur from universities to the local community.		

Impact on Seasonal Influenza

09 Sep 2020	**Influenza season 2020/2021** Hill, Keeling, Dyson, Tildesley	SPI-M-O
11 Aug 2021	**Impact of diminished influenza season (influenza season 2021/2022)** Hill, Keeling	SPI-M-O
Summary. Throughout the COVID-19 pandemic, there has been concern about the prospective scenario of overwhelmed healthcare capacities being put under further duress by the additional burden of seasonal influenza epidemics. Interventions to tackle the spread of SARS-CoV-2 have disrupted the respiratory pathogen landscape, including worldwide patterns of influenza activity. The implications of these disruptions for subsequent influenza seasons has been uncertain. These reports used a pre-existing age-structured, multi-strain compartmental model of influenza transmission and case severity, which also included propagation of immunity between influenza seasons and had been previously fit to historical data for England, to conduct scenario analyses ahead of the 2020/2021 and 2021/2022 influenza seasons.		

For the pre-2020/2021 influenza season analysis, the scenarios varied the level of vaccine uptake and the inclusion/exclusion of nonpharmaceutical interventions (NPIs), from which we estimated the relative amount of health episode occurrences (symptomatic cases resulting in a GP consultation, hospital inpatient admissions, fatalities).

In the pre-2021/2022 influenza season analysis, compared with a counterfactual case where influenza activity remained at the normal level in the 2020/2021 influenza season, we studied the change in the same set of health episode occurrences in the 2021/2022 influenza season when assuming there was no influenza in circulation during the 2020/2021 influenza season.

In the context of the time the work was originally conducted, the modelled scenarios indicated how bolstering vaccine coverage and reduction in contacts could likely allay resurgent seasonal influenza epidemics.

Omicron

30 Dec 2021	**Short-term Projections based on Early Omicron Variant Dynamics in England**. Keeling, Brooks-Pollock, Challen, Danon, Dyson, Gog, Guzman-Rincon, Hill, Pellis, Read, Tildesley	SPI-M-O SAGE 101
Summary. A comprehensive look at the UK Omicron data to that point and projections of likely scenarios (Plan B and shorter, tighter NPI controls). The work is available online as a preprint: Matt J Keeling, Ellen Brooks-Pollock, Robert J Challen, Leon Danon, Louise Dyson, Julia R Gog, Laura Guzman-Rincon, Edward M Hill, Lorenzo M Pellis, Jonathan M Read, Michael J Tildesley. (2021) "Short-term Projections based on Early Omicron Variant Dynamics in England" *medRxiv*. https://doi.org/10.1101/2021.12.30.21268307 **SAGE link:** https://www.gov.uk/government/publications/university-of-warwick-short-term-projections-based-on-early-omicron-variant-dynamics-in-england-23-december-2021		

13 Jan 2022	**Long Term Dynamics of COVID-19: Infection and Hospital Admissions.** Keeling, Hill, Tildesley, Dyson	SPI-M-O
Summary. There remains considerable uncertainty over the likely dynamics for the next 6-12 months even without the invasion of any novel variants. Here we have highlighted three sources of uncertainty: the degree to which depletion of susceptibles or behaviour change lead to the reduction in Omicron cases; the time-scale over which behaviour returns to pre-COVID normality; the level of vaccine protection and the time over which this eventually wanes.		

Precautionary Breaks

25 Nov 2020	**Adaptive management for fixed-term lockdowns update** Tildesley, Keeling, Riley, Atkins, Hill, Dyson, Galvao, Jit, Sandmann, Petrou, Edmunds, Vassall	SPI-M-O
Summary. The resurgence of SARS-CoV-2 infections in the UK in late 2020 posted substantial challenges for health policy decision makers. Stringent government-mandated physical distancing measures (lockdown) had been demonstrated to be epidemiologically effective, but were highly disruptive economically. The option of short fixed-term lockdowns had been suggested as a possible alternative to longer open-ended		

lockdowns. The duration and frequency of these precautionary breaks could, in theory, be tuned to minimise economic losses while maximising the impact on the disease.

This document reports on the use of the Warwick COVID-19 model to assess the health and economic implications of different strengths of intrinsic control together with potential short-term precautionary breaks (for a time-frame spanning the end of October 2020 to the end of June 2021). It was based upon the established health-economic concept of a "Willingness to Pay" for an improved health outcome - how much we are willing to pay to keep someone alive and healthy.

The work was a collaboration between infectious disease and health economic experts from the University of Warwick, the London School of Hygiene and Tropical Medicine and Imperial College London in the UK. It contributed to a subsequent publication that analysed the timing of COVID-19 mitigation measures in 2020 and 2021 when seeking to balance public health and economic impacts: Michael J. Tildesley, Anna Vassall, Steven Riley, Mark Jit, Frank Sandmann, Edward M. Hill, Robin N. Thompson, Benjamin D. Atkins, John Edmunds, Louise Dyson, Matt J. Keeling. (2022) "Optimal health and economic impact of non-pharmaceutical intervention measures prior and post vaccination in England: a mathematical modelling study" Royal Society Open Science. 9(8): 211746. https://doi.org/10.1098/rsos.211746

Roadmap Out of Lockdown

29 Mar 2021	**Road Map Scenarios & Sensitivity.** Keeling, Moore, Dyson, Tildesley, Hill	SPI-M-O SAGE 85
04 May 2021	**Road Map Scenarios and Sensitivity: Steps 3 and 4.** Keeling, Dyson, Hill, Moore, Tildesley.	SPI-M-O SAGE 88
08 Jun 2021	**Road Map Scenarios and Sensitivity: Step 4.** Keeling, Dyson, Hill, Moore, Tildesley.	SPI-M-O SAGE 92
06 July 2021	**Road Map Scenarios and Sensitivity: Step 4.** Keeling, Dyson, Hill, Moore, Tildesley.	SPI-M-O SAGE 93
12 Oct 2021	**Projections of SARS-CoV-2 transmission and COVID-19 disease until June 2022.** Keeling, Dyson, Hill, Moore, Tildesley.	SPI-M-O SAGE 96

Summary. Throughout 2021, there were a series of "Roadmap" documents that looked at the potential for relaxation of controls from the January lockdown to an absence of restrictions. Each of the above documents only refers to the final version of each of the six Roadmaps, whereas each document was the result of an iterated process, sharing preliminary results with the SPI-M-O group and SAGE before producing the final set of results.

The initial document helped provide the forward projections enabling the selection of the time-frame over which relaxation would occur. The next four documents were produced before each Step in the relaxation process and generally provided confidence to the government that none of the step-changes would overwhelm health-care resources. The initial Step 4 document on 08 June 2021 demonstrated the uncertainty in Step 4, due to the recent invasion of the Delta variant into the UK, and concerns that there may have been limited vaccine protection. The final document on 12 December 2021 considered the longer-term dynamics. Each of the documents shows increasing complexity and a deeper understanding of the roles of vaccination and human behaviour.

A scientific summary document and retrospective examination of the Roadmap projections (including a comparison to subsequent data) is now published: Matt J. Keeling, Louise Dyson, Michael J. Tildesley, Edward M. Hill, Sam Moore. (2022) Comparison of the 2021

COVID-19 roadmap projections against public health data in England. *Nature Communications* **13**: 4924. https://doi.org/10.1038/s41467-022-31991-0

SAGE links
SAGE 85: https://www.gov.uk/government/publications/university-of-warwick-road-map-scenarios-and-sensitivity-29-march-2021
SAGE 88: https://www.gov.uk/government/publications/university-of-warwick-roadmap-scenarios-and-sensitivity-steps-3-and-4-5-may-2021
SAGE 92: https://www.gov.uk/government/publications/university-of-warwick-road-map-scenarios-and-sensitivity-step-4-9-june-2021
SAGE 93: https://www.gov.uk/government/publications/university-of-warwick-roadmap-scenarios-and-sensitivity-step-4-6-july-2021
SAGE 96: https://www.gov.uk/government/publications/university-of-warwick-projections-of-sars-cov-2-transmission-and-covid-19-disease-until-june-2022-the-action-of-waning-efficacy-and-boosters-12-oc

School Closures and Reopening

07 Jul 2020	**Thoughts on School Closures Assessing False Positives**. Keeling & the Warwick Team	SPI-M-O
Summary. A major issue with closing for suspected cases is the potential for false positives – closing classes because of illness that is not COVID-19. Here we examine this problem for schools of different sizes and for mean levels of childhood illness; we conclude that "even if there is no transmission within schools, we expect large schools to commonly reach the threshold of 2 or more cases in 14 days"		

17 Dec 2020	**Report on COVID-19 in schools in England, September - December 2020**. Southall, Holmes, Atkins, Dyson, Hill, Keeling, Tildesley	SPI-M-O SAGE 74
Summary. This document analysed the Department for Education (DfE) Educational Settings data for England. These data record daily absences of students and staff for each school in England, along with information regarding the reason for that absence (e.g. confirmed infection with SARS-CoV-2, isolation as a result of being identified as a contact etc). It is important to note that these data did not record whether infection happened within schools. These data were utilised to indicate the likely prevalence of SARS-CoV-2 amongst those attending school through time from September to December 2020, and how that varied by NHS region and by the level of intervention (tier) that was in place at the time. We observed that the percentage of students with confirmed infection was greater in secondary schools than in primary schools, whilst infection levels in teachers appeared of similar magnitude in both secondary and primary schools. During the period under observation, we observed some regional variation in absences, whilst following the introduction of the tier system and the November 2020 lockdown (when schools remained open) absences in teachers were observed to decrease across all tiers, whilst absences in students increased until late November 2020. **SAGE link:** https://www.gov.uk/government/publications/tfc-children-and-transmission-update-paper-17-december-2020		

03 Mar 2021	**The impact of uptake and adherence on transmission and absences resulting from secondary school reopening strategies involving rapid testing.** Leng, Hill, Thompson, Tildesley, Keeling, Dyson	SPI-M-O SAGE 83
Summary. This document assessed the impact on transmission and absences resulting from school reopening strategies using lateral flow device tests (LFTs), and quantified the impact of uptake (pupils agreeing to participate in rapid testing), adherence (participating		

pupils actually taking tests at home), close contact group size, and transmission on within-school test days. We note that mass testing, with isolation or serial contact testing, can result in high levels of absences – as more infections are detected. There is therefore a trade-off between minimising infection (which required high levels of testing coupled with isolation) and minimising school absence (which occurs when testing is limited and few infections are detected).

24 Nov 2021 01 Dec 2021 08 Dec 2021 15 Dec 2021	**Analysis of School Absences and Lateral Flow Test results following return of all pupils to school in England in Autumn 2021** Leng, Southall, Holmes, Dyson, Thompson, Hill, Keeling, Tildesley	SPI-M-O
12 Jan 2022 19 Jan 2022 26 Jan 2022 02 Feb 2022 09 Mar 2022 23 Mar 2022	**Analysis of School Absences and Lateral Flow Test results for school-aged children in England in Winter 2021/22** Leng, Southall, Holmes, Dyson, Thompson, Hill, Keeling, Tildesley	SPI-M-O
23 Mar 2022	**Reporting and information loss in education absences data** Leng, Dyson, Thompson, Hill, Keeling, Tildesley	SPI-M-O
Summary. Further reports of school absences that were produced on a regular basis for SPI-M-O.		

Vaccination

02 Dec 2020	**COVID vaccine deployment scenarios.** Moore, Hill, Tildesley, Dyson, Keeling	SPI-M-O SAGE 72
13 Jan 2021	**COVID vaccine impact forecast**	SPI-M-O
27 Jan 2021	**COVID vaccine impact forecast**	SPI-M-O SAGE 76

Summary. The earliest work looked at the potential for vaccination to reduce R, this was performed with very limited data on the behaviour of vaccines and we conclude that the vaccine will have the greatest impact when targeted to the elderly and vulnerable – it is better to give protection to those most likely to experience severe illness, rather than those most responsible for transmission.

This work was later published as: Sam Moore, Edward M. Hill, Louise Dyson, Michael J. Tildesley, Matt J.Keeling. (2021) Modelling optimal vaccination strategy for SARS-CoV-2 in the UK. *PLoS Comp. Biol.* **17**(5): e1008849. https://doi.org/10.1371/journal.pcbi.1008849

The next series of papers looked in more detail at the timing of vaccination and whether this allowed the rapid relaxation of non-pharmaceutical interventions. This work was repeated as we needed to account for both the emergence of the Alpha variant and changing data on vaccination efficacy. We conclude that: "A high efficacy vaccine that provides a high level of transmission blocking offers a means of eventually relaxing controls without suffering a large subsequent wave of hospitalisations and deaths". However, we note that relaxation of controls has to be slow to avoid a rapid spike in cases and severe disease.

This work was later published as: Sam Moore, Edward M. Hill, Michael J. Tildesley, Louise Dyson, Matt J. Keeling. (2021) Vaccination and non-pharmaceutical interventions for

COVID-19: a mathematical modelling study. *Lancet Infectious Diseases*. **21**(6): 793-802. https://doi.org/10.1016/S1473-3099(21)00143-2

SAGE links
SAGE 72: https://www.gov.uk/government/publications/spi-m-o-insights-from-early-vaccination-modelling-9-december-2020
SAGE 76: https://www.gov.uk/government/publications/university-of-warwick-covid-19-vaccine-impact-forecast-13-january-2021

Variants (pre-Omicron)

22 Dec 2020	**Juniper on new variant to SPIM 22nd Dec 2020.** Dyson, Hill, Keeling, Tildesley & JUNIPER	SPI-M-O SAGE 74
Summary. This document represents initial analysis of the newly emerged Alpha (B.1.1.7) variant using S-gene deletion data. The work assesses the proportion of cases that are thought to be Alpha variant (S-) and the growth rate of S- cases compared to S+ cases by geography and by age. S- cases were shown to have a higher growth rate than S+ cases, while suggestions of different growth advantages by age are shown to be sensitive to the age stratification chosen. It is also clear that the Alpha variant was increasing relative to the original, even during lockdown. SAGE link: https://www.gov.uk/government/publications/juniper-consortium-notes-on-the-new-sars-cov-2-variant-22-december-2020		

Workplaces and Worker Patterns

18 May 2020	**Working patterns analysis.** Dyson, Tildesley, Hill	SPI-M-O
03 Jun 2020	**The impact of worker networks and contact tracing upon transmission in workplaces** Atkins, Dyson, Hill, Keeling, Tildesley	SPI-M-O
10 Jun 2020	**Workplace contact networks: the impact of forward and backward contact tracing and reactive closure of workplaces** Atkins, Dyson, Hill, Keeling, Tildesley	SPI-M-O

Summary. As part of a collective effort to protect public health by disrupting viral transmission of SARS-CoV-2, businesses implemented measures to minimise exposure to coronavirus in workplaces and premises open to the public. Adjustments in working practices can result in changes to patterns of interaction, altering the dynamics of viral spread.

This body of work assessed the impact of workplace targeted non-pharmaceutical disease controls against epidemic spread of SARS-CoV-2 amongst a population of workers. We used a network-based model with layered contacts capturing multiple encounter settings (workplaces, households, social and other). Following several model iterations, the model ultimately accounted for work sector, workplace size and the division of time between work and home (informed by UK data). We studied three workplace focused interventions: (i) a specified fraction of each work sector working from home; (ii) temporally asynchronous work patterns; (iii) introduction of COVID-secure workplaces. We also examined the role of adherence to isolation and test and trace measures. Our results indicated that isolation guidance and engaging with contact tracing alone could be an effective tool to curb transmission, but it was highly sensitive to adherence levels.

This work was the basis of the publication: Edward M. Hill, Benjamin D. Atkins, Matt J. Keeling, Louise Dyson, Michael J. Tildesley. (2021) "A network modelling approach to assess non-pharmaceutical disease controls in a worker population: An application to

SARS-CoV-2" PLoS Comp. Biol. 17(6): e1009058. https://doi.org/10.1371/journal.pcbi.1009058

Other Documents

29 Jul 2020	**Local Lockdown Strategies** Tildesley, Keeling, Hill, Dyson	SPI-M-O
Summary. This report outlined two separate models that illustrate different facets of transmission relevant to local control of an infectious disease outbreak. The first was a lattice model with discrete generations, whose findings indicated that there are no simple rules-of-thumb for the spatial scale and duration of control needed. The second was a kernel model, developed to investigate the impact of the spatial scale of lockdowns upon outbreaks. The results from this model suggest that the precise spatial scale of lockdown that should be implemented is dependent upon several factors including (i) the population density and spatial demography of the region, (ii) the effectiveness of lockdown and (iii) the spatial scale over which transmission takes place.		

05 Aug 2020	**Questions on local spatial spread** Dyson, Hill, Keeling, Tildesley	SPI-M-O
Summary. General thoughts on local transmission of infection and local-scale interventions, responding to questions posed by SPI-M-O secretariat.		

12 Aug 2020	**Questions on "larger events and venues"** Keeling, Hill, Tildesley, Dyson	SPI-M-O
Summary. General thoughts on the return of large events. Feeds into the 19 August 2020 SPI-M-O statement on gatherings: https://www.gov.uk/government/publications/spi-m-o-consensus-statement-on-events-and-gatherings-19-august-2020/spi-m-o-consensus-statement-on-events-and-gatherings-19-august-2020		

10 Feb 2021	**Minimising case numbers is essential to reduce the risk of vaccine escape** Thompson, Hill, Gog	SPI-M-O
Summary. In late 2020, a new variant of SARS-CoV-2 was detected in the UK that led to a sharp increase in cases in south-east England. The emergence of this variant, and a range of other SARS-CoV-2 variants worldwide, led to concerns that variants might emerge that render current COVID-19 vaccines less effective. We used a simple approach to explore the probability of vaccine escape variant emergence over different periods of time. Crucially, we find that this quantity is sensitive to background prevalence rates, with the risk of an escape variant appearing within a fixed time being an increasing function of prevalence. This work is now published: Robin N. Thompson, Edward M. Hill, Julia R. Gog (2021) "SARS-CoV-2 incidence and vaccine escape" Lancet Infectious Diseases. 21(7): 913-914. https://doi.org/10.1016/S1473-3099(21)00202-4		

13 Oct 2021	**Control Options for Mitigating a Rapid Rise in Infections.** Keeling, Read, Hill, House, Dyson, Tildesley, Challen	SPI-M-O SAGE 96
Summary. Here we consider three potential causes of a steep rise in infections, hospital admissions and deaths, and the merits of seven control options that could be enacted to control the rise (improved ventilation, improved public awareness, booster and greater vaccine uptake, test-trace-and-isolate, legal changes to restrictions, antivirals / pharmaceuticals, and travel restrictions). We conclude that a doubling of cases every		

week (or two weeks) would demand a dramatic change in precautionary behaviour, either voluntarily or enforced, to bring infection under control. **SAGE link:** https://www.gov.uk/government/publications/juniper-control-options-for-mitigating-a-rapid-rise-in-infection-12-october-2021

15 Feb 2022	**Long Term Dynamics of COVID-19: Infection and Hospital Admissions.** Keeling, Hill, Tildesley, Dyson	SPI-M-O
Summary. This document considered the long-term dynamics out to 100 years looking at the impact of waning immunity and repeat infections on the pattern of infection and hospital admissions. A key outcome of this analysis is that it may take several years before COVID-19 attains a regular cycle.		

Response to question 5: A summary of any articles you have written, interviews and/or evidence you have given

Research articles

I list below research articles I have contributed to, categorised into the following topics: Christmas Bubbles, Early dynamics & Exiting the First Wave, Higher Education, Immune escape, Precautionary Breaks, Roadmap Out of Lockdown, School Closures and Reopening, Vaccination, Variants, Workplaces and Worker Patterns.

This response concludes with "Other Research Articles" that were on topics outside those previously listed.

For each research article entry:

- "First online" gives the date the research article was initially posted online, usually as a yet to be peer-reviewed preprint.
- "Published" gives the date of publication of the research article in a peer-reviewed journal (if applicable).
- bibliographic information (for the peer-reviewed journal application where applicable, otherwise the information provided is for the preprint).

If there are multiple documents contained in a category, they are listed in chronological order of "First online" date.

Christmas Bubbles

First online: 06 Jul 2022	Edward M. Hill. (2022) "Modelling the epidemiological implications for SARS-CoV-2 of Christmas household bubbles in England" *medRxiv*. https://doi.org/10.1101/2022.06.13.22276316
Published:	
Summary: In November 2020, plans were published to allow individuals to socialise within "Christmas bubbles" with friends and family. This policy involved a planned easing of restrictions in England between 23-27 December 2020, with Christmas bubbles allowing people from up to three households to meet throughout the holiday period. Using a stochastic individual-based model for a synthetic population of 100,000 households, we estimated the epidemiological impact of both this and alternative bubble strategies that allowed extending contacts beyond the immediate household. We found that visiting family and friends over the holiday period for a shorter duration and in smaller groups was less risky than spending the entire five days together. The increases in infection from greater amounts of social mixing disproportionately impacted the eldest.	

Early dynamics & Exiting the First Wave

First online: 11 May 2020	Matt J. Keeling, Edward M. Hill, Erin E. Gorsich, Bridget Penman, Glen Guyver-Fletcher, Alex Holmes, Trystan Leng, Hector McKimm, Massimiliano Tamborrino, Louise Dyson, Michael J. Tildesley. (2020) "Predictions of COVID-19 dynamics in the UK: short-term forecasting and analysis of potential exit strategies" *PLoS Comp. Biol.* **17**(1): e1008619. https://doi.org/10.1371/journal.pcbi.1008619
Published: 22 Jan 2021	
Summary: In this very early paper we develop the "Warwick model" for SARS-CoV-2 transmission and COVID-19 disease burden. It considers how elements of quarantine and isolation can be included into the fundamental SIR epidemiological framework. From an applied perspective, we focus on potential exit strategies, such as different changes to the early lock-down restrictions, age-based easing of the lockdown and basing the lockdown	

on local ICU capacity. We conclude that any route out of lockdown that does not involve pharmaceutical interventions (such as vaccination) has been very slow and measured.

First online: 04 Aug 2020	Matt J. Keeling, Louise Dyson, Glen Guyver-Fletcher, Alex Holmes, Malcolm G Semple, ISARIC4C Investigators, Michael J. Tildesley, Edward M. Hill. (2022) "Fitting to the UK COVID-19 outbreak, short-term forecasts and estimating the reproductive number" *Stat Methods Med Res.* https://doi.org/10.1177/09622802211070257
Published: 17 Jan 2022	
Summary: Fitting models to data is key to understanding the dynamics, quantifying the current situation and generated projections of the short, medium or long-term. In this paper we outline the basic fitting methods used and consider the sensitivity to the way the data is aggregated.	

Higher Education

First online: 18 Oct 2020	Edward M. Hill, Benjamin D. Atkins, Matt J. Keeling, Michael J. Tildesley, Louise Dyson. (2021) "Modelling SARS-CoV-2 transmission in a UK university setting" *Epidemics* **36**: 100476. https://doi.org/10.1016/j.epidem.2021.100476
Published: 29 Jun 2021	
Summary: The higher education system in the United Kingdom comprises a large student population. Therefore, in the setting of the COVID-19 pandemic bringing together these student communities presents questions regarding the strength of interventions required to control transmission. We constructed a network-based model to capture the interactions of a student population in different settings within a university environment (housing, social and study) and ran an SEIR type epidemic process. Our work shows high adherence to isolation guidance and effective contact tracing both curbed transmission and reduced the expected time an adhering student would spend in isolation. Irrespective of the adherence to isolation measures, on average a higher proportion of students resident on-campus became infected compared with students resident off-campus. Room isolation as an additional intervention generated minimal benefits. Finally, a one-off mass-testing instance would not drastically reduce the term-long case load or end-of-term prevalence, but regular weekly or fortnightly testing could reduce both measures by more than 50% (compared to having no mass testing).	

First online: 22 Feb 2021	Jessica Enright, Edward M. Hill, Helena B. Stage, Kirsty J. Bolton, Emily J. Nixon, Emma L. Fairbanks, Maria L. Tang, Ellen Brooks-Pollock, Louise Dyson, Chris J. Budd, Rebecca B. Hoyle, Lars Schewe, Julia R. Gog, Michael J. Tildesley. (2021) "SARS-CoV-2 infection in UK university students: lessons from September-December 2020 and modelling insights for future student return" *Royal Society Open Science*. **8**(8): 210310. https://doi.org/10.1098/rsos.210310
Published: 04 Aug 2021	
Summary: A study on SARS-CoV-2 transmission in UK higher education settings that used multiple approaches to assess the extent of university outbreaks, how much those outbreaks may have led to spillover in the community, and the expected effects of control measures. Firstly, we found that the distribution of outbreaks in universities in late 2020 was consistent with the expected importation of infection from arriving students. The dynamics of transmission from university outbreaks to wider communities was complex (whilst sometimes spillover did occur, occasionally even large outbreaks did not give any detectable signal of spillover to the local population).	

Secondly, we performed prospective modelling on the effect of staggered returns of students to universities. The modelling suggested staggering the return of students to university residence was of limited value in terms of reducing transmission, whereas student adherence to testing and self-isolation was likely to be much more important for reducing transmission during term time. Finally, in an exploration of strategies for testing students in the context of a more transmissible variant, we found that frequent testing would be necessary to prevent a major outbreak.

Immune Escape

First online: 13 Apr 2021	Robin N. Thompson, Edward M. Hill, Julia R. Gog (2021) "SARS-CoV-2 incidence and vaccine escape" *Lancet Infectious Diseases*. **21**(7): 913-914. https://doi.org/10.1016/S1473-3099(21)00202-4
Published: 13 Apr 2021	
Summary: A key component of any plausible strategy towards the permanent removal of non-pharmaceutical interventions (NPIs) is ensuring low case numbers in the short to medium term using NPIs and vaccination. The work shows that when assuming a fixed vaccine escape mutation probability per infection, the vaccine escape risk is sensitive to background incidence; the risk of an escape variant appearing within a fixed time is an increasing function of incidence. It implies that reducing cases is not only beneficial for decreasing the pressure on health-care systems, but also for lowering the vaccine escape risk.	

First online: 28 Mar 2021	Julia R. Gog, Edward M. Hill, Leon Danon, Robin N. Thompson (2021) "Vaccine escape in a heterogeneous population: insights for SARS-CoV-2 from a simple model" *Royal Society Open Science*. **8**(7): 210530. https://doi.org/10.1098/rsos.210530
Published: 14 Jul 2021	
Summary: By developing and analysing a mathematical model of two population groupings with differing vulnerability and contact rates, this paper explored the impact of the deployment of vaccines among the population on the reproduction ratio, cases, disease abundance and vaccine escape pressure. The results from this model illustrate two insights: (i) vaccination aimed at reducing prevalence could be more effective at reducing disease than directly vaccinating the vulnerable; (ii) the highest risk for vaccine escape can occur at intermediate levels of vaccination. This work demonstrates a key principle: the careful targeting of vaccines towards particular population groups could reduce disease as much as possible whilst limiting the risk of vaccine escape.	

Omicron

First online: 30 Dec 2021	Matt J Keeling, Ellen Brooks-Pollock, Robert J Challen, Leon Danon, Louise Dyson, Julia R Gog, Laura Guzman-Rincon, Edward M Hill, Lorenzo M Pellis, Jonathan M Read, Michael J Tildesley. (2021) "Short-term Projections based on Early Omicron Variant Dynamics in England" *medRxiv*. https://doi.org/10.1101/2021.12.30.21268307
Published:	
Summary: The Omicron variant (B.1.1.529) was first reported to the WHO by South Africa on 24 November 2021 and was declared a variant of concern by the WHO on 26 November 2021. The variant was first detected in the UK on 27 November 2021 and has since been reported in a number of countries globally where it has been frequently associated with rapid increases in cases. We present analyses of UK data showing the earliest signatures of the Omicron variant and mathematical modelling that uses the UK data to simulate the potential impact of this variant in the UK. To account for the uncertainty at the time of writing (December 2021), we included a sensitivity analysis to	

assess the impact of variant characteristics (transmission advantage, vaccine escape and severity) on future risk.

Precautionary Breaks

First online: 14 Oct 2020 Published: 02 Dec 2021	Matt J. Keeling, Glen Guyver-Fletcher, Louise Dyson, Michael J. Tildesley, Edward M. Hill, Graham F. Medley. (2021) "Precautionary breaks: Planned, limited duration circuit breaks to control the prevalence of SARS-CoV-2 and the burden of COVID-19 disease" *Epidemics* https://doi.org/10.1016/j.epidem.2021.100526
Summary: Research undertaken in October 2020 examined the potential of a precautionary break (or "Circuit Breaker") to contain a growing epidemic. When cases of COVID-19 are rising exponentially, we considered the impact of a short 2-week period of intense control. Using two different modelling approaches we showed that a short, sharp 2-week break leads to a decline in cases, with similar declines in hospitalisation and mortality over a short period. A precautionary break is not a lasting control measure, but effectively buys more time to put other controls in place; it takes us 'back to a time when cases were lower'. To save lives over longer time scales requires driving *R* below one, however the reduction in cases generated by a precautionary break allows time for other measures to have an impact and could be beneficial when measures are resource limited (such as test-trace-and-isolate).	

First online: 25 Apr 2021 Published: 10 Aug 2022	Michael J. Tildesley, Anna Vassall, Steven Riley, Mark Jit, Frank Sandmann, Edward M. Hill, Robin N. Thompson, Benjamin D. Atkins, John Edmunds, Louise Dyson, Matt J. Keeling. (2022) "Optimal health and economic impact of non-pharmaceutical intervention measures prior and post vaccination in England: a mathematical modelling study" *Royal Society Open Science*. **9**(8): 211746. https://doi.org/10.1098/rsos.211746
Summary: Even with good progress on vaccination, SARS-CoV-2 infections in the UK may continue to impose a high burden of disease and therefore pose substantial challenges for health policy decision makers. Stringent government-mandated physical distancing measures (lockdown) have been demonstrated to be epidemiologically effective, but can have both positive and negative economic consequences. The duration and frequency of any intervention policy could, in theory, could be optimised to maximise economic benefits while achieving substantial reductions in disease. In this work we use a SARS-CoV-2 transmission model to assess the health and economic implications of different strengths of control through time in order to identify optimal approaches to non-pharmaceutical intervention stringency in the UK, considering the role of vaccination in reducing the need for future physical distancing measures. We find that the precise timing and intensity of interventions is highly dependent upon the objective of control. As intervention measures are relaxed, we predict a resurgence in cases, but the optimal intervention policy can be established dependent upon the willingness to pay (WTP) per QALY loss avoided. Our results show that establishing an optimal level of control can result in a reduction in net monetary loss of billions of pounds, dependent upon the precise WTP value. We therefore demonstrate how future health and non-health harms associated with infectious disease outbreaks could be quantified, employing mechanistic infectious disease transmission models to establish optimal levels of control for the ongoing COVID-19 pandemic.	

Roadmap Out of Lockdown

First online: 18 Mar 2022	Matt J. Keeling, Louise Dyson, Michael J. Tildesley, Edward M. Hill, Sam Moore. (2022) "Comparison of the 2021 COVID-19 roadmap projections against public health data in England" *Nature Communications* **13**: 4924. https://doi.org/10.1038/s41467-022-31991-0
Published: 22 Aug 2022	
Summary: A retrospective analysis of our six Roadmap documents generated in 2021 to assess the likely impacts of future relaxation steps in England. In each case we directly compare results generated at the time with more recent public health data (primarily hospital admissions, but also hospital occupancy and death) to understand discrepancies and potential improvements. We conclude that, in general, the model projections generated a reliable estimation of medium-term hospital admission trends, with the data points up to September 2021 generally lying within our 95% projection intervals. The greatest uncertainties in the modelled scenarios came from estimates of vaccine efficacy, hampered by the lack of data in the early stages of the Alpha and Delta variant waves, and from assumptions about human behaviour in the face of changing restrictions and changing risk.	

School Closures and Reopening

First online: 04 June 2020	Matt J. Keeling, Michael J. Tildesley, Benjamin D. Atkins, Bridget Penman, Emma Southall, Glen Guyver-Fletcher, Alex Holmes, Hector McKimm, Erin E. Gorsich, Edward M. Hill. (2021). "The impact of school reopening on the spread of COVID-19 in England" *Phil. Trans. R. Soc. B.* **376** (1829): 20200261. https://doi.org/10.1098/rstb.2020.0261
Published: 31 May 2021	
Summary: Here we used the Warwick COVID-19 model for the UK to investigate potential scenarios for reopening schools in England. We considered different combinations of years returning to school, including the potential for teaching students in smaller classes which reduces infection risk. We found that, on its own, returning children to school was unlikely to lead to a second wave of infection, however there remained uncertainty if other measures were relaxed simultaneously. Secondary school students returning led to higher increases than if only primary schools reopened, though in all scenarios the magnitude of changes depended upon the wider context when the reopening of schools occurred. However, the size of the increase due to schools returning was much smaller than the increase due directly to the increase in community transmission.	

First online: 12 Feb 2021	Trystan Leng, Edward M Hill, Robin N Thompson, Michael J Tildesley, Matt J Keeling, Louise Dyson. (2022) "Assessing the impact of lateral flow testing strategies on within-school SARS-CoV-2 transmission and absences: A modelling study" *PLoS Comp. Biol.* **18**(5): e1010158. https://doi.org/10.1371/journal.pcbi.1010158
Published: 27 May 2022	
Summary: We developed an individual-based model to understand the impact of school control measures on pupil-to-pupil transmission, pupil absences and testing volume. Using an individual-based model of a secondary school implementing a bubbling strategy at the level of year-groups, and simulating infections over the course of a seven-week half-term, we evaluated a range of strategies with differing isolation and rapid test strategies. In particular, we found that a policy of daily contact testing resulted in a similar reduction in transmission to an isolation of year-groups policy, but markedly reduced absences.	

First online:	

17 Feb 2021 Published: 07 Jun 2021	Emma Southall, Alex Holmes, Edward M. Hill, Benjamin D. Atkins, Trystan Leng, Robin N. Thompson, Louise Dyson, Matt J. Keeling, Michael J. Tildesley (2021) "An analysis of school absences in England during the Covid-19 pandemic" *BMC Medicine*, **19** (137). https://doi.org/10.1186/s12916-021-01990-x
Summary: We analysed data on pupil and staff absences due to confirmed COVID-19 infection during September-December 2020. During this early phase there was no significant evidence to suggest that schools were playing a substantial role in driving spread in the community. We conclude that careful monitoring was required as schools re-opened in 2021 to determine the effect associated with open schools upon community incidence.	

First online: 16 Jul 2021 Published: 01 Mar 2022	Trystan Leng, Edward M Hill, Alex Holmes, Emma Southall, Robin N Thompson, Michael J Tildesley, Matt J Keeling, Louise Dyson. (2021) "Quantifying within-school SARS-CoV-2 transmission and the impact of lateral flow testing in secondary schools in England" *Nature Communications* **13**, 1106. https://doi.org/10.1038/s41467-022-28731-9
Summary: We incorporated various data into an individual-based model of secondary schools to quantify SARS-CoV-2 transmission between secondary school pupils in England. We used community swab testing data to inform community prevalence for schools according to their local area and to inform a school's level of participation in lateral flow testing; We also used secondary school absences data to inform the size of group a school isolates upon identification of a positive case. We then fit this model to the community swab testing data in 11-16 year olds and secondary school absences data. With this fitted model, we simulated outbreaks from 31st Aug 2020 - 21st May 2021 to quantify SARS-CoV-2 transmission in secondary schools in England. We evaluated the impact of twice weekly lateral flow testing of pupils on transmission, finding that twice weekly mass testing likely played an important role in controlling pupil-to-pupil transmission in secondary schools in England. We also considered the counterfactual impact of alternative strategies, finding that strategies involving mass testing have the potential to control within-school transmission while substantially reducing absences.	

Vaccination

First online: 24 Sep 2020 Published: 06 May 2021	Sam Moore, Edward M. Hill, Louise Dyson, Michael J. Tildesley, Matt J. Keeling. (2021) "Modelling optimal vaccination strategy for SARS-CoV-2 in the UK" *PLoS Comp. Biol.* **17**(5): e1008849. https://doi.org/10.1371/journal.pcbi.1008849
Summary: In an early extension to the Warwick COVID-19 model, we introduced a vaccinated class and a population with health conditions that are believed to have a significant impact on COVID-19 outcomes. At the time a number of different vaccine candidates were in development and the results from clinical trials were not fully available, leading to a large degree of uncertainty regarding the performance of these products. We therefore tested a range of efficacies (including reduced efficacy in the elderly) and three different types of vaccine each delivering a different level of protection. This paper highlighted the importance of prioritising vaccination towards the oldest and most vulnerable in the population, as this generates the maximum reduction in deaths and other severe outcomes.	

First online: 02 Jan 2021 Published:	Sam Moore, Edward M Hill, Michael J. Tildesley, Louise Dyson, Matt J Keeling. (2021) "Vaccination and non-pharmaceutical interventions for COVID-19: a mathematical modelling study" *Lancet Infectious*

18 Mar 2021	*Diseases.* **21**(6): 793-802. https://doi.org/10.1016/S1473-3099(21)00143-2
Summary: By combining models of vaccination with the methods of forwards projection, we considered the interaction between the relaxation of non-pharmaceutical interventions (NPIs) and the protection offered by the vaccine. This paper set the tone for unlocking the UK in 2021: Our modelled scenarios highlighted the risks associated with early or rapid relaxation of NPIs, stressing the need for slow release of control measures if large-scale waves of infection are to be avoided. We conclude that while the vaccines against SARS-CoV-2 offer a potential exit strategy for the pandemic, success is highly contingent on the precise vaccine properties and population uptake.	

First online: 24 Mar 2021 Published: 01 Sep 2021	Edward M. Hill, Matt J. Keeling. (2021) "Comparison between one and two dose SARS-CoV-2 vaccine prioritization for a fixed number of vaccine doses" *Interface.* **18**(182): 20210214. https://doi.org/10.1098/rsif.2021.0214
Summary: Focusing on data from England, we investigated prioritisation of a one dose or two dose SARS-CoV-2 vaccination schedule given a fixed number of vaccine doses and with respect to a measure of maximising averted deaths. This work highlighted the advantage of a longer separation between first and second, as it enables more vulnerable people to be protected early in the epidemic, and therefore reduces hospital admissions and deaths from the pandemic.	

First online: 10 Nov 2021 Published:	Matt J. Keeling, Amy Thomas, Edward M. Hill, Robin N. Thompson, Louise Dyson, Michael J. Tildesley, Sam Moore. (2021) "Waning, Boosting and a Path to Endemicity for SARS-CoV-2" *medRxiv.* https://doi.org/10.1101/2021.11.05.21265977
Summary: In many countries, an extensive vaccination programme has substantially reduced the public-health impact of SARS-CoV-2, limiting the number of hospital admissions and deaths compared to an unmitigated epidemic. The observed waning of vaccine efficacy over time suggests that booster doses may be required to maintain population immunity especially in the most vulnerable groups. Here, using data and models for England, we consider the dynamics of COVID-19 over a two-year time-frame, and the role that booster vaccinations can play in mitigating the worst effects. Although formulated for the Delta variant, this paper has key implications for Omicron.	

First online: 27 Jan 2022 Published:	Sam Moore, Edward M. Hill, Louise Dyson, Michael J. Tildesley, Matt J. Keeling (2021) The impacts of increased global vaccine sharing on the COVID-19 pandemic; a retrospective modelling study *medRxiv* DOI: 10.1101/2022.01.26.22269877
Summary: We use an age-structured model of SARS-CoV-2 dynamics, matched to national data from 152 countries, to investigate the global impact of different vaccine sharing protocols during 2021. We assume a direct relationship between the emergence of variants with increased transmissibility and the cumulative amount of global infection, such that lower global prevalence leads to a lower reproductive number within each country. We compared five vaccine sharing scenarios, from the current situation, through sharing once a particular within-country threshold is reached (e.g. all over 40s have received 2 doses), to full sharing where all countries achieve equal age-dependent vaccine deployment. Compared to the observed distribution of vaccine uptake, we estimate full vaccine sharing would have generated a 1.5% (95% prediction interval (PI): -0.1 - 4.5%) reduction in infections and a 11.3% (PI: 0.6 - 23.2%) reduction in mortality globally by January 2022. The greatest benefit of vaccine sharing would have been experienced by low- and middle-income countries, who see an average 5.2% (PI: 2.5% - 10.4%) infection reduction and	

26.8% (PI: 24.1% - 31.3%) mortality reduction. Many high-income countries, that have had high vaccine uptake (most notably Canada, Chile, UK and USA), suffer increased infections and mortality under most of the sharing protocols investigated, assuming no other counter measures had been taken. However, if reductions in vaccine supply in these countries had been offset by prolonged use of non-pharmaceutical intervention measures, we predict far greater reductions in global infection and mortality of 64.5% (PI: 62.6% - 65.4%) and 62.8% (PI: 44.0% - 76.3%), respectively.

First online: 24 Aug 2022	Matt J Keeling, Bridget Penman, Edward M Hill, Sam Moore. (2022) "The Impact of SARS-CoV-2 Vaccine Dose Separation and Dose Targeting on Hospital Admissions and Deaths from COVID-19 in England" *medRxiv*. https://doi.org/10.1101/2022.08.22.22278973
Published:	
Summary: In late 2020, the JCVI (the Joint Committee on Vaccination and Immunisation) made two important recommendations for the initial roll-out of the COVID-19 vaccine. The first was that vaccines should be targeted to the elderly and vulnerable, with the aim of maximally preventing disease rather than infection. The second was to increase the interval between first and second doses for 3 to 12-weeks. Here, using data on vaccine efficacy (as of August 2022) we re-examine these recommendations through a mathematical model, to understand their short and medium-term impacts in England. Model outputs indicates that targeting the most vulnerable had the biggest immediate impact, compared to targeting younger individuals who may be more responsible for transmission.	

Variants (pre-Omicron)

First online: 07 Jun 2021	Robert Challen, Louise Dyson, Christopher E. Overton, Laura M. Guzman-Rincon, Edward M. Hill, Helena B. Stage, Ellen Brooks-Pollock, Lorenzo Pellis, Francesca Scarabel, David J. Pascall, Paula Blomquist, Michael Tildesley, Daniel Williamson, Stefan Siegert, Xiaoyu Xiong, Ben Youngman, Juniper, Jonathan M. Read, Julia R. Gog, Matthew J. Keeling, Leon Danon. (2021) "Early epidemiological signatures of novel SARS-CoV-2 variants: establishment of B. 1.617. 2 in England" *medRxiv.* https://doi.org/10.1101/2021.06.05.21258365
Published:	
Summary: We considered the early data on the Delta variant looking at its transmission advantage compared to the Alpha variant - leading from a transition from a declining epidemic to an increasing one. Using a variety of different methods to calculate real-time growth estimates of S-gene positive (likely Delta) cases compared to S-gene negative (likely Alpha) cases, the analysis showed a sustained, consistent advantage of Delta over Alpha in multiple regions of England. We used the normalisation of age distributions to argue that this transmission advantage was inherent to the Delta variant and was not a result of early higher transmission in specific subpopulations.	

First online: 10 Jun 2021	Louise Dyson, Edward M Hill, Sam Moore, Jacob Curran-Sebastian, Michael J Tildesley, Katrina A Lythgoe, Thomas House, Lorenzo Pellis, Matt J Keeling. (2021) "Possible future waves of SARS-CoV-2 infection generated by variants of concern with a range of characteristics" *Nature Communications* **12**: 5370. https://www.nature.com/articles/s41467-021-25915-7
Published: 30 Sep 2021	
Summary: We used three mathematical models to examine the potential drivers of SARS-CoV-2 VOC epidemics in England. We found epidemiological trajectories for putative VOCs are wide-ranging and dependent on their transmissibility, immune escape capability, and the introduction timing of a postulated VOC-targeted vaccine. In particular, a variant that is less transmissible, but shows partial immune-escape, could provoke a wave of infection that would not be revealed until control measures are further relaxed.	

Workplaces and Worker Patterns

First online: 20 Nov 2020	Edward M. Hill, Benjamin D. Atkins, Matt J. Keeling, Louise Dyson, Michael J. Tildesley. (2021) "A network modelling approach to assess non-pharmaceutical disease controls in a worker population: An application to SARS-CoV-2" *PLoS Comp. Biol.* **17**(6): e1009058. https://doi.org/10.1371/journal.pcbi.1009058
Published: 16 Jun 2021	

Summary: As part of a concerted pandemic response to protect public health, businesses can enact non-pharmaceutical controls to minimise exposure to pathogens in workplaces and premises open to the public. Amendments to working practices can lead to the amount, duration and/or proximity of interactions being changed, ultimately altering the dynamics of disease spread. We used an individual-based network model to analyse transmission of SARS-CoV-2 amongst a working population that was stratified into work sectors.

Our study found the progress of an outbreak to be significantly hindered by instructing a significant proportion of the workforce to work from home. Furthermore, asynchronous work patterns may help to reduce infections when compared with scenarios where all workers work on the same days, particularly for longer working weeks. Finally, smaller work teams and a greater reduction in transmission risk led to a flatter temporal profile for both infections and the number of people isolating, and reduced the probability of large, long outbreaks.

Other Research Articles

First online: 13 Nov 2020	Seb Funk et al. (2020) "Short-term forecasts to inform the response to the Covid-19 epidemic in the UK" *medRxiv*. https://doi.org/10.1101/2020.11.11.20220962
Published:	

Summary: A paper evaluating the performance of model forecasts, generated between 24 March and 14 July 2020, to monitor expected healthcare utilisation and population impacts in real time. In most cases, individual models performed better than the null model, and ensembles models were well calibrated and performed comparatively to the best individual models. Ensembles of multi-model forecasts can help assess future resource needs and expected population impact of morbidity and mortality.

First online: 09 Nov 2021	Trystan Leng, Edward M. Hill, Matt J. Keeling, Michael J. Tildesley, Robin N. Thompson. (2022) "The effect of notification window length on the epidemiological impact of COVID-19 contact tracing mobile applications" *Communications Medicine* **2**:74. https://doi.org/10.1038/s43856-022-00143-2
Published: 27 Jun 2022	

Summary: The reduction in SARS-CoV-2 transmission from contact tracing applications (apps) depends both on the number of contacts notified and on the probability that those contacts quarantine after notification. Referring to the number of days preceding a positive test that contacts are notified as an app's *notification window*, we use an epidemiological model of SARS-CoV-2 transmission that captures the profile of infection to consider the trade-off between notification window length and active app-usage. We focused on 5-day and 2-day windows, the lengths used by the NHS COVID-19 app in England and Wales before and after 2nd August 2021, respectively. Short windows can be more effective at reducing transmission if they are associated with higher levels of active app usage and adherence to isolation upon notification, demonstrating the importance of understanding adherence to control measures when setting notification windows for COVID-19 apps.

First online: 05 Jan 2022	Laura M Guzmán-Rincón, Edward M Hill, Louise Dyson, Michael J Tildesley, Matt J Keeling. (2022) "Bayesian Estimation of real-time

Published:	Epidemic Growth Rates using Gaussian Processes: local dynamics of SARS-CoV-2 in England" *medRxiv*. https://doi.org/10.1101/2022.01.01.21268131
Summary: Key to the quantitative assessments of the recent state of an epidemic and short-term projections into the near future is the ability to rapidly and robustly measure the speed with which the epidemic is growing or decaying. Frequently, epidemiological trends are addressed in terms of the (time-varying) reproductive number R. In this study we take a more parsimonious approach and calculate the exponential growth rate using a Bayesian hierarchical model to fit a Gaussian process to the epidemiological data. We apply the methods to SARS-CoV-2 cases and testing in England, making use of the available high-resolution spatio-temporal data to determine long-term patterns of national growth, highlight regional growth and spatial heterogeneity.	

Plus magazine articles

I have contributed to the following Plus magazine articles:

- Pandemics and psychology
- COVID-19 and universities: What do we know?
- Vaccination: Where do we stand and where are we going?

Science Media Centre contributions

I have contributed to the following Science Media Centre "expert reactions":

- expert reaction to a study looking at mandatory face masks and number of COVID-19 infections in New York, Wuhan and Italy (12 June 2020)
- expert comments about preparing for a second wave, re the open letter calling for a review of the UK's preparedness for a second wave (24 June 2020)
- expert reaction to modelling study looking at SARS-CoV-2 transmission during COVID-19 vaccination campaigns and likelihood of emergence of vaccine-resistant variants (30 July 2021)

I have also been a speaker in two press briefings hosted by the Science Media Centre.

Date: 15 Feb 2021	New preprint on schools and COVID-19 spread. https://www.sciencemediacentre.org/new-preprint-on-schools-and-covid-19-spread/
Speakers: • Michael Tildesley (University of Warwick) • Edward Hill (University of Warwick) **Summary**: This briefing to journalists was on the research paper "An analysis of school absences in England during the Covid-19 pandemic", which analysed data on school absences due to COVID-19 infection between September and December 2020, and how that varied through time as other measures in the community were introduced.	

Date: 01 Mar 2021	Preprint on COVID-19 and universities. https://www.sciencemediacentre.org/preprint-on-covid-19-and-universities/
Speakers: • Julia Gog (University of Cambridge) • Michael Tildesley (University of Warwick) • Edward Hill (University of Warwick) • Jessica Enright (University of Glasgow)	

Summary: This briefing to journalists was on the research paper "SARS-CoV-2 infection in UK university students: lessons from September–December 2020 and modelling insights for future student return". The study analysed the spread of SARS-CoV-2 on university campuses during the autumn term 2020, carried out prospective modelling on the effect of staggered returns of students to universities and prospective modelling on the impact of asymptomatic testing.

Other media interviews

Interview for comment in a BBC news online article
- *Date:* 05 Jun 2020
- *Topic:* Re-opening of schools
- *Article link:* https://www.bbc.co.uk/news/health-52933323

Radio interview on BBC Coventry & Warwickshire
- *Date:* 08 Jun 2020
- *Topic:* Re-opening of schools

Radio interview on BBC Coventry & Warwickshire
- *Date:* 01 Jul 2020
- *Topic:* Local lockdowns

Radio interview on Free Radio
- *Date:* 14 Oct 2020
- *Topic:* Precautionary breaks

Interview for comment in a Reuters online article
- *Date:* 01 Dec 2020
- *Topic:* COVID-19 interventions and impact on seasonal influenza
- *Article link:* https://www.reuters.com/article/uk-health-coronavirus-europe-influenza-a/analysis-could-covid-knock-out-flu-in-europe-this-winter-idUKKBN28B538?edition-redirect=uk

Interview with Euronews
- *Date:* 14 Apr 2021
- *Topic:* Roadmap out of lockdown and relaxation of interventions

Interview for the Plus magazine podcast series "On the Mathematical Frontline".
- *Date:* 03 Mar 2022
- *Topic:* Included discussions of work modelling transmission of SARS-CoV-2 on close contact settings (specifically, workplaces and universities).
- *Podcast link:* https://plus.maths.org/content/mathematical-frontline-ed-hill

Response to question 6: Views on whether work of the groups in responding to the COVID-19 pandemic succeeded in its aims

The composition of SPI-M-O and diversity of expertise
At the time I became a participant of SPI-M-O in April 2020, the group was expanding as more individuals with different skillsets became involved. Its composition had modelling expertise from across the UK, including many early career researchers (which has provided us with training and preparation for future situations).

Commissioning of work & independent modelling contributions
As no individual model can exactly replicate reality, when gathering model-based evidence to address each question of interest SPI-M-O did not rely on just one model. SPI-M-O considered a wide range of views on the data available from several independent groups, who may use different approaches and thus produce a varying set of responses.

The motivation behind having a diversity of voices and peer challenge was to strengthen confidence that the resulting evidence was robust. Where these independent approaches gave similar answers, it gave greater confidence in those outputs; if they differed then it was informative to discern the reasons for the discrepancies. Through comparing and challenging different models' result, a consensus position was agreed.

The advice given and/or recommendations that were made
When a novel pathogen emerges, there is typically a great amount of uncertainty in its epidemiological characteristics. As a result, as new information on an outbreak arises our ideas and understanding are liable to change. This is not a failing, but rather it reflects the scientific method (process of investigation to explore observations and answer questions).

Pressures to produce results in a quick time also brought challenges. However, this was not at the expense of compromising the quality of the science, rather it acknowledges that the work had more uncertainty and caveats than it would have had outside of the policy arena.

In my opinion, there was a tremendous response from the academic community to help respond to the COVID-19 pandemic.

The extent to which SAGE and its sub-groups worked effectively together
As part of pandemic preparedness, there are communication issues that could be scrutinised and addressed before a future pandemic. One example was the apparent limited direct communication between SPI-M-O and other SAGE subgroups (such as SPI-B and NERVTAG). There did not appear to be a well-defined route for information to be linked into other committees. There may also be scope to streamline the provision of information from academics to SPI-M-O to SAGE to policy makers.

That being said, would like to strongly emphasise the view that these did not significantly affect the advice that was provided by SAGE and its sub-groups.

Resources and support: SPI-M-O secretariat
SPI-M-O secretariat provided phenomenal support. They were consistently swift in responding to requests for help and providing advice. It should not be understated how the ceaseless work of the SPI-M-O secretariat helped ensure that commissions were comprised of tasks that were amenable to investigation via mathematical modelling enable, and that the academics delivered analyses (in a timely fashion) that would be of relevance within the policy arena.

Resources and support: Funding for academic groups

From November 2020, funds awarded by UKRI saw the formation of the Joint UNIversities Pandemic and Epidemiological Research (JUNIPER) consortium, comprising epidemiological modelling groups from seven universities (Bristol, Cambridge, Exeter, Lancaster, Manchester, Oxford and Warwick). Without the provision of these funds, it would not have been viable to support multiple post-doctoral researchers to work as part of the modelling response to the COVID-19 pandemic. Nevertheless, without ongoing support these step-changes in methods and collaborative working that was required by the pandemic will be lost.

Response to question 7: Views on lessons that can be learned from the UK's response to the COVID-19 pandemic

From my viewpoint as a contributor to SPI-M-O, I describe three issues: (i) Ability to scale-up advisory groups & support for early-career researchers; (ii) Data considerations; (iii) Move away from disciplinary silos & promote interdisciplinary decision making.

(i) Ability to scale-up advisory groups & support for early-career researchers
At the time I was invited to be a participant in SPI-M-O (April 2020), I was one of several new contributors to the sub-group. From my perspective, the integration of those joining at that time with long-standing members of SPI-M and the secretariat went relatively smoothly.

Nevertheless, I believe it would be worthwhile to appraise the procedures for "scaling-up" the size of the advisory committee. Specifically, identifying what worked well in this regard for the COVID-19 pandemic response, and what improvements to these procedures could be made and ultimately enacted in the event of the emergence of another pandemic threat that requires SPI-M to be operationalised.

I would also like to stress that an essential component to the larger membership of SPI-M-O were early-career researchers (of which I was one of several that contributed to SPI-M-O). Though participating in open and collaborative analytical research projects with real-world impact, these activities are not suitably captured in traditional academic metrics; these issues are comprehensively presented in a perspective article*. These circumstances raises concern that early career-researchers may seek alternative career opportunities. A consequential talent drain would be detrimental to the scientific community, resulting in a dearth of personnel with the requisite skills to aid a response in the times of a public health emergency.

*AJ Kucharski, S Funk, RM Eggo RM (2020) The COVID-19 response illustrates that traditional academic reward structures and metrics do not reflect crucial contributions to modern science. PLOS Biology 18(10): e3000913. https://doi.org/10.1371/journal.pbio.3000913.

(ii) Data considerations
Models of real-world systems cannot, and do not try to, account for every possible detail. Instead, such models are a simplified representation of reality that try to capture the important aspects. They are often limited by the available data and the models' outputs are only as good as the quality of the data that goes into them. Epidemiological models are no exception to this.

As working with large data sources becomes commonplace, it is important that the interface between public-health and academia matches these innovations. Either academic institutions need to be trusted with large volumes of data, such that the power of university computer systems can be used to analyse the dynamics, or data access needs to be provided in secure environments with plenty of flexibility and processing power such that the same analyses can be performed.

There were also instances of variable quality and formatting of data between the four nations, with different countries providing different data in very different formats. These inconsistencies create extra barriers. These delays can ultimately prevent analyses being conducted in the timeframes required for its insights to help inform the decision-making process.

(iii) Move away from disciplinary silos & promote interdisciplinary decision making
Both SAGE and SPI-M-O had clearly defined remits. SAGE was responsible for ensuring that timely and coordinated scientific advice was made available to support government decision makers. SPI-M-O reported to SAGE and provided advice in response to the COVID-19 pandemic based on infectious disease modelling and epidemiology.

Yet, the epidemiological models and projections contributed to SPI-M-O (and consensus statement from SPI-M-O to SAGE) are only one part of a holistic decision-making process. It is imperative to use the best evidence available at the time to get a clearer picture of not only the epidemiological impacts, but also the economic, social and wider impact of different policies. We may therefore benefit from having a bespoke committee whose purpose is to deliver integrated thinking between different research fields.

Response to question 8: Brief description of documents held relating to these matters

Files generated are primarily epidemiological data, model code, model output, presentations, reports (as summarised in Question 4) and research articles (as summarised in Question 5).