Health Sociology Review

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rhsr20

Mathematical models as public troubles in COVID-19 infection control: following the numbers

Tim Rhodes & Kari Lancaster

To cite this article: Tim Rhodes & Kari Lancaster (2020) Mathematical models as public troubles in COVID-19 infection control: following the numbers, Health Sociology Review, 29:2, 177-194, DOI: 10.1080/14461242.2020.1764376

To link to this article: https://doi.org/10.1080/14461242.2020.1764376

Published online: 13 May 2020.

HEALTH SOCIOLOGY REVIEW
2020, VOL. 29, NO. 2, 177–194
https://doi.org/10.1080/14461242.2020.1764376

Mathematical models as public troubles in COVID-19 infection control: following the numbers

Tim Rhodes[a,b] and Kari Lancaster[b]

[a]London School of Hygiene and Tropical Medicine, London, UK; [b]University of New South Wales, Sydney, Australia

ABSTRACT
Mathematical models are key actors in policy and public responses to the COVID-19 pandemic. The projections from COVID-19 models travel beyond science into policy decisions and social life. Treating models as 'boundary objects', and focusing on media and public communications, we 'follow the numbers' to trace the social life of key projections from prominent mathematical models of COVID-19. Public deliberations and controversies about models and their projections are illuminating. These help trace how projections are 'made multiple' in their enactments as 'public troubles'. We need an approach to evidence-making for policy which is emergent and adaptive, and which treats science as an entangled effect of public concern made in social practices. We offer a rapid sociological response on the social life of science in the emerging COVID-19 pandemic to speculate on how evidence-making might be done differently going forwards.

ARTICLE HISTORY
Received 7 April 2020
Accepted 29 April 2020

KEYWORDS
Mathematical models; COVID-19; boundary object; uncertainty; evidence-making; expertise

Introduction

Public health emergencies are rarely studied as they happen. But they should be. They offer unique opportunities to reflect on how science and intervention are in the process of being made. By investigating science and intervention as they happen, we can appreciate how these *emerge together*. This science-in-action approach follows a tradition in science studies which explores how the products of science generate social effects once released from their sites of production (Latour, 1987). The evidence produced in mathematical projections of SARS-CoV-2, the virus linked to COVID-19, is the focus of our analysis. Drawing on the twin ideas of mathematical models as 'boundary objects' (Star & Griesemer, 1989), and enumerations as 'relational beings' (Verran, 2015), we 'follow the numbers' of key projections from prominent models of COVID-19 into their assemblages of implementation to trace these as 'evidence-making interventions' (Rhodes & Lancaster, 2019).

In the COVID-19 pandemic, the evidence produced from mathematical models has been critical in shaping rapid policy responses in infection control. This is especially

CONTACT Tim Rhodes tim.rhodes@lshtm.ac.uk

the case in the UK. Modelled projections also entangle in social life as public concerns. At the same time, policies of infection control shaped by models, such as strategies of 'protective immunity', 'social distancing', 'lock-down' and 'quarantine', are not without controversy, and generate multiple uncertainties, especially given the scale of their potential. Modelled evidence is at once a response to contingency in the face of unknowns while emergent and adaptive. The modelled projections of COVID-19, themselves uncertain and becoming, are 'made multiple' in their emergence as relational beings, entangling science as a matter of vital concern and as an object of public trouble. By offering a rapid sociological response on the social life of science inside the emerging COVID-19 pandemic, we begin to consider how modelling science in policy and public responses might be done differently. We highlight 'working through contingency' and 'working through participation' as two key elements in an 'emergent science' approach.

Projections as infection control

In response to COVID-19, and very quickly, mathematical models have projected transmission and epidemic futures and the potentials of infection controls (Ferguson et al., 2020; Hellewell et al., 2020; Kucharski et al., 2020; Lourenço et al., 2020). National responses are contingent upon fast-evolving modelling assumptions. In the UK, policy decisions in relation to COVID-19 infection control have been informed by emerging projections, shaped largely from pandemic influenza models, and produced by different teams of mathematical modellers since February of this year. One critical event in adaptive policy making linked to evidence produced in mathematical models was the move, in March 2020, from a national infection control strategy based on assumptions of protective community (or 'herd') immunity to one based on the assumed protective effects of lockdown through combined measures of social distancing and restrictions on population movement. Linked to a particular set of modelled projections (Ferguson et al., 2020), this policy move had high public profile.

Mathematical projections have become ubiquitous as tools of anticipatory governance (Adams, Murphy, & Clarke, 2009; Aykut, Demortain, & Benbouzid, 2019; Bauer, 2013; Callon & Numiesa, 2005). In the control of infections, models produce evidence for policy decisions in response to novel viral outbreaks (Glasser, Hupert, McCauley, & Hatchett, 2011; Kucharski, 2020a; Rivers et al., 2019), and as efforts to eliminate chronic infections (Heffernan, Cooke, Nayagam, Thursz, & Hallett, 2019; Martin, Boerekamps, Hill, & Rijnders, 2018; Vesga et al., 2019). Projections, as with other metrics, work to standardise and stabilise the objects of health, population and future in particular ways (Miller, 2001; Miller, 2001; Shore & Wright, 2015; Strathern, 2000). They therefore have governing potential in relation to population health.

Evidencing the unknown through projection is a means to taming the uncertainties of the present (Hacking, 1990). In an 'evidence-based' approach to decision-making (Sackett, Straus, Richardson, Rosenberg, & Haynes, 2000), models offer a 'bridge' to knowing through abstraction when empirical evidence is absent, or present but uncertain (Sismondo, 1999). Projections therefore produce *what becomes known*, affording a sense of security through calculus, by *closing down* unknowns, and dis-ease, into a governable present (Rhodes & Lancaster, 2020). This means that projections are not mere numerical or theoretical possibilities, but are lived as *anticipated potentials*, affecting actions, publics and policies in the here-and-now (Michael, 2000). Through models, we move from *limited actuals* – based on emergent case reports and empirical observations in particular sites – to *detached abstractions* – based on a mix of biosocial plausibility and mathematical probability – to *materialised practices* – wherein projections are actualised and particularised in social practices of the everyday. This is also why projections *themselves* can 'go viral', taking flight, as they are 'made multiple' as 'becoming matter' in material worlds, with affects, beyond those of scientific calculus (Callon & Law, 2005; Myers, 2015).

Evidence-making intervention assemblages

In this analysis, we approach projections as performative actors which are afforded life potential through their assemblages of implementation (See also, Rhodes & Lancaster, 2020). This approach draws on the foundational work of Michel Callon and others in the field of economics, which accentuates models as performative (Callon & Numiesa, 2005; Mackenzie, 2006). Models perform in their social relations, by tacitly embedding these in their assumptions and calculations (for example, Jasanoff, 2010; Leach & Scoones, 2013), but they also affect and *make* these realities, generating performative effects. Projections shaping financial markets is a classic case (Callon & Numiesa, 2005). This means that we envisage projections, as with any enumeration, as 'relational beings'. Here, we draw on the work Helen Verran (2015), who distinguishes between 'numbers' and 'enumerated entities'. Whereas the former 'belongs in a stable state of being', an enumerated entity 'exists in the dynamic of emergence realness' (Verran, 2015, p. 367). Projections are 'relational beings' because they are situated 'events or happenings in some actual present here and now' (Verran, 2015, p. 367). Rather than fixed, universal and transcendent, as numbers tend to be imagined (Porter, 1995), approaching projections as relational beings attends to their contingency and fluid potential on account of their local materialisations.

Treating projections as relational beings concentrates attention towards their assemblages of implementation. By assemblage, we refer to the multiple actors and elements which *come together,* and *intra-act,* in an event to bring about an affect (Barad, 2003; Fox & Allred, 2017). In assemblage thinking, all objects have equal ontological footing and are entirely relational, made-up as affective flows in assemblage relations. This shifts our attention from 'presumed objects' (thinking of numbers as stable and immutable) to the 'relations involved in their becoming' (thinking of enumerated entities as mutable and relational) (Bacchi & Goodwin, 2006, p. 33). In our analysis, we trace how COVID-19 projections *come to life* through their assemblage relations in policy and public life. This allows us to trace what projections *do*, and how they are *made to matter*, in their situated implementations.

A critical event shaping the life of COVID-19 projections during the here-and-now of this analysis, undertaken through the month of March 2020, is a UK policy shift from a strategy of infection control rooted in assumptions of protective community immunity to one rooted in the assumed protective effects of lockdown. To trace how projections entangle as actors inside this event, we engage with media materials, both news reporting and social media communications, in the weeks immediately following the release, on March 16 2020, of the mathematical models shaping the public communication of the policy change (Ferguson et al., 2020). The projections of models are folded into this policy event as relational beings, 'becoming-with' multiple actors, human and otherwise (such as mathematicians, publics, governments, media agencies, universities, models, calculations, social and digital media, discourses). We therefore draw attention to the fluidity afforded to projections as an effect of their assemblages of evidence-making intervention, in which the policy event is a key moment (Fox & Alldred, 2020).

Lastly, we treat mathematical models as a 'boundary object' (Star & Griesemer, 1989). Boundary objects are entities that enhance the capacity of an idea or practice to translate across boundaries, especially communities of knowledge (Fox, 2011). The concept has been applied as a means of tracing how scientific objects translate within scientific communities as well as into policy (Shackley & Wynne, 1996; Van Egmond & Zeiss, 2010; Wood, Ferlie, & Fitzgerald, 1998). Boundary objects have the power to afford multiplicity by creating space to move objects across epistemic boundaries into varieties of concern (Star & Griesemer, 1989). This makes the boundary object a particularly useful way to think about models and how they translate as matters-of-concern (Latour, 2004). Models are a particularly 'messy category' since they 'stand between worlds' of the empirical and theoretical, and present and future, generating different forms of evidence into quantifications and qualifications (Callon & Law, 2005; Sismondo, 1999). This affords models their fluidity as well as novelty.

Taken together, we emphasise that modelled evidence, itself an intervention, is *in-the-making* and *emergent* through the various methods and practices which produce knowledge, including expertise beyond science. Whereas 'evidence-*based* intervention' approaches tend to idealise prior scientific evidence being translated into interventions in new settings (Sackett et al., 2000), an 'evidence-*making* intervention' approach emphasises how evidence *emerges* in the *here-and-now* of particular assemblages (Rhodes & Lancaster, 2019).

The social life of COVID-19 models

Modelled projections not only evidence-make rapid policy decisions, but affect public understandings and social responses. COVID-19 has come to be known in mathematical models in a way quite unlike novel viruses before it. The coming to know of COVID-19 in maths and models can be traced not simply in the rapid publication and release of modelling studies, but through the thirst for media stories, and social media attention, about models, their projections, and how these are shaping policies as well as public concerns (Rhodes, Lancaster, & Rosengarten, 2020).

Through COVID-19, modelling science has gone *public*. In public communications, COVID-19 is being enacted in *calculations* and *metrics*, via daily updates, nowcasts, forecasts and 'coronacasts' (ABC Radio, 2020), and through media stories of projections and mathematicians (Montgomery & Engelmann, 2020; Rhodes et al., 2020). COVID-19 has generated an intensity and scale of public engagement with the products and methods of mathematical modelling like never before, including a thirst for knowing and debating the calculus of reproduction rates, mortality rates, and how to 'flatten the curve'. There is an emerging citizen modelling science energised by COVID-19, wherein publics *input* rather than merely receive science, through interacting with models and simulations, feeding models into advocacy (as with social media campaigns to '#Flattenthecurve'), and building alternative models as well as questioning the assumptions of the modelling science publicly communicated (See *Economist*, 2020; *New York Times*, 2020; *Washington*

Post, 2020b). The modellers themselves are engaging with publics directly by promoting and defending their science via social media.

COVID-19 may be altering the way that modelling science is being done. This is a way of doing science that is at once emergent, complex, and *social*. We cannot isolate the COVID-19 that is evidenced in mathematical models from its evidence-making in public enactments and social interactions. Science and society *entangle*. We get to trace how models are *materialised*. We get to observe how abstracts become *actuals*. In pandemics, we turn to models to make evidence to enable decisions in the absence of knowing, not only in policy but in the everyday. With COVID-19, we are evidence-making a '*model society*' (Rhodes et al., 2020).

Because models and publics entangle so prominently in the evidence-making of the COVID-19 pandemic, the question of how modelling translates in policy and social practices is critical to learning how evidence is made-to-matter. Rather than approaching science as separate from society, as if scientific *facts* can be isolated from social *concerns*, we attend here to how science is *being done*, in social life, *in-the-now*. Our focus in this analysis then, is less on how social science can inform the logics and parameters of models by attuning model 'inputs' to the complexity of social life, but on how modelled 'outputs' *travel* and *perform*. In keeping with a science-in-action approach (Latour, 1987), we therefore 'follow the numbers' to trace how the projections produced by prominent COVID-19 models are 'made public' and 'made social' as well as 'made in' public and social life.

Following the numbers of COVID-19 models

Deliberations in science, especially controversies, offer ways to observe how contingency is handled (Callon, Lascoumes, & Barthe, 2009; Whatmore, 2009). To make our analysis, we 'follow the numbers' of selected projections from mathematical models of COVID-19 infection which have 'gone public'. We trace these projections in media and social media communications in the weeks immediately following their release in March 2020. The first case concentrates on matters of *adaptation* in the making of evidence and policy in UK COVID-19 infection control informed by modelling science (Ferguson et al., 2020). This case concerns an abrupt policy shift in the UK national COVID-19 response from 'mitigation' to 'suppression', moving from assumptions of herd immunity to lockdown. The case shows how modelled projections of COVID-19 mortality travel in assemblages which make-up and put-to-use these projections in multiple ways. The second case concentrates further on matters of *controversy* in the evidence-making of projections, focusing on modelled estimates of unknown infection in the UK population (Lourenço et al., 2020). This case also traces how projections circulate as public concern in the balance struck between strategies of herd immunity and lockdown. Each of the cases therefore relate to one another as elements in an atmosphere of evidence and policy uncertainty. Because adaptation and uncertainty are defining characteristics of emergent science, we can use these initial analyses of COVID-19 projection as a science-in-action lesson for the challenges which lie ahead.

Case 1: 510,000, 250,000 and 20,000

Based on mathematical models of pandemic influenza (Ferguson et al., 2006), projections generated by Imperial College are informing U.K. Government COVID-19 infection control policies, including via the Department of Health and Social Care New and Emerging Respiratory Virus Threats Advisory Group and Parliamentary Select Committee on Science and Technology (Ferguson et al., 2020). The Imperial College models have generated unprecedented social impact. The lead modeller, Neil Ferguson, has become a household name. Released without peer review in preprint format, and direct to publics online, the models have energised extended social media and public engagement. Most visibly, they are mobilised as prime sources of evidence in public communications of national policy decisions.

The prime projections which have travelled in public communication from the models are 510,000, 250,000 and 20,000.[1] The first of these – 510,000 – is a projection of COVID-19 mortality resulting from a 'do nothing' scenario based on an assumed basic reproduction number (R_0) of 2.6.[2] The second of these numbers – 250,000 – are COVID-19 deaths projected in an infection control policy of 'mitigation', and the third – 20,000 – are deaths in a policy of 'suppression', both assuming R_0 of 2.6 (lower estimates of R_0 produce fewer deaths). The models therefore project deaths being halved by mitigation over doing nothing, and reduced to manageable case levels not exceeding 20,000 when R_0 is reduced to below one by suppression. Whereas suppression combines social distancing of the entire population with home isolation or school and university closures over five months and longer, mitigation comprises partial and lower intensity non-pharmaceutical intervention over three months but allows for some population immunity to build. Following the projections, the modelling team advised that a policy of 'suppression is the only viable strategy at the current time', noting that in a mitigation scenario 'even if all patients were able to be treated, we predict there would still be in the order of 250,000 deaths in Great Britain' (Ferguson et al., 2020).

The projections are released as these conclusions are drawn, with evidence produced, communicated and altering policy simultaneously. This followed the team tweaking their parameters by doubling the assumed National Health Service (NHS) case demand (from an estimated 15% of hospital cases to 30%), based on personal communications of evolving intensive care demand elsewhere, largely from Italy: 'The intensive care requirements will be nearly twice what we had anticipated' (*Financial Times*, 2020a). The tweaking of the model was said to have led to a 'sudden focusing of minds' in the days prior to briefing the UK government towards a policy of suppression (*Nature*, 2020). A suppression strategy thus became the 'most likely one to ensure that critical care bed requirements would remain within surge capacity' (Ferguson et al., 2020). Going forwards, an 'adaptive policy' is recommended wherein strict suppressions are 'switched on and off' following viral rebounds when critical cases reach threshold against a background of a slow population immunity building. The dramatic yet unpredictable social effects of the projections are emphasised, noting that 'no public health intervention with such disruptive effects on society has been previously attempted' (Ferguson et al., 2020).

How though, do these projections *travel*? How are they *in-the-making* as they *transform* into social networks beyond their calculus? That is, how are projections afforded *agency* and *potential* of their *own making* as they are enacted into public concern, and with what effects? In asking these questions, we shift our attention from the 'laboratory to society', to see how science is being done, in action, in the everyday.

On their release, media stories hone attention on the sharp contrast between the numbers of 250,000 with 20,000, enacting this as the difference between the 'terrible choices' of herd immunity and lockdown (*Financial Times*, 2020b; *Guardian*, 2020a): 'We've gone from the idea of gradually infecting a large chunk of the population through mitigation measures – so as to achieve so-called 'herd immunity' – to suppression' (*Financial Times Alphaville*, 2020a). The difference in policy is enacted as a change in the *numbers* (*Guardian*, 2020a). We are told that a policy of mitigation has been 'abruptly junked' for a new strategy which 'abandons the idea of 'herd immunity'' on the basis of model projections that 'about 250,000 people would have died under the government's previous strategy' (*Financial Times*, 2020a). It was reportedly a 'modelling change' that 'sent UK policy careering toward lockdown' (*Bloomberg*, 2020a; *Guardian*, 2020a). The communication of abrupt policy change at the level of the population entangles with the careful refinement of model projections adapted in relation to new parameter values of critical care demand (see above). Through their connections in public space, we move between small-scale matters-of-fact enacted through parameter value tweaks and big-scale matters-of-concern enacted through policy shifts of life and death decision.

A controversy is being made, where mortality projections – the *numbers themselves* – appear to have altered in big jumps from 510,000 to 250,000 to 20,000 (*Guardian*, 2020a; *Washington Post*, 2020a, 2020b). Here is one media report of some quoted speech: 'If you remember, that was the report that said there would be 500,000 deaths in the UK and 2.2 million deaths in the United States. They've adjusted that number in the UK to 20,000. So, half a million to 20,000' (*Washington Examiner*, 2020; *Wall Street Journal*, 2020). Alex Berenson, a former reporter with the *New York Times*, takes to Twitter, on March 26: 'This is a remarkable turn from Neil Ferguson, who led the @imperialcollege authors who warned of 500,000 UK deaths'. Andrew Neil, former Editor with the *Times*, also takes to Twitter: 'Guidance, please. Is Imperial's Neil Ferguson, whose modelling gave us the 250,000 deaths projection and led to lockdown, now saying UK deaths 'could be substantially lower' than 20,000, and two-thirds would have died in the next 6 months anyway?'. This feeds doubt. Others in the Twitter conversation claim that 'going from herd immunity' to 'never mind, 20k, and the hospital system will be fine' constitutes 'a joke'. Media reports describe an 'about turn' in policy, reinstating that the NHS 'should now be able to cope' (*New Scientist*, 2020). There are even some reports that the modellers may have 'adjusted' and 'drastically downgraded' their 'faulty' estimates from around 500,000 to 20,000 deaths because 'far more people likely have the virus than [they] figured' (*Daily Wire*, 2020; *Financial Times Alphaville*, 2020b; *Washington Examiner*, 2020).

Days after the UK policy change from mitigation to suppression, which holds out hope of a coping NHS, COVID-19 is reconstituted by the NHS as no longer a 'high consequence infectious disease'. In response to the emerging controversy, Neil Ferguson also takes to Twitter, March 26, in an attempt to 'clear up some confusion' that 'we have substantially revised our assessments of mortality impact' which 'is not the case'. An element in the controversy is modellers holding on to the 'fact' that their *numbers have not changed*, and that the *models are not new*, but that what *is fluid* is how the models are being publicly communicated (*Financial Times Alphaville*, 2020b; *National Review*, 2020; Horton, 2020). There are multiple Twitter calls for the modelling code, and other citizen appeals to get inside the model, for example: 'What's taking you so long to make the code for your projections open source?' (Twitter, March 27). Given media reporting of national policy shifts being publicly communicated on the basis of 'new' models and projections (*Guardian*, 2020a), there have been repeated calls to make modelling evidence more transparent in public communications and policy decisions (Horton, 2020; *The Times*, 2020).

The projections of 250,000 and 20,000, tweaked in light of evolving estimates of case demand, thus travel into the hinterland of controversy generated by the public troubles of herd immunity policy. This initial strategy of mitigation was reported to play 'second fiddle to mathematical modelling' (*Guardian*, 2020b). Models were reportedly afforded *too much agency*, with Government 'instructions' said to result from attempts to 'control the UK epidemic by mathematical modelling' (*Guardian*, 2020b). Prior to the modelling team advocating a move to suppression as the 'only viable strategy', media stories warned of the dangers of modelled assumptions: 'They are also solely intended to flatten the curve, when even a *flat curve will kill thousands*. These approaches would be an acceptable experiment if there were no alternatives, but we have strategies from elsewhere which have been shown to work'. We are then, located in a cycle of evidence-making intervention in which successive adaptive models entangle, in diffuse and complex ways, with their social and material worlds. Importantly, the controversy *itself* – in policy *and* models – is evidence-making the COVID-19 projections (*Financial Times Alphaville*, 2020b; *Guardian*, 2020c; *Bloomberg*, 2020a, 2020b).

Appreciating that the evidence that projections make is located in the messy practices of social life, and not simply those of science, helps us see that projections are not stable calculations but fluid effects of the complex and partial connections which form the assemblages which enact them. The numbers of 510,000, 250,000 and 20,000 are not immutable and universal but malleable and situated. They are *made multiple* in their materialisations, with their transformations much *messier* than simple 'translation' (Greenhalgh & Wieringa, 2011). We move from an 'evidence-based' approach valorising 'cold, hard numbers' as calculations which potentiate universal truths (Porter, 1995), to a more open and malleable 'evidence-making' approach which appreciates numbers as relational beings which also intervene as *qualifications* (Callon & Law, 2005). As we see here, what the projections become, and how they are qualified to matter, is indexed to a particular set of assemblage relations, in a moment of policy change. The projections are 'nothing' without their relations.

Case 2: 68%

A University of Oxford mathematical model recently projected COVID-19 infections in the UK (Lourenço et al., 2020). The model and its projections were quickly troubled, including in public and media communications, and among experts (*British Medical Journal*, 2020; *Financial Times*, 2020c; Kucharski, 2020b). In this model, an assumed 0.1% of the population at risk of severe COVID-19 and a R_0 of 2.25 projects that 68% of the UK population are likely exposed (an assumption of 1% at risk of severe disease requiring hospitalisation yields 40% already exposed at R_0 2.75 and 36% at R_0 2.25) (Lourenço et al., 2020). Media reports respond by declaring that 'half of the UK population' may be infected (*New York Post*, 2020; *Financial Times*, 2020d). At the same time, the maths and methods of the model *become the story*, with coronavirus said to 'expose the problems and pitfalls of modelling', resulting from 'assumptions in the absence of data' (*Guardian*, 2020c). The upper estimates of asymptomatic infection producing the 68% estimate had 'no empirical justification', and the assumption of fewer than 1:1000 hospitalisations was at odds with empirical reports (*Financial Times*, 2020c; *British Medical Journal*, 2020). We are reminded that while models conjure virtual precisions (here, 68%), these are 'assumptions', a 'hypothesis and nothing more', because there is 'no hard data' and that the 'true figure' is 'unknown' (*Guardian*, 2020c). We are also warned that 68% is a number we *want to believe*, enacting COVID-19 as 'so mild' that 'most of us' have it already along with 'some degree of immunity' (*Financial Times*, 2020e).

The controversy surrounding this new projection diffuses into the atmosphere of unease concerning the evidencing of UK policy shifts between herd immunity and lockdown (see Case 1 above). Public reports that it is the Imperial College *projections* of death that have altered, from 250,000 to 20,000, entangle with the Oxford University projection of 68%, that many more people have the virus, with less serious consequences, and with potential for greater protective immunity, than previously estimated (*Financial Times Alphaville*, 2020b). The projections from *different models* enact an 'absent-presence' in relation to one another through public deliberations concerning the value of different policies (of lockdown and protective immunity) and modelling methods (regarding their empirical claims) (*Bloomberg*, 2020a; Ioannidis, 2020). Projections from entirely different models, each with particular aims, logics and assumptions, are mobilised on a *single plane* of deliberation regarding national policy decisions. One model projects how to flatten the epidemic curve (Ferguson et al., 2020), and the other how infections might have spread (Lourenço et al., 2020), but each are made-to-matter in their assemblages of implementation and not merely by their modes of calculation.

With COVID-19, our knowing through models is not only contingent on theoretical projections in the relative absence of 'real-world' data, but publics are variously *folded into contingency* as elements of evidence-making deliberation. With COVID-19, we are not simply receivers of translated scientific output, as if cushioned from the uncertainties of the projections, and neither do we observe such science-making 'as if from a bridge' (Puig de la Bellacasa, 2017, p. 33), but we are *wrapped up inside* the making of contingency as *matter* of public concern. Modelled projections at once materialise, and are materialised in, *public troubles*.

Frictions in uncertain science

Our effort to 'follow the numbers' attends to the messiness and uncertainty of evidence translations. While the two cases of projection we have traced relate to the particularities of their materialisations in UK policy shifts, they generate wider lessons for how engagements with COVID-19 models enact projections as objects of public trouble. Modelling not only becomes the *story* in relation to the making of controversy (*Bloomberg*, 2020a, 2020b; *Guardian*, 2020c; *Financial Times Alphaville*, 2020b), but the *matter* through which controversy is materialised. How then, is modelling science as an object of public trouble to be navigated?

In media stories of models as public troubles, we are warned of 'self-appointed data analysts' and 'armchair epidemiologists', and told that we are better off with the more measured uncertainties of 'actual epidemiologists' (*Bloomberg*, 2020b). We are reminded also that the 'underlying uncertainty' of models 'gives rise to misunderstandings, and when leaned on too heavily, to policy mistakes' (*Bloomberg*, 2020a). And we are cautioned that the virtual precision of models makes them 'deceptive' because it 'masks all the uncertainty' (*Bloomberg*, 2020a). Of course, 'actual' epidemiologists themselves are also in public disagreement about the trust they place in different models (as we have seen above). Some epidemiologists have taken to the media to claim that COVID-19 is a 'once-in-a-century evidence fiasco' which is generating 'tremendous uncertainty' through 'utterly unreliable' estimates (Ioannidis, 2020).

Modelling materialised as public trouble constitutes an embodied uncertainty, which in times of emergent vital concern, enacts ontological insecurity (Giddens, 1991). This is not detached calculative deliberation in relation to science as matter-of-fact, but affective engagement in relation to evidence as matter of urgent material concern (Latour, 2004). An affective desire for security via projection *amplifies uncertainty* when models are enacted as public troubles, and as attention shifts towards the contingency and unpredictability of enumerations. We adapt from an immediate urge in outbreak science to enumerate (Rivers et al., 2019), to doubting projections and a trust in numbers, as their contingency is evidence-made (Glasser et al., 2011), and as we engage reflexively in the uncertain science that we are making. Here, the more that is made known, the more that our knowing becomes unsettled. This is obviously not 'evidence-based' deductive science progressing towards a stable truth as we know it (Sackett et al., 2000), but an emergent, and messier, science that 'evidence-makes' as it proceeds through recursive moves in a model of 'emergent causation' (Connolly, 2004; Rhodes & Lancaster, 2019).

In stories of models as public troubles, there is a crisis of expertise enacted which is therefore said to be best solved by distinguishing 'armchair' from 'actual' experts:

> What emerges is a bit of an epistemological disaster: Experts uncertain based on the absence of empirical facts may be triggering in us the impulse to distrust experts which in turn leads us to make even more unreliable judgements under the illusion that we can do it ourselves, even though that we don't know the empirical facts, either. (*Bloomberg*, 2020b)

There are increasing calls for evidence of the 'real' and 'actual' alongside the theoretical and abstract. In the public troubles of COVID-19 science, this call is largely being made via advocacy for *real data* on *concrete cases*, including through testing and surveillance (Lourenço et al., 2020). Here is an example: 'Perhaps the best available basis on which to make actual decisions today isn't so much what the modellers can tell us about coronavirus, but the experiential evidence' (*Bloomberg*, 2020a). These calls for relative certainty through an empirical realism seek to re-draw the imagined boundaries of public engagement in relation to uncertain modelling science. This is a push-back which enacts a binary of separation of modelling science from its society via isolating the abstract from the actual to make modelling less 'public trouble' in its uncertainty. Perhaps this is a modelling science which we might not want, right now, after all. Perhaps we need to hold off, *until the real*. Perhaps we need to hold on, *to the real*. This friction in expertise – between the apparent actual and abstract, between publics and science, and between the more-or-less certain of realist 'evidence-based' science and the more-or-less contingent of emergent 'evidence-making' science – is captured here in the enactment of publics desiring certainty as separate to the 'bubble' of the modelling world: 'Those of us outside their bubble want to assuage our uncertainty' (*Bloomberg*, 2020a). We, the publics, are also matter being made in the evidencing of models as public troubles.

Discussion: lessons for an emergent science

While there is a tendency to imagine the world of maths and calculus as pure and separate from the material world, COVID-19 is telling us otherwise. With COVID-19, engaging with projections is a way of *living with*, while *acting on*, the virus and its contingency. By attending to evidence-making as a *process* based in practices in which science and society are not apart but always entangled, we can appreciate that evidence and expertise are always 'made multiple', as *relational beings*, in particular evidence-making intervention assemblages. The mathematical model then, works as a *boundary object* in creating space for *deliberation* among multiple actors engaging with projections and their multiple potential as epistemic and affective concerns (Star and Griesemer (1989); Shackley & Wynne, 1996; Van Egmond & Zeiss, 2010). Deliberation potentiates *speculation*, and this leads us to consider how evidence-making in policies and in publics might be done differently.

The model as boundary object

There are different versions of boundary object proposed by Star and Griesemer (1989), and summarised by Fox (2011), but we suggest that mathematical models, especially in novel situations lacking in empirical detail, enact abstractions that produce a knowledge which is 'good enough' to energise the multiple concerns of varying actors and publics. The combination of virtual precision (for example, enacted by a number or projection) with qualification (for example, enacted by an imagined scenario or situation) affords latitude which makes models 'flexible enough' to be put-to-use multiply (Callon & Law, 2005; Rhodes & Lancaster, 2020). This makes models *lively* (Myers, 2015), as we have seen.

The flexibility that models afford as boundary objects is perhaps what makes them 'messy' as a category of knowing and as a means of policy-making (Sismondo, 1999; Van Egmond & Zeiss, 2010). But we see the mess and flexibility of models as core and generative, as well as unavoidable, in an 'emergent science' or 'adaptive policy' approach. Boundary objects are *good* for emergent science. They *enable deliberation* across multiple communities of practice or knowledge which might otherwise not come into dialogue (Fox, 2011). Projections enacted as public troubles are therefore not a 'problem' for the purity of science, even if this might be the immediate reaction of those of an 'evidence-based' persuasion. Rather, projections enacted as public troubles tell us that models create a space, a *working relationship*, in which dialogue around an innovation or speculation is made possible (Landström, Whatmore, & Lane, 2013). Importantly, this potentiates models working not simply as epistemic boundary 'crossings' – moving across different versions of expertise – but as modes of *enactment* – by *altering* and *making* new versions of expertise (Landström et al., 2013; Myers, 2015). We therefore need to engage with the mess (Law, 2004) and stay with the trouble (Haraway, 2016).

Working through contingency

One element in 'staying with the trouble' is contingency. With COVID-19 evidence-making, we get to observe the frictions at play between the desire to know as precisely as possible in order to tame uncertainty so as to act decisively, and the reflexive awareness that *knowing precisely is not possible*. Especially in emergency situations, modelled projections are not simply released as 'abstracted possibilities', awaiting careful empirical verification over time, but alter the material present *in-the-now*, as 'actualised potentials', in policies and in publics. The projections of COVID-19 models constitute shocks as well as fluid potentials. In their public release, they shape immediate and decisive actions of dramatic impact in social and public life, yet they do so in an *adaptive policy* approach (Ferguson et al., 2020). This friction – acting *adaptively* in-the-now in relation to *shocks* of an unpredictable future – inevitably materialises contingency in the moment, in *every moment*, of evidence-making and intervening. The question then, is not *whether* science can hold on to the ideal of an 'evidence-based' approach which tames uncertainty through the hope of objective knowing, and which proceeds to an imagined stable truth through iteration, but *how* science and policy can be done differently to *live with* uncertainty in an emergent approach in relation to multiple matters-of-concern (Stengers, 2018). This is not a way of 'working through contingency' in the sense of moving beyond it, as a realist version of iterative science would presume, but a way of 'working through contingency' as the *matter*, as the *material,* through which science is being done (Latour, 1987).

Our first concluding point then, is that contingency *is* the matter of intervention. An emergent science is the *only way* to make evidence in the face of novelty and uncertainty, and this requires us to engage in, and find a way of *living with*, troubles. This, for instance, is how the World Health Organization attempted to manage the contingencies of the science and response linked to the H1N1 pandemic in 2009 (Abeysinghe, 2014). Rather than present the science *as if* certain, the WHO accentuated its contingency, and the unpredictability, even unknowability, of the pandemic. The challenge of this, as the WHO found, is that this materialised science at odds with prevailing epistemic standards of evidence-based intervention. The WHO was accused at the time, including by other global agencies, of having no 'objective' or 'factual' basis to govern a pandemic response, and even of 'faking' the pandemic (Abeysinghe, 2014). This gets to the core of the onto-epistemological challenge in doing adaptive policy through an emergent science in and against time: How to act with *emergent precision* in-the-now. We are not only arguing that the business-as-usual of evidence-based intervention is insufficient in times of emergency (the idea that iteratively moving towards greater certainty and an objective measure of knowing is complicated by time), but that *another science is possible*, one which works with, and through, contingency in an emergent approach (Stengers, 2018). In our view, the 'problem' with handling science and pandemics as contingent is fundamentally a problem of holding on to the narrow ideal of science as we know it, that is, as an objective matter-of-fact that can know with certainty.

Working through participation

This leads to a second concluding point. This is that models, as boundary objects, afford a way of working through contingency as modes of *participation*. In creating a space of latitude for calculation and qualification in relation to multiple matters-of-concern, in policies as well as publics, models are devices of deliberation in which multiple actors and experts participate. The 'making public' of models in the time of COVID-19, and the materialisation of such models as 'public troubles', is not a lesson for how to communicate emergency science 'more cleanly' but an opportunity to participate well. Here, we want to draw specific attention to the work of Catharine Landström and Sarah Whatmore on 'participatory modelling' approaches and how these can enable a redistribution of expertise in events of public controversy (Landström et al., 2011, 2013; See also, Lancaster, Ritter, & Diprose, 2018).

Rather than treating public troubles as events of failed governance, they can be approached as a dynamic source of change through public participation (Callon et al., 2009). Controversies engage publics, through deliberation, in relation to concerns, while drawing attention to the legitimacy of science and policy, thereby potentiating the redistribution of expertise (Landström et al., 2011). Rather than envisaging models as participatory in the sense of enabling debate and consultation leading to the democratisation of expertise (Jasanoff, 2003), there is the potential for participatory modelling to co-produce new expertise, and experts, into being (Callon et al., 2009; Landström et al., 2011, 2013). In the participatory modelling experiments facilitated by Landström and colleagues in response to flood risk, the participating scientists were invited to 'dissociate' from the tools and methods of their science, and from their institutions of expertise, and 'attach' to an open deliberation process which also involved *re-making* their models in relation to emerging matters-of-concern. The participatory model acts here as a boundary object which does not so much seek to 'bring-in' the expertise of publics into models (as consultative approaches might do) than 'bring science out' of its networks of bounded expertise into publics (Landström et al., 2011). The model becomes a situated intervention in staging collaboration between experts and their different tools, repertoires and practices of evidence-making (Stengers, 2018).

Conclusion

Projections of COVID-19 are materialised as public troubles, and it does not help to assume that modelling science is anything but a matter of its social relations. Public troubles can be treated as generative events for energising new forms of expertise, as well as for remaking experts and publics, through participation. Models, as boundary objects in the deliberation of uncertainty, afford this potential. This becomes especially apparent when it is the models themselves that constitute the matter of controversy, as in the case of COVID-19 infection control. There are experimentations in participatory models in a variety of policy fields (Falconi & Palmer, 2016; Landström et al., 2011, 2013; Scoones et al., 2017; Videira, Antunes, Santons, & Gamito, 2003). We see potential for experimenting with the mathematical model as a boundary object for working through contingency and as a mode of participation in COVID-19 infection control. Projections will likely continue to shape policy and public responses in the COVID-19 pandemic, including as the social and economic complexities of policy decisions become apparent and as empirical data is generated. Projections informing rapid COVID-19 policy decisions to date have developed largely as if they are detached from the social worlds in which they entangle. There is a need now, and going forwards, to give careful attention to the social effects that projections materialise, and to experiment in doing modelling science and policy differently, including through participatory collaborations.

Notes

1. It is important to note that the models informing policy decisions generate multiple projections in relation to multiple scenarios contingent upon various parameters and value ranges, and that the projections travelling into public communications can be those representing best or worse-case scenarios and/or are selected for particular attention as well as variously reported.
2. The basic reproduction number, R_0, also termed the basic reproductive ratio, is the assumed number of cases directly generated by one case in a population susceptible to infection in a situation where there is no vaccination or community immunity. This is distinct from the effective reproduction number, *R*, which denotes the number of cases generated in a population, which does not have to be in an uninfected state, such as when vaccination or community immunity exists. R_0 is a critical parameter in estimating infection spread and the proportion of a population in need of vaccination or protection to achieve infection control. Generally, the larger the value of R_0, the greater the challenges of infection control, with control strategies aiming to achieve $R_0 < 1$.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

ABC Radio. (2020). *Coronacast*, https://www.abc.net.au/radio/programs/coronacast/

Abeysinghe, S. (2014). An uncertain risk: The World Health Organization's account of H1N1. *Science in Context*, *27*, 511–529.

Adams, V., Murphy, M., & Clarke, A. E. (2009). Anticipation: Technoscience, life, affect, temporality. *Subjectivity*, *28*, 246–265.

Aykut, S. C., Demortain, D., & Benbouzid, B. (2019). The politics of anticipatory expertise: Plurality and contestation of futures knowledge in governance. *Science and Technology Studies*, *32*, 2–12.

Bacchi, C., & Goodwin, S. (2006). (Eds.) *Poststructural policy analysis*. New York: Palgrave.

Barad, K. (2003). Posthumanist performativity: Toward an understanding of how matter comes to matter. *Signs*, *28*, 801–831.

Bauer, S. (2013). Modeling population health. *Medical Anthropology Quarterly*, *27*, 510–530.

Bloomberg. (2020a, April 6). Science isn't a clear-cut pandemic guide, https://www.bloomberg.com/opinion/articles/2020-03-31/what-the-coronavirus-models-are-trying-to-tell-us

Bloomberg. (2020b, March 30). Will the armchair coronavirus experts please sit down, https://www.bloombergquint.com/gadfly/predicting-coronavirus-should-be-left-to-the-experts

British Medical Journal. (2020, March 25). Covid-19: Experts question analysis suggesting half UK population has been infected. *British Medical Journal*, *368*, m1216.

Callon, M., Lascoumes, P., & Barthe, Y. (2009). *Acting in an uncertain world*. Cambridge: MIT Press.

Callon, M., & Law, J. (2005). On qualculation, agency and otherness. *Environment and Planning*, *23*, 717–723.

Callon, M., & Numiesa, F. (2005). Economic markets as calculative and calculated collective devices. *Organization Studies*, *26*, 1229–1250.

Connolly, W. E. (2004). Method, problem, faith. In I. Shapiro, R. M. Smith, & T. E. Masoud (Eds.), *Problems and methods in the study of politics* (pp. 332–349). London: Cambridge University Press.

Daily Wire. (2020, March 26). Epidemiologist behind highly cited coronavirus model drastically downgrades projection, https://www.dailywire.com/news/epidemiologist-behind-highly-cited-coronavirus-model-admits-he-was-wrong-drastically-revises-model

Economist. (2020, February 29). Covid-19 is now in 50 countries, and things will get worse, https://www.economist.com/briefing/2020/02/29/covid-19-is-now-in-50-countries-and-things-will-get-worse
Falconi, S. M., & Palmer, R. N. (2017). An interdisciplinary framework for participatory modelling design and evaluation: What makes models effective participatory decision tools? *Water Resources Research*, *53*, 1625–1645.
Ferguson, N. M., Cummings, D. A., Fraser, C., Cajka, J. C., Cooley, P. C., & Burke, D. S. (2006). Strategies for mitigating an influenza pandemic. *Nature*, *442*, 448–452.
Ferguson, N. M., Laydon, D., Nedjati-Gilani, G., Imai, N., Ainslie, K., Baguelin, M., … Ghani, A. C. (2020). *Impact of non-pharmaceutical interventions (NPIs) to reduce COVID-19 mortality and healthcare demand*. Imperial College COVID-19 Response Team.
Financial Times. (2020a, March 16). UK's original coronavirus plan risked 'hundreds of thousands' dead, https://www.ft.com/content/249daf9a-67c3-11ea-800d-da70cff6e4d3
Financial Times. (2020b, March 19). The shocking coronavirus study that shocked the UK and USA, https://www.ft.com/content/16764a22-69ca-11ea-a3c9-1fe6fedcca75
Financial Times. (2020c, March 26). Letter: The Oxford study figure has no empirical justification, https://www.ft.com/content/ebab9fcc-6e8d-11ea-9ca-bf503995cd6f?shareType=nongift
Financial Times. (2020d, March 24). Coronavirus may have infect half the UK population, https://www.ft.com/content/5ff6469a-6dd8-11ea-89df-41bea055720b
Financial Times. (2020e, March 27). Why it's tempting to believe the Oxford study on coronavirus, https://www.ft.com/content/14df8908-6f47-11ea-9bca-bf503995cd6f
Financial Times Alphaville. (2020a, March 17). That Imperial coronavirus report, in detail, https://ftalphaville.ft.com/2020/03/17/1584439125000/That-Imperial-conoavirus-report-in-detail-/
Financial Times Alphaville. (2020b, March 27). Let's flatten the coronavirus confusion curve, https://ftalphaville.ft.com/2020/03/06/1585245384000/Let-s-flatten-the-coronavirus-confusion-curve/
Fox, N. (2011). Boundary objects, social meanings and the success of new technologies. *Sociology*, *45*, 70–85.
Fox, N., & Allred, P. (2017). *Sociology and the new materialism*. London: Sage.
Fox, N. J., & Alldred, P. (2020). Re-assembling climate change policy: Materialism, posthumanism, and the policy assemblage. *British Journal of Sociology*, *71*, 269–283.
Giddens, A. (1991). *Modernity and self-Identity. Self and society in the late modern age*. Cambridge: Polity.
Glasser, J. W., Hupert, N., McCauley, M. M., & Hatchett, R. (2011). Modeling and public health emergency responses: Lessons from SARS. *Epidemics*, *3*, 32–37.
Greenhalgh, T., & Wieringa, S. (2011). Is it time to drop the 'knowledge translation' metaphor? A critical literature review. *Journal of the Royal Society of Medicine*, *104*, 501–509.
Guardian. (2020a, March 16). New data, new policy: Why UK's coronavirus strategy changed, https://www.theguardian.com/world/2020/mar/16/new-data-new-policy-why-uks-coronavirus-strategy-has-changed?CMP=Share_iOSApp_Other
Guardian. (2020b, March 17). 'There is a policy of surrender': Doctor on UK's Covid-19 failures, https://www.theguardian.com/world/2020/mar/17/there-is-a-policy-of-surrender-doctor-on-uks-covid-19-failures
Guardian. (2020c, March 25). Coronavirus exposes the problems and pitfalls of modelling, https://www.theguardian.com/science/2020/mar/25/coronavirus-exposes-the-problems-and-pitfalls-of-modelling
Hacking, I. (1990). *The taming of chance*. Cambridge: Cambridge University Press.
Haraway, D. (2016). *Staying with the trouble*. Durham, NC: Duke University Press.
Heffernan, A., Cooke, G. S., Nayagam, S., Thursz, M., & Hallett, T. B. (2019). Scaling up prevention and treatment towards the elimination of hepatitis C: A global mathematical model. *Lancet*, *393*, 1319–1329.
Hellewell, J., Abbott, S., Gimma, A., Bosse, N. I., Jarvis, C., Russell, T., … van Zandvoort, K. (2020). Feasibility of controlling COVID-19 outbreaks by isolation of cases and contacts. *Lancet*, doi:10.1016/S2214-109X(20)30074-7

Horton, R. (2020, March 18). Scientists have been sounding the alarm on coronavirus for months: Why did Britain fail to act? *Guardian*, https://www.theguardian.com/commentisfree/2020/mar/18/coronavirus-uk-expert-advice-wrong?CMP=Share_iOSApp_Other
Ioannidis, J. P. A. (2020, March 17). A fiasco in the making? As the coronavirus pandemic takes hold we are making decisions without reliable data. *STAT*, https://www.statnews.com/2020/03/17/a-fiasco-in-the-making-as-the-coronavirus-pandemic-takes-hold-we-are-making-decisions-without-reliable-data/
Jasanoff, S. (2003). Technolgies of humility: Citizen participation in governing science. *Minerva*, *41*, 223–244.
Jasanoff, S. (2010). A new climate for society. *Theory, Culture and Society*, *27*, 233–253.
Kucharski, A. (2020a). *Rules of Contagion*. London: Profile Books.
Kucharski, A. (2020b, March 26). Can we trust the Oxford study on COVID-19 infections. *Guardian*, https://www.theguardian.com/commentisfree/2020/mar/26/virus-infection-data-coronavirus-modelling
Kucharski, A. J., Russel, T. W., Diamondm, C., Liu, Y., Edmunds, J., Funk, S., & Eggo, R. M. (2020). Early dynamics of transmission and control of COVID-19: A mathematical modelling study. *Lancet Infectious Diseases*, doi:10.1016/S1473-3099(20)30144-4
Lancaster, K., Ritter, A., & Diprose, R. (2018). Recasting participation in drug policy. *Contemporary Drug Problems*, *45*, 351–365.
Landström, C., Whatmore, S., & Lane, S. N. (2013). Learning through computer model improvisations. *Science, Technology and Human Values*, *38*, 678–700.
Landström, C., Whatmore, S., Lane, S. N., Odoni, N. A., Ward, N., & Bradley, S. (2011). Coproducing flood risk knowledge: Redistributing expertise in critical 'paricipatory modelling'. *Environment and Planning A*, *43*, 1617–1633.
Latour, B. (1987). *Science in action: How to follow scientists and engineers through society*. Cambridge: Harvard University Press.
Latour, B. (2004). Why has critique run out of steam? From matters of fact to matters of concern. *Critical Inquiry*, *30*, 225–248.
Law, J. (2004). *After method: Mess in social science research*. London: Routledge.
Leach, M., & Scoones, I. (2013). The social and political lives of zoonotic disease models. *Social Science and Medicine*, *88*, 10–17.
Lourenço, J., Paton, R., Ghafari, M., Kraemer, M., Thompson, C., Simmonds, P., … Gupta, S. (2020). Fundamental principles of epidemic spread highlight the immediate need for large-scale serological surveys to assess the stage of the SARS-CoV-2 epidemic. doi:10/1101/2020.03.24.20042291.
Mackenzie, D. (2006). *An engine, not a camera: How financial models shape markets*. Cambridge, MA: MIT Press.
Martin, N., Boerekamps, A., Hill, A. M., & Rijnders, B. J. A. (2018). Is hepatitis C elimination possible among people living with HIV and what will it take to achieve it? *Journal of the International AIDS Society*, *21*(S2), e25062.
Michael, M. (2000). Futures of the present: From performativity to prehension. In N. Brown, B. Rappert, & A. Webster (Eds.), *Contested futures: A sociology of prospective techno-science* (pp. 21–42). Aldershot: Ashgate Publishing.
Miller, P. (2001). Governing by numbers: Why calculative practices matter. *Social Research*, *68*(2), 379–396.
Montgomery, C., & Engelmann, L. (2020, Apri 10). Epidemiological publics? On the domestication of mathematical modes in the era of COVID-19. *Somatasphere*, https://somatosphere.net/2020/epidemiological-publics-on-the-domestication-of-modelling-in-the-era-of-covid-19.html/
Myers, N. (2015). *Rendering life molecular: Models, modelers and excitable matter*. London: Duke University Press.
National Review. (2020, March 26). No, a COVID scientist didn't walk back his prediction, https://www.nationalreview.com/corner/coronavirus-pandemic-neil-ferguson-did-not-walk-back-covid-19-predictions/

Nature. (2020, April 2). The simulations driving the world's response to COVID-19. *Nature*, https://www.nature.com/articles/d41586-020-01003-6
New Scientist. (2020, March 25). UK has enough intensive care units for coronavirus, expert predicts, https://www.newscientist.com/article/2238578-uk-has-enough-intensive-care-units-for-coronavirus-expert-predicts/
New York Post. (2020, March 24). Coronavirus may have already infected half of UK, study says, https://nypost.com/2020/03/24/coronavirus-may-have-already-infected-half-of-uk-study-says/
New York Times. (2020, March 17). Flattening the coronavirus curve, https://www.nytimes.com/2020/03/11/science/coronavirus-curve-mitigation-infection.html
Porter, T. (1995). *Trust in numbers*. Princeton, NJ: Princeton University.
Puig de la Bellacasa, M. (2017). *Matters of care*. Minneapolis: University of Minnesota Press.
Rhodes, T., & Lancaster, K. (2019). Evidence making interventions in health: A conceptual framing. *Social Science and Medicine*, *238*, doi:10.1016/j.socscimed.2019.112488
Rhodes, T., & Lancaster, K. (2020). How to think with models and targets: Hepatitis C elimination as a numbering performance. *International Journal of Drug Policy*, doi:10/1016/j.drugpo.2020.102694
Rhodes, T., Lancaster, K., & Rosengarten, M. (2020). A model society: Maths, models and expertise in viral outbreaks. *Critical Public Health*, doi:10/1080/09581596.2020.1748310
Rivers, C., Chretien, J.-P., Riley, S., Pavlin, J. A., Woodward, A., Brett-Major, D., … Snyder, M. R. (2019). Using 'outbreak science' to strengthen the use of models during epidemics. *Nature Communications*, doi:10.1038/s41467-019-11067-2
Sackett, D. L., Straus, S. E., Richardson, W. S., Rosenberg, W., & Haynes, B. R. (2000). *Evidence-based medicine* (2nd ed.). Edinburgh: Churchill Livingston.
Scoones, I., Jones, K., Lo Iacono, G., Redding, D. W., Wilkinson, A., & Wood, J. L. N. (2017). Inegrative modelling for one health: Pattern, process and participation. *Philosophical Transactions B*, *372*, 20160164.
Shackley, S., & Wynne, B. (1996). Representing uncertainty in global climate change science and policy: Boundary-ordering devices and authority. *Science, Technology and Human Values*, *21*, 275–302.
Shore, C., & Wright, S. (2015). Governing by numbers: Audit culture, rankings and the new world order. *Social Anthropology*, *23*, 22–28.
Sismondo, S. (1999). Models, simulations, and their objects. *Science in Context*, *12*, 247–260.
Stengers, I. (2018). *Another science is possible*. Cambridge: Polity Press.
Star, S. L., & Griesemer, J. R. (1989). Institutional ecology, "translations" and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-1939. *Social Studies of Science*, *19*, 387–420.
Strathern, M. (2000). *Audit cultutres*. London: Routledge.
The Times. (2020, March 14). Coronavirus modelling 'must be made clear', https://www.thetimes.co.uk/article/coronavirus-modelling-must-be-made-clear-3zcl7x578
Van Egmond, S., & Zeiss, R. (2010). Modelling for policy: Science-based models as performative boundary objects for Dutch policy making. *Science Studies*, *23*, 58–78.
Verran, H. (2015). Enumerated entities in public policy and governance. In E. Davis & P. Davis (Eds.), *Mathematics, Substance and Surmise* (pp. 365–379). NJ: Springer.
Vesga, J. F., Hallett, T. B., Reid, M. J., Sachdeva, K. S., Rao, R., Khaparde, S., … Arinaminpathy, N. (2019). Assessing tubercolusis control priorities in high-burgen settings: A modelling approach. *Lancet Global Health*, *7*, E585–E595.
Videira, N., Antunes, P., Santons, R., & Gamito, S. (2003). Participatory modelling in environmental decision-making. *Journal of Environmental Assessment and Policy Management*, *5*, 421–447.
Wall Street Journal. (2020, March 27). Worst-case coronavirus science, https://www.wsj.com/articles/worst-case-coronavirus-science-11585351059
Washington Examiner. (2020, March 26). Imperial College scientist who predicted 500k coronarvus deaths in UK revises to 20k or less, https://www.washingtonexaminer.com/news/imperial-college-scientist-who-predicted-500k-coronavirus-deaths-in-uk-revises-to-20k-or-less

Washington Post. (2020a, March 27). Coronavirus modelers factor new public health risk: Accusations their work is a hoax, https://www.washingtonpost.com/health/2020/03/27/coronavirus-models-politized-trump/

Washington Post. (2020b, March 14). Why outbreaks like coronavirus spread exponentially and how to "flatten the curve", https://www.washingtonpost.com/graphics/2020/world/corona-simulator/

Whatmore, S. J. (2009). Mapping knowledge controversies. *Progress in Human Geography*, *33*, 587–598.

Wood, M., Ferlie, E., & Fitzgerald, L. (1998). Achieving clinical behaviour change: A case of becoming indeterminate. *Social Science & Medicine*, *47*, 1729–1738.