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Transmission dynamics of the COVID-19 epidemic in England

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ABSTRACT

Background: The ongoing coronavirus disease 2019 (COVID-19) pandemic has caused a tremendous health burden and impact on the world economy. The UK Government implemented the biggest lockdown of society during peacetime in British history at the end of March 2020, aiming to contain the rapid spread of the virus. The UK lockdown was maintained for 7 weeks, but the effectiveness of the control measures in suppressing disease transmission remains incompletely understood.
Methods: A Bayesian SEIR (susceptible–exposed–infected–removed) epidemiological model was used to rebuild the local transmission dynamics of the spread of COVID-19 in nine regions of England.
Results: The basic reproduction number (R_0) in England was found to be relatively high compared with China. The estimate of the temporally varying effective reproduction number (R_t) suggests that the control measures, especially the forced lockdown, were effective to reduce transmissibility and curb the COVID-19 epidemic. Although the overall incidence rate in the UK has declined, forecasting highlights the possibility of a second epidemic wave in several regions.
Conclusion: This study enhances understanding of the current outbreak and the effectiveness of control measures in the UK.

Introduction

The unexpected emergence and outbreak of coronavirus disease 2019 (COVID-19), caused by severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) (Lam et al., 2020; Lu et al., 2020a; Zhou et al., 2020), has caused a tremendous health burden and impact on the world economy. Early cases were reported in Wuhan, China in late December 2019 (Huang et al., 2020a; Li et al., 2020; Wang et al., 2020). Subsequently, geographical spread of the disease was expedited by the return-to-home migration during Chinese New Year, which led to reports of numerous successive outbreaks in other provinces of China (Jia et al., 2020; Kang et al., 2020).

The World Health Organization (WHO) declared a Public Health Emergency of International Concern on 30 January 2020. Although great efforts were made to contain the disease, with only a few imported cases initially reported in Europe and North America in early February 2020, the outbreak soon became global. Outbreaks were reported almost simultaneously in Lombardy, Italy (Grasselli et al., 2020); Daegu, South Korea (Shim et al., 2020); and Qom, Iran (Safavi et al., 2020), and quickly spread to neighbouring countries. This resulted in WHO characterizing COVID-19 as a pandemic on 11 March 2020.

The first confirmed case in the UK was identified in York on 31 January 2020. This was followed by several cases reported sporadically between 1 and 27 February 2020. Most of these early cases had a clear overseas travel history, and they were quarantined and received immediate supportive care. As of 14 February 2020, eight of the nine confirmed cases had recovered. However, the number of confirmed cases in the four nations (England, Scotland, Wales and Northern Ireland) of the UK began to increase rapidly from 28 February 2020.

Initially, London was the most severely affected, where the confirmed number of cases accounted for almost one-third of the total in England by 31 March 2020. Local transmission chains were identified between large cities and neighbouring towns and rural areas in almost every region of the UK by the end of May 2020. The death toll increased along with the number of cases, resulting in the UK overtaking Italy as the country with the highest death toll in

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Europe and the second highest in the world on 5 May 2020. As of 24 June 2020, there had been over 306,000 confirmed cases of COVID-19 and almost 43,000 deaths in the UK.

Although the majority of infected patients show mild symptoms (Chen et al., 2020), including fever and cough (Guan et al., 2020), some patients develop critical symptoms following hospital admission with likely immune-mediated and aggravated disease (Ye et al., 2020). No effective treatment options have been identified definitively, as demonstrated by well-designed randomized controlled trials (Zhai et al., 2020), and clinical trials of candidate SARS-CoV-2 vaccines are still in their early stages (Zhu et al., 2020). Thus, the lack of pharmaceutical interventions, together with the high transmissibility of the virus, was clearly exacerbating the COVID-19 pandemic in the UK and elsewhere (Huang et al., 2020b).

In addition, it is still unclear whether and how SARS-CoV-2 will circulate and interact with other seasonal human coronaviruses, in the UK and globally, and to what extent it may become seasonal (HCoV-229E, HCoV-NL63, HCoV-OC43 and HCoV-HKU1) (Liu et al., 2020; Shi et al., 2020; Xie and Zhu, 2020; Yao et al., 2020). Nevertheless, given the ongoing COVID-19 activities in tropical regions, it is now very unlikely that the current UK epidemic will end naturally during the summer. Therefore, identifying effective, practical and economic public health interventions, both for now and in the future, will be critical to contain the spread of the virus and alleviate the pressure on healthcare systems.

The Chinese Government banned all transportation to and from Wuhan on 23 January 2020 and subsequently closed the border of remaining cities in Hubei Province. Similar measures aimed to reduce human mobility were issued in other Chinese cities, and have been shown to mitigate the spread of infection (Kraemer et al., 2020; Tian et al., 2020). In Europe, Italy was the first country to implement a national lockdown on 11 March 2020. This was followed by Spain on 15 March and France on 17 March, and finally the UK on 23 March (https://www.gov.uk/government/speeches/pm-address-to-the-nation-on-coronavirus-23-march-2020).
These measures eventually proved to be effective in curtailing local COVID-19 outbreaks in these countries by reducing the effective reproduction number to <1 (Aleta and Moreno, 2020; Gatto et al., 2020; Kwok et al., 2020).

Therefore, exploring the transmission dynamics of SARS-CoV-2 and investigating the effectiveness of various control measures is important to acquire better understanding of this ongoing pandemic to develop and improve public health intervention policies. Studies focusing on China, Continental Europe and North America (e.g. Kucharski et al., 2020; Leung et al., 2020; Liang, 2020; Linka et al., 2020; Pan et al., 2020; Wu et al., 2020; Yang et al., 2020; Zhang et al., 2020) have been performed, but few studies have analysed the UK COVID-19 epidemic specifically in terms of local transmission dynamics and evaluation of control measures.

This study applied a Bayesian SEIR (susceptible–exposed–infected–removed) epidemiological model that incorporates internal migration data and the regional daily number of laboratory-confirmed cases to reveal local epidemic progression of COVID-19 in nine regions of England: East Midlands, East of England, London, North East, North West, South East, South West, West Midlands, and Yorkshire and the Humber. The regional basic reproduction number (R_0) and temporally varying effective reproduction number (R_t) were estimated by a sequential Monte Carlo method to identify the effectiveness of control measures. In addition, forecasts are provided for the number of daily cases for these nine regions.

Methods

Data sources

Two datasets were used in this study to rebuild the transmission dynamics of the COVID-19 epidemic in England: the daily number of laboratory-confirmed cases between 27 February and 31 May 2020, collected from the publicly available dashboard provided by Public Health England (PHE; https://coronavirus.data.gov.uk/); and the internal migration data collected from the UK Office of National Statistics (https://www.ons.gov.uk/).

PHE publishes a case dataset that comprises the number of laboratory-confirmed cases of COVID-19 within different types of administrative areas of England (i.e. region, upper-tier local authority and lower-tier local authority).

The laboratory-confirmed cases were identified in local National Health Service laboratories by testing specimens from people eligible for SARS-CoV-2 testing, according to the national guidance active at that time. The geographical location of each specimen was tracked by the home postcode of the person being tested. If repeat tests were conducted, the date when the first positive test occurred was recorded. Redundant tests from the same person were removed so there was no double record. Cases were aggregated according to the corresponding administrative area. Not all local authorities had complete records, and some administrative regions were too small and did not seem to have significant or continuous outbreaks. Therefore, this study focused on regional level data.

The model used in this study only considered local transmissions; therefore, cases reported prior to 27 February 2020 (the

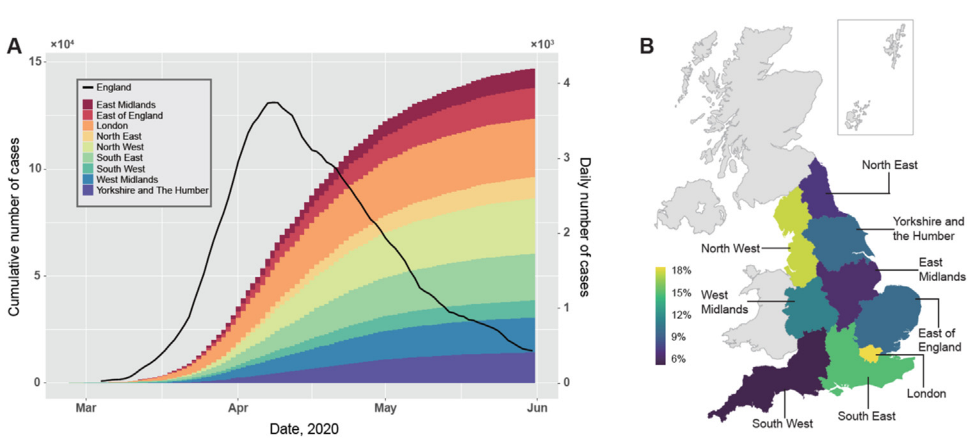

Figure 1. (A) Regional cumulative number of laboratory-confirmed cases of coronavirus disease 2019 (COVID-19) in England, and the corresponding national daily number of confirmed cases, calculated using a 7-day moving average. (B) Geographical distribution of regional proportion of cumulative number of laboratory-confirmed cases of COVID-19 as of 31 May 2020 in England.

date when local transmission was considered to commence) were excluded. It should be noted that data were not always up-to-date as some community test results would have been delayed (including care home figures). Therefore, the daily numbers of laboratory-confirmed cases from all nine regions were collated on 7 June 2020 (1 week after the last date of collected data) and are shown in Figure 1. It is likely that the epidemic peak in England was reached on 8 April 2020. By 1 June 2020, the highest number of cumulative cases had occurred in London (18.4%), followed by the North West (17.6%).

Annual mid-year internal migration (i.e. residential moves across the boundaries of the nine English regions) data were used to account for movement of the population between regions when modelling disease transmission. The latest available annual data, from 2018, were used. Inflow and outflow data were aggregated across sex and age. In order to have a constant population size in the model, the inflow and outflow data involved in the model were transformed so that they were both equal to the mean of the observed inflow and outflow data.

Mathematical model

A SEIR compartmental model, which is widely used in infectious disease modelling to describe transmission dynamics within a community, was applied in this study. The model divides the population into susceptible (S), exposed (E; but not infectious), infected (I) and removed (R) compartments, and people progress between these disease states which have been clinically described elsewhere (Guan et al., 2020; Huang et al., 2020a; Wang et al., 2020).

The early advice from PHE was targeted at those who exhibited COVID-19 symptoms, and recommended that they should stay at home and self-isolate. However, several studies had already reported the existence of asymptomatic COVID-19 cases (Cai et al., 2020; Lu et al., 2020b), so it was very likely that an unknown proportion of the population in England had been infected and recovered from COVID-19 without ever being diagnosed or tested. Hence, people in the infected (I) compartment were divided into two groups: a diagnosed group (I_a), representing people who had severe symptoms and were subsequently diagnosed; and an undiagnosed group (I_b), representing people who may have recovered without being diagnosed due to mild symptoms. The proportions of hospitalized and community patients are significant (Bird et al., 2020; Tang et al., 2020). It was assumed that a proportion δ of the exposed population will enter I_a, and a uniform prior distribution U[0,1] is used to account for uncertainty about δ. Equations of changes in each compartment are set as follows:

$$\begin{aligned}\frac{dS(t)}{dt} &= -\frac{\beta(t)I(t)}{N}S(t) + L_{in} - L_{out}\frac{S(t)}{N-I_a(t)},\\ \frac{dE(t)}{dt} &= \frac{\beta(t)I(t)}{N}S(t) - \eta E(t) - L_{out}\frac{E(t)}{N-I_a(t)},\\ \frac{dI_a(t)}{dt} &= \delta\eta E(t) - \mu I_a(t),\\ \frac{dI_b(t)}{dt} &= (1-\delta)\eta E(t) - \mu I_b(t) - L_{out}\frac{I_b(t)}{N-I_a(t)},\\ \frac{dR(t)}{dt} &= \mu(I_a(t)+I_b(t)) - L_{out}\frac{R(t)}{N-I_a(t)},\end{aligned} \tag{1}$$

where it is assumed that there are no imported cases. In addition to the compartment model, a testing module was added to account for the reporting delay:

$$\begin{aligned}\frac{dW(t)}{dt} &= \delta\sigma E(t) - \rho W(t),\\ \frac{dC(t)}{dt} &= \rho W(t).\end{aligned} \tag{2}$$

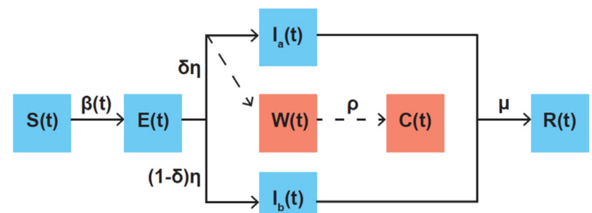

Figure 2. Augmented susceptible–exposed–infected–removed (SEIR) structure. The SEIR module and transitions are indicated by blue squares and solid lines; and the testing module and transitions are indicated by red squares and dashed lines.

The model is depicted in Figure 2. In this model, N is the total population size of the region of interest. $S(t)$, $E(t)$, $I(t)$ and $R(t)$ are the numbers of susceptible, exposed, infectious and removed people at time t, respectively. L_{in} and L_{out} are the inflow and outflow inferred from the internal migration dataset, respectively, and it was assumed that inflow and outflow stopped after the national lockdown. It was assumed that people show symptoms once they enter I_a. $W(t)$ is the number of people who are waiting for their test result after showing symptoms at time t. $C(t)$ is the estimated cumulative number of cases, η is the rate of being infectious (i.e. inverse of the incubation period), μ is the rate of recovery (i.e. inverse of the infectious period, which equals the mean serial interval minus the incubation period) (Lipsitch et al., 2003), and $1/\rho$ is the number of days between showing symptoms and receiving test results. $1/\eta$ was set as 5.2 days and $1/\mu$ was set as 2.3 days according to estimates from a comprehensive study of the early transmission dynamics of COVID-19 (Li et al., 2020). $1/\rho$ was set as 4 based on estimates from Chen et al. (2020). Following Kucharski et al. (2020), a temporally varying transmission rate $\beta(t)$ that follows a log-normal sequential update was assumed [i.e. $\log(\beta(t)) \sim \mathbf{N}(\log(\beta(t-1)),\sigma)$, given standard deviation σ], and the effective reproduction number R_t at time t was approximated by (see online Supplementary material):

$$\widehat{R}_t = \frac{\beta(t)S(t)}{\mu N}. \tag{3}$$

A Poisson generating model was assumed for the observed daily number of laboratory-confirmed cases $Y(t)$, given R_0 and transmission rate $\beta_{1:t}$ from the start to time t:

$$P(Y(t)|R_0,\beta_{1:t}) \sim \mathbf{Pois}(\rho W(t)). \tag{4}$$

To account for the early period when the virus started to seed in each region of England before the public became aware, a preliminary model similar to Eq. (1) was run, except with a constant β derived from R_0. The preliminary model assumes that a single infected person enters the region of interest 14 days before the date of the first confirmed local case after 27 February 2020.

Analysis was conducted using R Version 4.0. The sequential Monte Carlo method was used to draw samples of R_0, and $\beta_{1:t}$ from the posterior distribution, where the optimal standard deviation σ that gives the highest likelihood was selected by an exhaustive search. Sensitivity analysis is available in the online Supplementary material.

Results and discussion

Basic reproduction number

R_0 is an important parameter that quantifies disease transmissibility at the start of an epidemic. Estimated R_0 numbers for each of the nine regions are listed in Table 1 (histograms of the posterior samples are shown in Figure S1, see online Supplementary

Table 1
Estimated basic reproduction number (R_0) and corresponding 95% credible interval (CI) in each English region.

Region	Median R_0	95% CI (lower)	95% CI (upper)
East Midlands	3.2	2.4	5.3
East of England	3.2	2.7	4.6
London	3.9	3.4	5.3
North East	2.8	2.1	4.7
North West	3.6	3.0	5.2
South East	3.9	3.0	5.5
South West	3.9	3.4	4.7
West Midlands	3.5	2.8	5.2
Yorkshire and the Humber	3.0	2.5	4.5

material). All regions have R_0 between 2.8 and 3.9, which is significantly higher than 1.

Notably, estimated R_0 numbers were found to be positively correlated with population size in each region. Spearman's rank correlation was 0.77, which is significantly higher than 0 ($P < 0.05$). These estimates were relatively high (seven of the nine regions had median values >3) compared with the early estimate in China by WHO (1.4–2.5), although a high R_0 (3.8–8.9) was also reported in China more recently (Sanche et al., 2020).

Compared with other major airborne viruses, SARS-CoV-2 in England has an estimated R_0 similar to that of SARS-CoV-1 but significantly higher than that of Middle East respiratory syndrome coronavirus (MERS-CoV) and other human influenza viruses (Chen, 2020). This indicates that SARS-CoV-2 has very strong transmissibility in the early stages, and the infected population size will expand rapidly without human intervention in all nine regions. The estimates of R_0 in England are largely consistent with estimates from other major European countries (e.g. Italy: 3.49–3.84; France: 3.1–3.3) (Distante et al., 2020; Gatto et al., 2020; Roques et al., 2020; Yuan et al., 2020). This might explain the rapid spread and high pandemic potential of COVID-19 when relatively few control measures were implemented in Europe.

Effectiveness of control measures

On 25 February 2020, the UK Government announced its general strategy, which aimed to reduce the impact of the disease by four successive phases: contain; delay; research; and mitigate. The respective aims of these four phases were to: detect, trace and isolate early cases; slow the spread and delay the peak until warmer months; develop diagnostic tests, drugs and vaccines; and save lives and maintain nationwide order once the disease is widespread. This announcement was followed by advice that travellers from heavily hit countries should self-isolate. On 12 March, the UK Government started to issue policies for local residents, advising those with respiratory symptoms to self-isolate at home.

After the release of the controversial herd immunity strategy, the UK Government advised people against 'non-essential' travel and use of public entertainment venues on 16 March 2020. This was followed by the closure of all pubs, cafes, restaurants, bars, gyms, etc. on 20 March 2020. On 23 March 2020, a restrictive national lockdown was announced by the UK Government, and the police force was provided with powers to ensure compliance on 26 March 2020.

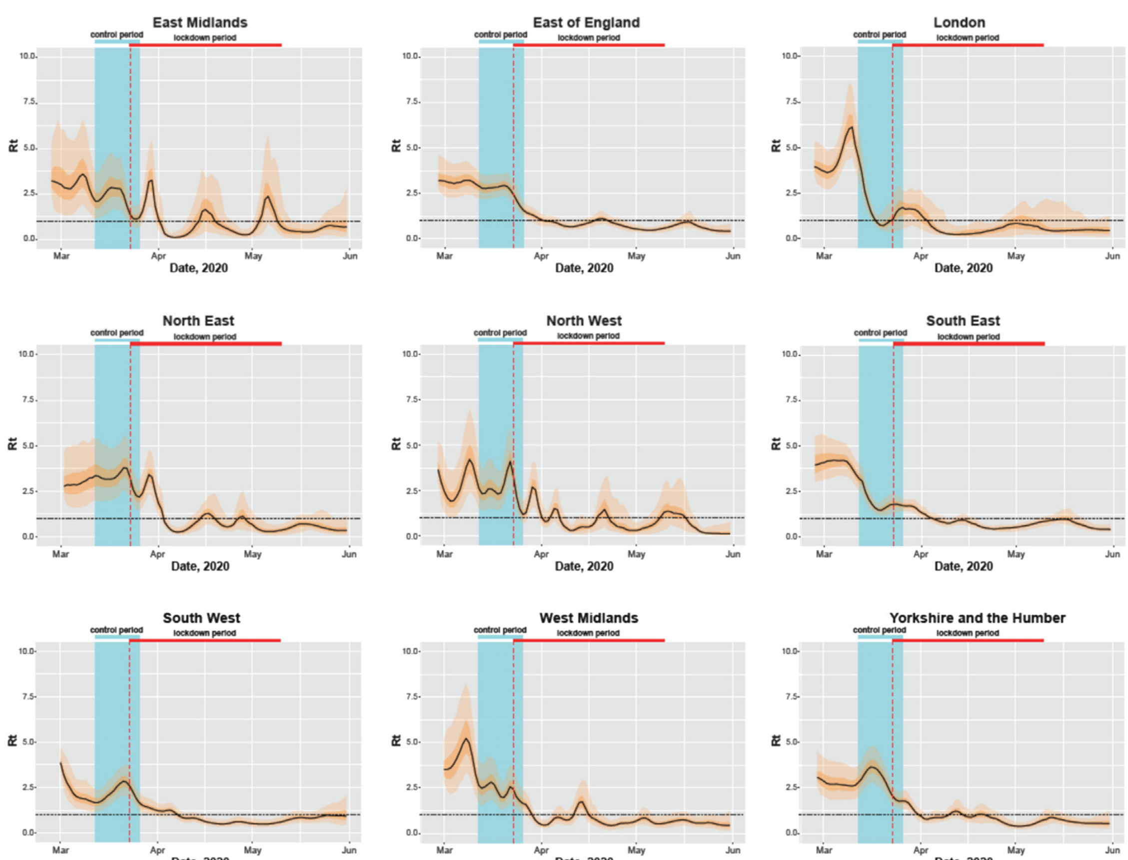

Figure 3. Temporal dynamics of effective reproduction number (R_t) estimates based on the daily number of laboratory-confirmed cases of coronavirus disease 2019 (COVID-19) between 27 February and 31 May 2020 in nine English regions. The light and dark shaded areas are 95% credible intervals and interquartile ranges, respectively. Vertical blue shaded areas indicate the control period (12–26 March 2020). Vertical red dashed lines mark the start of national lockdown (23 March 2020). Horizontal black dashed lines mark the epidemic threshold R_t = 1.

From this time, people were only allowed to leave their homes for limited reasons, gatherings of more than two people were forbidden, and social distancing was required in shops. Use of public transport declined significantly during the lockdown period. Control measures began to ease gradually from 10 May 2020 when the UK Government allowed certain groups of people to work and encouraged outdoor exercise, yet people were warned to 'stay alert'. Given these measures, the control period was defined in this paper as 12–26 March 2020 and the lockdown period was defined as 26 March–10 May 2020.

Estimated R_t numbers are shown in Figure 3. For all nine English regions, R_t exhibited an overall decreasing trend during the control period. London, West Midlands and South East showed a mostly decreasing R_t during the control period. In the remaining regions, although R_t increased or oscillated at the beginning of the control period when measures were largely mild suggestions, it started to decrease when the more restrictive and forceful national lockdown was implemented. This reveals the effectiveness of issuing forceful control measures to contain an epidemic. Although R_t numbers in East Midlands, North East and North West rose after the control period, it subsequently decreased towards 1 within 1 week for all regions. These transmission dynamics patterns are also consistent with some country-level estimates in the literature (Kwok et al., 2020).

In general, the control measures issued in England in March 2020 were effective to contain the spread of COVID-19 in all nine English regions. This finding is consistent with a previous study which investigated the effect of the reduction of social contacts on transmissibility based on surveys (Jarvis et al., 2020). It is noteworthy that R_t remained slightly <1 during most of the lockdown period, rather than diminishing to 0. This suggests that local transmissions were maintained, possibly in small towns and communities, although the overall epidemic was contained, and the virus might have circulated between different areas within each English region.

Estimation of the daily number of new cases

To verify the model, the estimated daily number of cases was compared with the observed daily number of confirmed cases. The result is shown in Figure 4 (estimates of the number of infected population and susceptible population are shown in Figure S2, see online Supplementary material). Although the observed number fluctuates over time, the overall trend in daily cases is well captured by the model.

Broadly, the daily number of confirmed cases in the nine English regions peaked in early April 2020. Notably, London was the first region where the daily number of new cases rose rapidly in early March 2020. The study findings highlight the serious epidemic in London during the early phase. This may have been because London receives the highest proportion of inbound visitors from other English regions, and is the most densely populated area among all English regions. In addition, a constantly high daily number of cases was maintained in Yorkshire and the Humber in April 2020, as more infected population may have been seeded prior to lockdown, resulting in transmission to their household contacts during lockdown. This may explain the delay in the reduction of R_t. The daily number of cases in two regions of the Midlands increased briefly in late April 2020, but this started to decline from the beginning of May 2020. The daily number of cases in the remaining regions declined during late April and May 2020. These results correspond with the authors' previous estimate that R_t was generally <1 during the lockdown period. This indicates the effectiveness of the control measures in all regions.

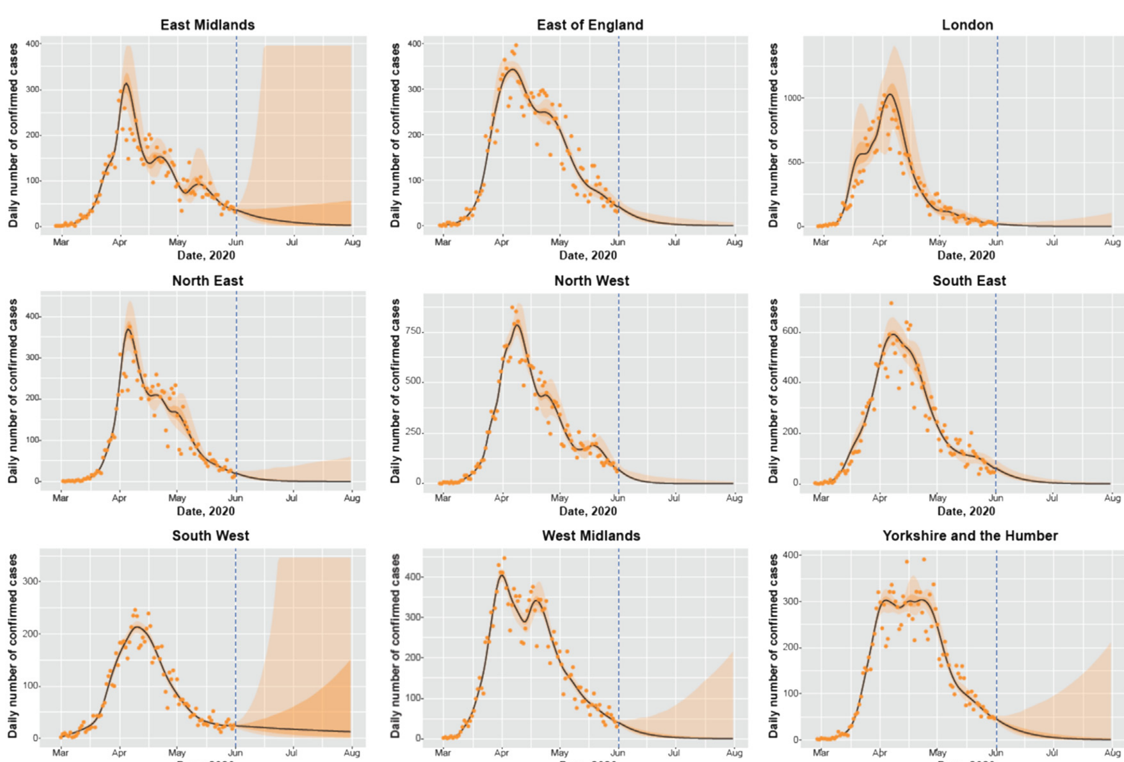

Figure 4. Estimates and forecasting of the daily number of confirmed cases of coronavirus disease 2019 (COVID-19) based on data between 27 February and 31 May 2020 in nine English regions. The light and dark shaded areas are 95% credible intervals and interquartile ranges, respectively. Dots mark the observed daily number of confirmed cases. Vertical blue dashed lines mark the last date of collected data (31 May 2020). Forecasted results are to the right of the dashed lines.

Forecasting potential second wave outbreaks

In model forecasting, it was assumed that R_t stayed constant after 31 May 2020, and the posterior samples of R_t on that day were used to forecast the daily number of confirmed cases in June and July 2020. As the lockdown was lifted on 1 June 2020, it was assumed that inflow and outflow of the population would restart. Relevant results are shown in Figure 4.

Although the daily number of new cases is expected to decrease in most regions, it is estimated that, except in the East of England, North West and South East where R_t remains significantly <1, other regions may witness a second wave of outbreaks.

In particular, East Midlands, South West, West Midlands, and Yorkshire and the Humber may experience a rebound in incidence after June 2020, as projected by the upper 95% credible interval of the daily number of new cases (which may go up to ≥40% of the number at the March/April peak).

Notably, Leicester (East Midlands: BBC News, 2020a) and Cleckheaton (Yorkshire: BBC News, 2020b) recently reported surges in cases, which corroborates the model forecast. Moreover, as the estimated R_t in the South West includes high values on 31 May 2020, it will likely maintain a relatively high median number of infected population until August 2020 (>100 individuals). While the UK Government has been considering lifting some control measures to restore the economy, particular attention should be paid to regions at risk of a second wave.

Conclusion

This study demonstrated the use of a Bayesian SEIR model to reconstruct the transmission dynamics of COVID-19 in nine English regions. Although the true dynamics of transmission of COVID-19 is a complex process, the estimated daily number of cases closely follows the trend of the observed daily number of cases, indicating the validity of the model. The findings show that R_0 in England is generally higher compared with China but is in line with some major European countries. The effective reproduction number estimates present a temporally varying trend of transmissibility. The present results suggest that transmissibility of COVID-19 was reduced effectively by the control measures adopted by the UK Government. This led to a decline in the number of infected population in May 2020. Notably, although critics may argue that restriction of the free movement of people violates basic human rights when milder measures such as social distancing can be equally useful, such strict measures within a national lockdown were efficient to contain transmission in some regions. The forecasting data highlight the possibility of early secondary outbreaks, so close monitoring of the rate of transmission and R_t will be required after the lockdown measures are lifted.

Ethical approval

Not required.

Conflict of interest

None declared.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ijid.2020.12.055.

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