

Acceleration of plague outbreaks in the second pandemic

Electronic Supplemental Information

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March 12, 2020 @ 13:42

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1 Historical human population estimates for London

Table S1: Population estimates for London previously published by Finlay (1, 2)(3, p.108) and Creighton (4, p.660). These data are plotted in Figure S1.

Year	Population	Source
1340	45,000	Finlay
1500	50,000	Finlay
1550	110,000	Finlay
1600	180,000	Finlay
1603	250,000	Creighton
1625	320,000	Creighton
1650	340,000	Finlay
1665	460,000	Creighton
1700	445,000	Finlay

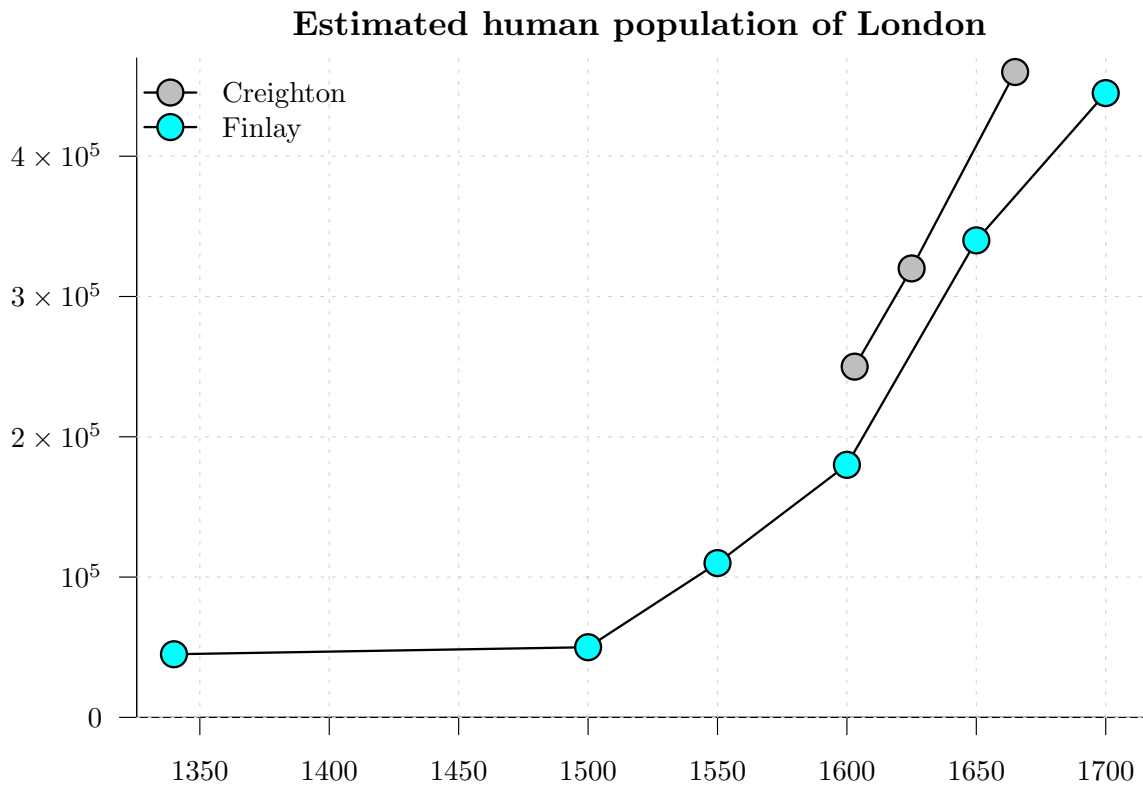


Figure S1: Historical population of London, England, as estimated by Finlay (1, 2) (Table S1). Earlier estimates of Creighton (4, p.660) are shown for the specific plague years 1603, 1625 and 1665.

2 Disease-related data sources

Table S2 lists our data sources. Below we provide a few additional comments and details not described in the text of the main paper.

Table S2: Disease-related data used in this paper.

Epoch	Year range	Data type	Frequency	Source
Early	1340–1380	Last Wills and Testaments	Daily	Court of Husting
Late	1540–1680	Last Wills and Testaments	Daily	Prerogative Court of Canterbury (PCC)
	1540–1680	Mortality from all causes	Weekly	Parish records
	1563–1666	Mortality from plague	Weekly	London Bills of Mortality (LBoM)

2.1 Last wills and testaments

London 1348–1375: Cohn (5) presents his monthly counts of wills (proved by the Court of Husting, London (6)) in his Figures 7.33 (1348), 7.34 (1361) and 7.35 (1375); Cohn does not show data for 1368. Monthly aggregations of our daily counts agree nearly perfectly with Cohn’s plots for the three epidemics he studied. Most of the slight discrepancies are probably attributable to a small number of wills that were written during the plague epidemics but probated much later (so not included by Cohn (5)).

London 1384–1678: The wills proved by the Prerogative Court of Canterbury (PCC) provide a substantial sample of London wills, but certainly not all the wills written by Londoners at the time, as the following quote from the National Archives website makes clear.

“Most people who left a will used the appropriate church court. The Prerogative Court of Canterbury was the highest church court in England and Wales until 1858, when the national court was established, but even in the late 1850s it was only proving about 40% of the national total of 21,653 wills.

Until 1858 there were more than 200 church courts each of which kept separate registers of wills – there was no central index.

...

Wills proved in the Prerogative Court of Canterbury (PCC) mainly relate to testators resident in the south of England, although all parts of England and Wales are represented in the records.”

– The UK National Archives

Before the 17th century, the number of PCC wills is too small to detect an epidemic signal (see the PCC wills plotted in the top two panels of [Figure S6](#), which we have not used for growth rate estimates). Consequently, studying potential plague epidemics in the 15th century—after the period when many London wills were probated in the Court of Husting and before many London wills were probated in the Court of Canterbury—would probably require analysis of the records of a substantial fraction of church courts. Creighton (4, Ch. IV) gives numerous historical references that indicate specific plague epidemics in London between 1375 and 1540. Unfortunately, none of these sources provides an outbreak time series, so there is no possibility of estimating epidemic growth rates.

2.2 Will dates vs. probate dates

The Calendar of Wills probated in the Court of Husting (6) is organized by court dates, so every will is associated with a definite date on which it was probated; in contrast, only 64% of the wills provide information on the date of writing (7). Despite this lower sample size and the fact that wills were in some cases written long before death, dates of writing actually provide a much more plausible representation of the epidemic patterns in the 14th century than probate dates ([Figure S2](#)). Graphs in the main text ([Figures 1 to 3](#)) are based on counts of wills written. See “[Wills and testaments](#)” in the Data section of the main text for further discussion.

2.3 London Bills of Mortality (LBoM)

London 1563–1583: The earliest weekly plague mortality records are tabulated by Creighton (4) for 1563–1564 (4, p. 305) and 1578–1583 (4, p. 341–344).

London 1593: The extant records of weekly plague mortality in London in 1593 ([Figure S6](#), second panel) are implausible. One possibility is that many earlier deaths were added to the counts for two of the weeks in July, but there is no way to be sure. Creighton (4, pp. 351–360) discusses all the data ever found for the epidemic of plague in 1592–1593, states that the weekly data probably originate from marginal notes in a broadside of 1603, and comments (p. 354) that “the weekly mortalities in it for those weeks that had little plague are an absurdity for 1593. Whatever the source of this table, it is not genuine for 1593 ...”

London 1603–1680: Creighton (4) tabulates data for 1606–1610 (4, p. 494) and 1636 (4, p. 530). Bell (8) and Creighton (4) both tabulate weekly mortality from 1605 to the end of 1665, which includes the majority of the Great Plague in 1665–1666 (4, p. 662). We entered all weekly mortality data from 1662 to 1680 directly from the London Bills of Mortality.

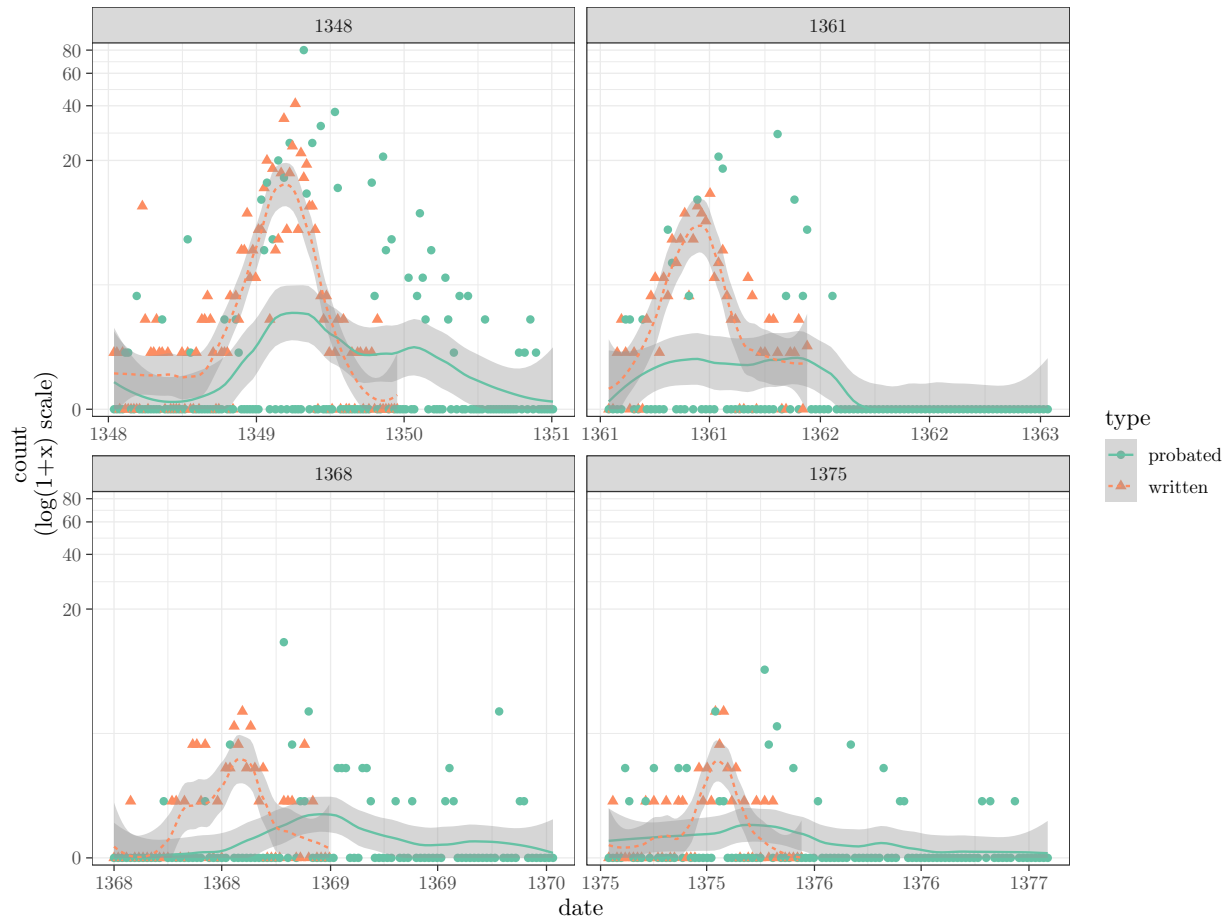


Figure S2: Counts of wills written vs. wills probated during each of the four 14th century plague epidemics in London, based on wills probated in the Court of Husting (6). Smooth lines represent loess fits with $\text{span}=0.5$ (shaded regions are 95% confidence intervals).

2.4 Parish registers

Cummins *et al.* (9) obtained parish register data from ancestry.com and have made the weekly counts of deaths available at <http://neilcummins.com>. For the 16th and 17th century epidemics, the parish data provide a third source. For 1593, these are the only reliable data (we consider them to be reliable because they are part of a continuous weekly time series from 1538 onwards).

2.5 Major vs minor plague epidemics

Figure S3 shows all weekly reports of plague deaths from the LBoM from 1563 to 1666, scaled by population size (estimated by interpolating from Table S1). Epidemics with peak plague mortality above 5 per 1000 individuals per week were classified as *major*. With the exception of 1593 (for which we do not use LBoM data; see above), all these major epidemics peak above 14 on this scale; all the other (*minor*) epidemics peak below 3. The raw plague

mortality data are shown in [Figure S4](#).

We classify all the 14th century epidemics as ‘major’, although we do not have appropriate data to distinguish major from minor epidemics in this early epoch.

Weekly time series for all the major epidemics are shown in [Figures S5](#) and [S6](#).

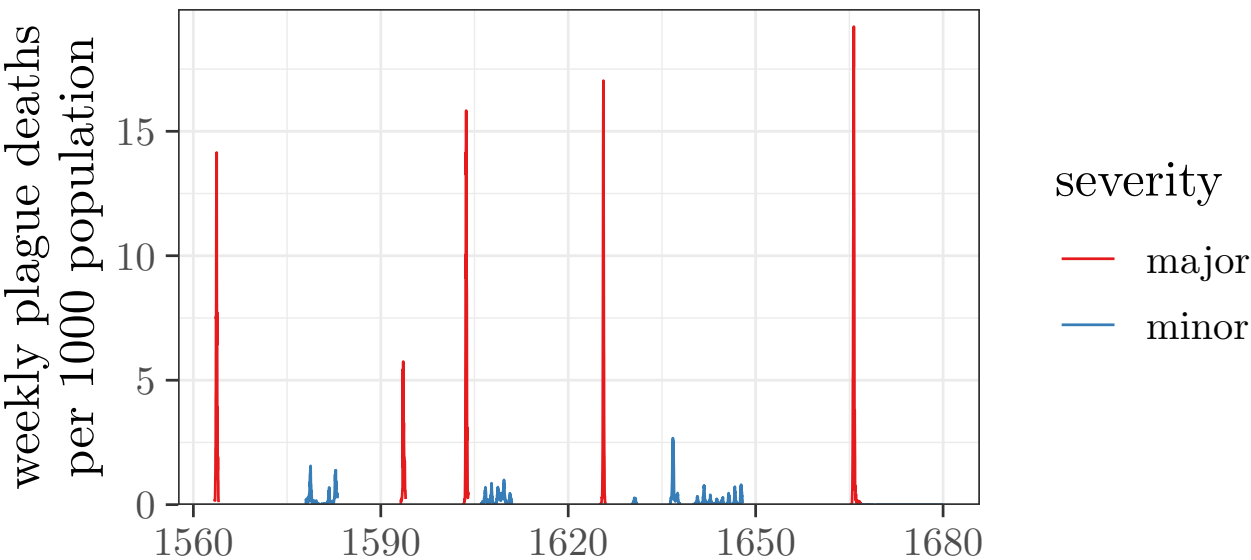


Figure S3: Plague deaths per 1000 persons per week, from 1563 to 1666. Epidemics that exceeded 5 on this scale were classified as *major*. Analysis of the major epidemics is shown in [Table S4](#) and [Figures 2](#) and [3](#). Corresponding analyses of all of the minor epidemics are presented in [Table S6](#) and [Figure S8](#).

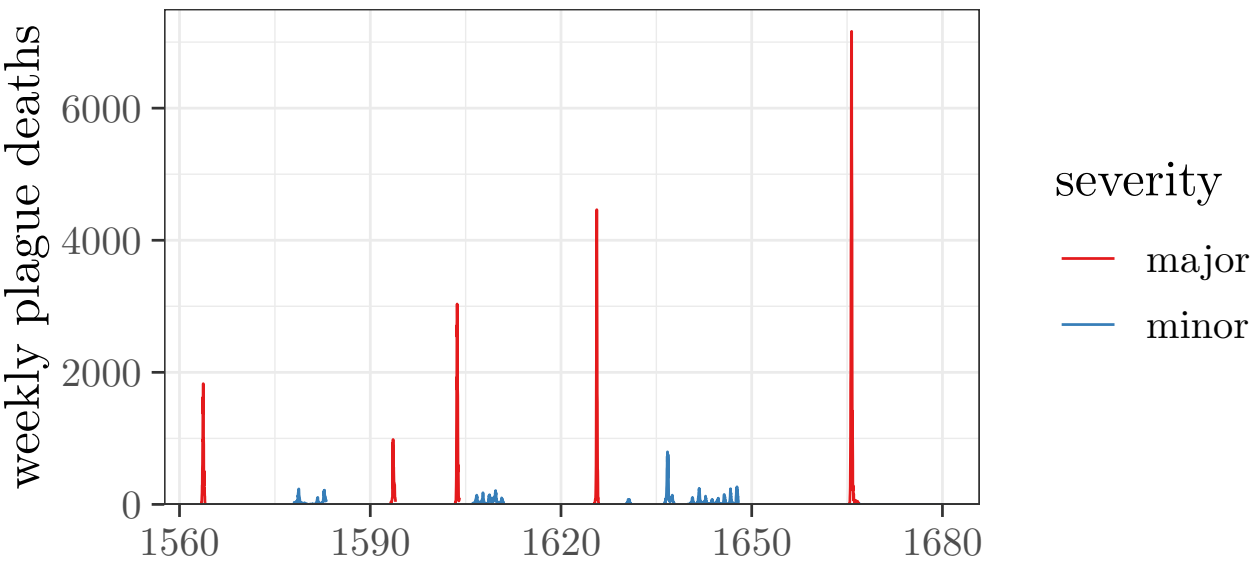


Figure S4: All plague deaths reported in London from 1563 to 1666.

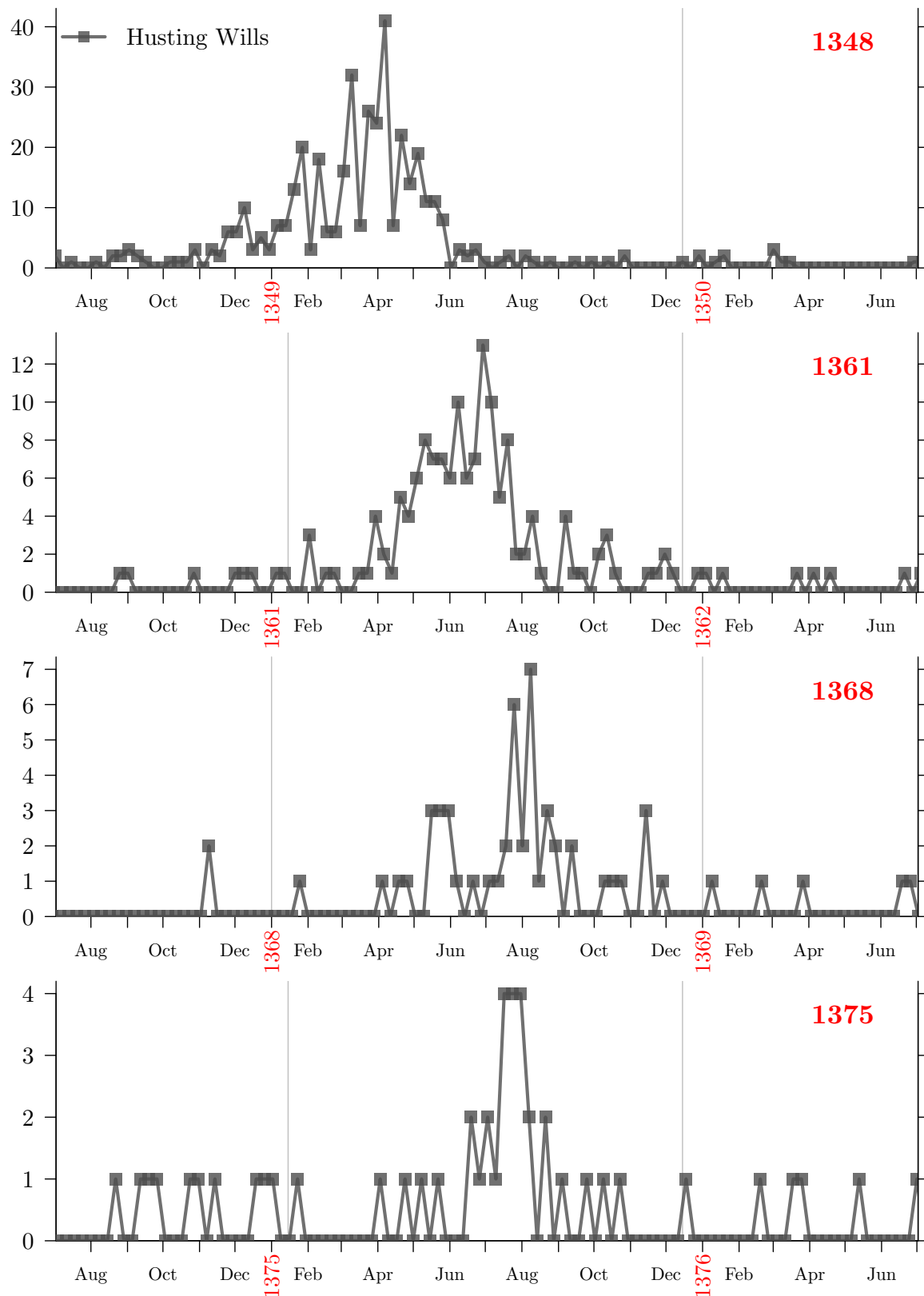


Figure S5: Weekly numbers of wills written during plague epidemics in London, England, in the 14th century. Vertical grey lines indicate the “outbreak window” specified in [Table S7](#).

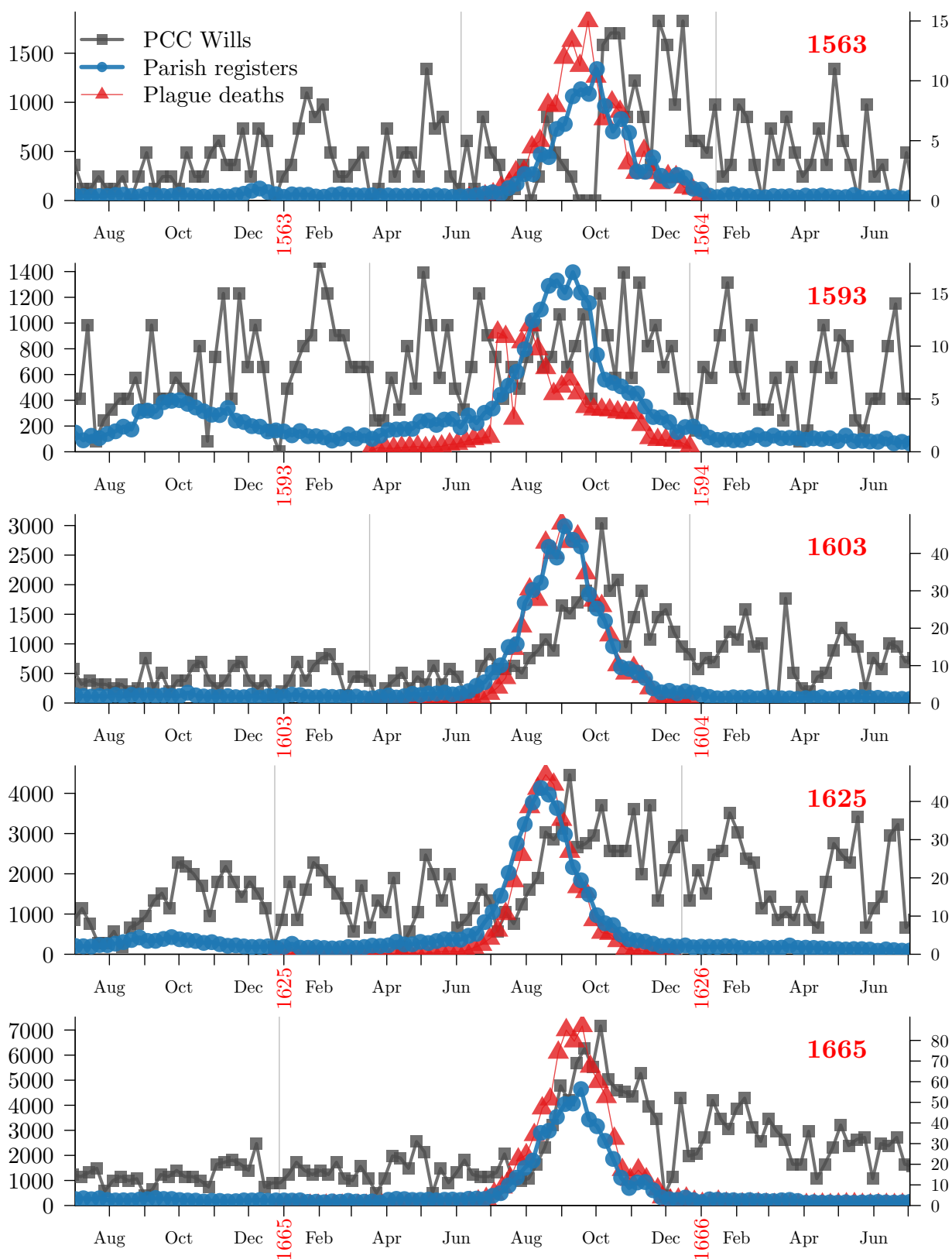


Figure S6: Weekly deaths and numbers of wills written during major plague epidemics in London, England, since 1540. For each epidemic, vertical grey lines indicate the beginning and end of the period during which deaths from plague were listed in the bills of mortality. The left (right) scale refers to deaths (wills).

3 Generation interval for bubonic plague

For pneumonic plague, sufficiently detailed data exist for a number of modern outbreaks to allow an estimate of the latent and infectious periods (and hence of the generation interval distribution) (10), which we can use to estimate \mathcal{R}_0 for a given value of r . Much less data is available for bubonic plague; in addition, the more complex host-vector life cycle of bubonic plague complicates the estimation of the generation interval. However, we can say that the elapsed time between the onset of infectiousness of a rat and the time when a rat in the next epidemic cycle becomes infectious is:

$$\begin{aligned} & \text{rat} \rightarrow \text{flea infection time} \\ & + \max(\text{flea incubation period}, \{\text{time to rat death} + \text{flea searching time}\}) \\ & + \text{flea} \rightarrow \text{rat infection time} \\ & + \text{rat incubation period} \end{aligned} \quad (\text{S1})$$

From (11), we can gather that

- fleas bite rats ≈ 4 times/day; the rat \rightarrow flea infection probability is ≈ 0.2 and the flea \rightarrow rat infection probability is ≈ 0.28 , suggesting that both the rat \rightarrow flea and flea \rightarrow rat infection times are ≈ 1 day;
- the rat infectious period (time until infected rats die) is ≈ 4 days ((11) cite (12) for this value; (13) give a value of ≈ 18 days, which seems unrealistically long — another source, (14), gives values ranging from ≈ 4 –9 days)
- the flea incubation period is long (but very variable), ranging from 9–26 days ((11), citing (15))
- the flea searching time is not explicitly defined by (11), but we guess it is relatively short (< 1 –2 days)
- (11) give a value of ≈ 1 –3 days for the rat incubation period

Since the flea incubation period is typically longer than the combination of rat death time and flea searching time (9–26 days vs. (4–9 + 1–2) days), we can approximate the generation interval as $\approx (1 \text{ day}) + (9\text{--}26 \text{ days}) + (1 \text{ day}) + (1\text{--}3 \text{ days})$; we use a value of $T_g = 18$ days in the main text.

4 Relationship between rat density and \mathcal{R}_0 (in rats)

One factor that might have contributed to the observed increase in epidemic growth rates in London is the density of rats. We do not have data that allow us to estimate rat densities in Medieval England, but we can ask—all else being equal—by what factor would rat density have to have changed in order to account for the observed change in growth rates?

In the idealized situation in which the generation interval is exponentially distributed (as in the standard SIR model) then (16), as mentioned in the Discussion in the main text,

$$r = \frac{\mathcal{R}_0 - 1}{T_g}, \quad (\text{S2})$$

where T_g is the mean generation interval. Consequently, if this simple relationship holds and the mean generation interval *does not change*, then a change in growth rate $r_1 \rightarrow r_2$ implies a change in basic reproduction number $\mathcal{R}_{0,1} \rightarrow \mathcal{R}_{0,2}$, where

$$\frac{\mathcal{R}_{0,2}}{\mathcal{R}_{0,1}} = \frac{r_2 T_g + 1}{r_1 T_g + 1}. \quad (\text{S3})$$

If we assume the estimate of $T_g = 18$ days obtained in Section 3 above, and the MLE growth rates from early and late wills listed in Table S4, the relative change in reproduction number that needs explanation is

$$\frac{\mathcal{R}_{0,2}}{\mathcal{R}_{0,1}} \approx \frac{23 \cdot \frac{18}{365} + 1}{5.86 \cdot \frac{18}{365} + 1} \approx \frac{2.13}{1.29} \approx 1.65. \quad (\text{S4})$$

where the second subscript (1 or 2) denotes the early or late epoch, respectively.

Keeling and Gilligan (13, p. 2226) relate the basic reproduction number to rat density via

$$\mathcal{R}_0 = \frac{\beta_R K_F}{d_F} \left[1 - \exp(-a K_R) \right], \quad (\text{S5})$$

where β and K denote transmission rate and carrying capacity, respectively, and the subscripts F and R denote fleas and rats, respectively. Equation (S5) implies

$$\frac{\mathcal{R}_{0,2}}{\mathcal{R}_{0,1}} = \frac{1 - \exp(-a K_{R,2})}{1 - \exp(-a K_{R,1})}, \quad (\text{S6})$$

which, for $a K_{R,j} \ll 1$, simplifies to

$$\frac{\mathcal{R}_{0,2}}{\mathcal{R}_{0,1}} \approx \frac{K_{R,2}}{K_{R,1}}. \quad (\text{S7})$$

The approximation (appropriate in the limit $a K \rightarrow 0$) provides a lower bound to the true relationship, indicating that rat density would have had to increase by at least a factor of to account for a similar increase in \mathcal{R}_0 .

Figure S7 shows the exact relationship (S6) for several values of $a K_{R,1}$, together with the approximation for small $a K$ (S7). Keeling and Gilligan (13, Table 1, p. 2221) adopt values of a and K_R that yield $a K_R = 10$. If this is the correct order of magnitude for $a K_{R,1}$ then Equation (S6) implies that no increase in rat density would be sufficient to yield an increase in \mathcal{R}_0 by a factor of 1.7 (or any factor detectably greater than 1).

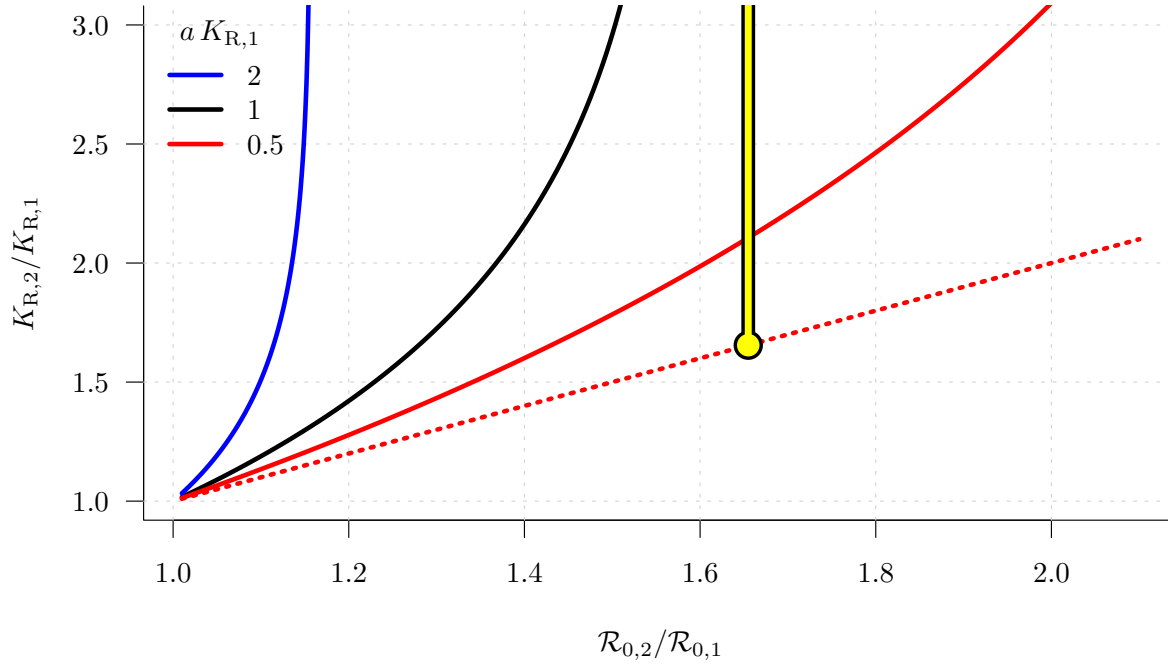


Figure S7: Relative change in rat carrying capacity K_R as a function of relative change in basic reproduction number \mathcal{R}_0 . Solid curves are based on Equation (S6). The dotted red line is based on Equation (S7). The 1.65-fold increase in \mathcal{R}_0 that requires explanation is indicated in yellow.

5 Effects of rat ecology on growth rates

In the Discussion in the main text, we listed “ecological and demographic changes” as a possible cause of acceleration of plague epidemics. Could changes in rat ecology plausibly have contributed to changes in epidemic growth rates?

As a vector-borne disease, the rate of bubonic plague spread is primarily affected by the flea-rat ratio. In the traditional Ross-MacDonald model for vector-borne epidemics, \mathcal{R}_0 is proportional to the square of vector-host ratio because vectors must independently bite hosts twice (once to become infected and a second time to infect a susceptible host). In the rat-flea model, \mathcal{R}_0 is instead proportional to V/H because *all* infected fleas on a host disperse and bite other hosts when their initial host dies. From Keeling and Gilligan’s plague model (13), the expected change in r for a change in flea-rat ratio from K_{F0} to K_F is $(K_F/K_{F0})^S$, where S is the sensitivity (≈ 1.5). Thus in order to see a fivefold increase in r we would need a change of $5^{(1/S)} \approx 2.9$, not in the rat density, but in the number of fleas per rat, which seems unlikely.

As noted in the main text, rat density has an additional, indirect effect on growth rate r and reproduction number \mathcal{R}_0 : increasing rat density will increase the probability that fleas leaving dying rats will find new, susceptible rat hosts. To crudely estimate the magnitude

of this effect, if we again consider Keeling and Gilligan’s model (13) then the maximum possible effect of rat density on \mathcal{R}_0 by this mechanism would be proportional (if fleas have very low success in finding new rat hosts). That is, in order for $\mathcal{R}_{0,B}$ to increase from ≈ 1.3 in the 14th century to ≈ 2.1 in the late epoch, rat density would have to increase by at least 62%. If fleas were already fairly successful at finding hosts in the 14th century, then changes in rat density would be expected to have only a small effect on \mathcal{R}_0 in rats.

6 Analysis of delays between wills and other sources

In order to determine the relative timing of epidemics recorded by different sources, we interpolated the parish data (which are recorded at different times from the LBoM) to find values corresponding to the LBoM dates. We quantify the relative timing in two different ways, (1) measuring the maximum cross-correlation and the lag at which this cross-correlation occurs, and (2) measuring the time difference between the epidemic peaks. As expected, the parish records are strongly correlated with LBoM (maximum correlation 0.97–0.996) and approximately synchronous (CCF lag 0–1 weeks, peak lag -0.7–1.1 weeks). The wills data are more weakly correlated (maximum correlation 0.49–0.73) and more delayed (CCF lag 3–10 weeks, peak lag 3.3–5.4 weeks).

Table S3: Observed cross-correlation and delay between London Bills of Mortality (LBoM) records and other sources. All lags measured in weeks. Rows corresponding to wills data are highlighted in grey.

source	outbreak year	CCF lag	max CCF	peak	peak lag
parish	1563	1	0.966	1563.75	1.07
parish	1603	0	0.993	1603.68	0.23
wills	1603	4	0.489	1603.78	5.45
parish	1625	0	0.986	1625.62	-0.68
wills	1625	10	0.486	1625.71	4.28
parish	1665	0	0.996	1665.70	0.15
wills	1665	3	0.726	1665.76	3.30

7 Details of numerical optimization

Robustly fitting phenomenological epidemic curves to small, noisy data sets proved to be surprisingly challenging¹. In the course of developing the full model we experimented with a range of optimizers — specifically the BFGS and Nelder-Mead options for R’s `optim` function as well as R’s `nlminb` function; we also tried an approach that iterated back and forth between Nelder-Mead and BFGS until convergence was achieved or the fit was sufficiently stable. We chose `nlminb` because it gave the best results (highest log likelihood) for point estimates.

¹See “monsters in the basement”, <https://redpenblackpen.tumblr.com/post/145304820562/monsters-in-the-basement>.

In general, we used the standard link functions proposed by Ma *et al.* (17), but we found that the scaled-tangent link proposed by (17) ($\eta = \tan((x/2 - 1) \cdot \pi/2)$) declined too slowly in the tails, leading to numerical instability; we replaced it with a more standard logit link ($\eta = \log(x/(1 - x))$).

With this approach we failed to achieve good (convergent) fits for only two combinations of source and outbreak year, both for minor outbreaks (London bills for 1578, Canterbury wills for 1581); these cases are excluded from the tables and figures shown below.

In the future, we would suggest that further work on reparameterization, including parameterizing the logistic by the time at which half of the final size is achieved rather than by the initial number infected, and possibly the reparameterization and regularization methods suggested by (18) for the Richards model, would be useful.

8 Supplementary tables cited in the main text

Table S4: Maximum likelihood estimates (MLEs) of the initial exponential growth rate (r) and doubling time ($(\log 2)/r$) with their 95% confidence intervals (CIs), obtained from the time series shown in Figure 2 (see [Methods](#)). The goodness of fit measure (R^2) is the proportional reduction in the mean squared error, *i.e.*, $1 - d^2/\sigma^2$ where d^2 is the model mean squared error and σ^2 is the (population) variance of the data; predictions and observations are aggregated to weekly before computing the R^2 for wills, for consistency among data sources. The implied basic reproduction numbers ($\mathcal{R}_{0,P}$) and attack rates (Z_P), assuming the generation interval distribution for Modern pneumonic plague (10), are also shown. All MLEs and associated CIs are shown in Figure 3.

Source	Epidemic	Growth rate [1/year]	Doubling time [days]	Assuming pneumonic plague		R^2
				$\mathcal{R}_{0,P}$	Attack rate Z_P	
Husting wills	1348	4.5 (3.4,6.2)	55.6 (41.1,74.1)	1.06 (1.04,1.09)	0.11 (0.08,0.16)	0.439
Husting wills	1361	9.2 (4.9,15.4)	27.5 (16.4,51.6)	1.14 (1.07,1.25)	0.23 (0.12,0.37)	0.693
Husting wills	1368	8.4 (3.3,21.7)	30.2 (11.7,77.2)	1.12 (1.04,1.38)	0.21 (0.08,0.49)	0.333
Husting wills	1375	20.3 (6.0,60.3)	12.5 (4.2,42.2)	1.35 (1.08,2.41)	0.47 (0.15,0.88)	0.669
London bills	1563	21.8 (20.1,23.7)	11.6 (10.7,12.6)	1.38 (1.34,1.42)	0.49 (0.46,0.52)	0.961
London parish	1563	20.6 (18.9,22.5)	12.3 (11.2,13.4)	1.35 (1.32,1.39)	0.47 (0.44,0.51)	0.978
London parish	1593	15.9 (14.2,17.3)	15.9 (14.6,17.8)	1.26 (1.23,1.29)	0.38 (0.35,0.41)	0.986
Canterbury wills	1603	14.0 (8.3,23.8)	18.0 (10.6,30.4)	1.23 (1.12,1.42)	0.34 (0.21,0.53)	0.853
London bills	1603	29.1 (26.5,31.8)	8.7 (8.0,9.5)	1.54 (1.48,1.60)	0.61 (0.57,0.64)	0.927
London parish	1603	19.9 (18.2,21.8)	12.7 (11.6,13.9)	1.34 (1.30,1.38)	0.46 (0.43,0.49)	0.988
Canterbury wills	1625	27.1 (11.4,53.5)	9.3 (4.7,22.3)	1.49 (1.18,2.19)	0.58 (0.28,0.84)	0.900
London bills	1625	27.3 (25.9,28.4)	9.3 (8.9,9.8)	1.50 (1.46,1.52)	0.58 (0.56,0.60)	0.996
London parish	1625	23.0 (22.3,23.7)	11.0 (10.7,11.3)	1.40 (1.39,1.42)	0.51 (0.50,0.53)	0.999
Canterbury wills	1665	35.8 (17.6,47.5)	7.1 (5.3,14.4)	1.69 (1.29,2.01)	0.69 (0.42,0.80)	0.842
London bills	1665	22.2 (21.0,23.4)	11.4 (10.8,12.0)	1.39 (1.36,1.41)	0.50 (0.48,0.52)	0.984
London parish	1665	23.2 (20.6,26.0)	10.9 (9.7,12.3)	1.41 (1.35,1.47)	0.52 (0.47,0.56)	0.987
Husting wills	early	5.9 (3.5,9.8)	43.2 (25.7,72.5)	1.08 (1.04,1.15)	0.15 (0.08,0.25)	
Canterbury wills	late	23.0 (11.7,45.0)	11.0 (5.6,21.5)	1.40 (1.18,1.94)	0.51 (0.29,0.78)	
London bills	late	23.9 (21.3,26.7)	10.6 (9.5,11.9)	1.42 (1.37,1.48)	0.53 (0.49,0.57)	
London parish	late	20.4 (18.3,22.8)	12.4 (11.1,13.8)	1.35 (1.31,1.40)	0.47 (0.43,0.51)	

Table S5: Summary statistics for the model estimating differences across epochs. All parameters are in units of $\log(\text{growth rate})/\text{year}$. The model includes fixed effects of epoch (early [14th c.] vs. late [16th - 17th c.]) and source (wills, parish, London Bills of Mortality) and a random effect of outbreak year. Variability for each observation is assumed to be proportional to the uncertainty in its $\log(r)$ estimate (see main text, *Growth rate estimates*). In Wilkinson-Rogers notation, the model formula is: $\log.r \sim \text{epoch} + \text{source} + (1|\text{outbreak.year}), \text{disp} \sim 1 + \text{offset}(\log(\text{sdvals}^2))$. Parameter estimates are given on the $\log(r)$ scale; Wald confidence intervals are given in parentheses.

	estimate	95% CI
Intercept (14th-c. wills log growth rate)	1.768	(1.250 – 2.286)
epoch (late vs. early)	1.366	(0.517 – 2.215)
source (parish vs. wills)	-0.118	(-0.786 – 0.550)
source (LBoM vs. wills)	0.039	(-0.628 – 0.707)
nobs	16	

Table S6: Parameter estimates for minor plague epidemics. Plague epidemics with $\hat{r} < 1/\text{yr}$ or $\hat{r} > 100/\text{yr}$, representing unreliable fits, are excluded; confidence limits that are < 0.1 or > 200 are replaced with NA. See [Methods](#).

Source	Epidemic	Growth rate [1/year]	Doubling time [days]	R^2
Wills	1578	19.4 (8.4, 55.0)	13.0 (4.6, 30.1)	0.404
LBoM	1578	3.7 (3.1, 4.2)	69.2 (60.1, 81.8)	0.825
Parish	1578	20.7 (14.3, 27.8)	12.2 (9.1, 17.7)	0.927
LBoM	1581	15.4 (12.9, 17.7)	16.4 (14.3, 19.6)	0.915
Parish	1581	25.2 (12.9, 42.4)	10.0 (6.0, 19.6)	0.784
Parish	1582	17.3 (7.4, 25.2)	14.6 (10.0, 34.3)	0.794
LBoM	1606	4.6 (4.1, 5.1)	55.3 (50.1, 62.0)	0.911
LBoM	1607	10.3 (7.6, 12.7)	24.6 (19.9, 33.1)	0.947
Parish	1607	41.0 (14.9, 81.6)	6.2 (3.1, 16.9)	0.757
Wills	1608	74.8 (25.8, 146.8)	3.4 (1.7, 9.8)	0.670
LBoM	1608	10.3 (8.4, 12.0)	24.5 (21.1, 30.3)	0.921
Parish	1608	17.5 (8.6, 27.9)	14.4 (9.1, 29.3)	0.728
Wills	1609	50.1 (13.0, 113.9)	5.1 (2.2, 19.5)	0.403
LBoM	1609	16.3 (10.2, 21.1)	15.5 (12.0, 24.7)	0.863
Parish	1609	91.5 (7.9, NA)	2.8 (1.1, 31.9)	0.608
LBoM	1609.5	10.2 (7.2, 12.6)	24.7 (20.1, 34.9)	0.888
Parish	1609.5	13.8 (11.0, 16.5)	18.4 (15.4, 23.0)	0.954
LBoM	1610	5.0 (4.2, 5.8)	50.3 (43.7, 60.3)	0.897
Wills	1630	24.8 (10.6, 43.4)	10.2 (5.8, 23.9)	0.415
LBoM	1630	8.6 (6.1, 13.2)	29.5 (19.2, 41.2)	0.846
Parish	1630	6.9 (3.7, 12.0)	36.6 (21.1, 69.3)	0.665
Wills	1636	40.3 (15.4, 85.4)	6.3 (3.0, 16.5)	0.663
LBoM	1636	9.3 (8.3, 11.3)	27.1 (22.5, 30.3)	0.947
Parish	1636	13.8 (9.4, 18.1)	18.4 (14.0, 26.8)	0.959
Wills	1639	14.6 (2.1, 27.2)	17.3 (9.3, 120.3)	0.063
LBoM	1639	11.2 (8.9, 13.2)	22.7 (19.1, 28.3)	0.958
Parish	1639	31.9 (11.5, 64.5)	7.9 (3.9, 21.9)	0.575
LBoM	1641	9.7 (8.1, 11.2)	26.0 (22.6, 31.3)	0.964
Parish	1641	13.3 (10.3, 16.0)	19.1 (15.8, 24.5)	0.974
Wills	1642	33.4 (6.2, NA)	7.6 (1.1, 40.5)	0.643
LBoM	1642	3.4 (2.7, 4.2)	73.8 (60.8, 94.2)	0.757
LBoM	1643	4.5 (3.5, 5.6)	55.8 (45.2, 73.1)	0.766
LBoM	1644	6.0 (4.2, 7.5)	42.3 (33.6, 59.9)	0.860
LBoM	1645	19.6 (17.3, 21.9)	12.9 (11.5, 14.6)	0.978
LBoM	1646	11.1 (9.7, 12.4)	22.8 (20.5, 26.1)	0.843
Parish	1646	22.1 (16.6, 27.9)	11.4 (9.1, 15.3)	0.946
LBoM	1647	22.7 (19.2, 26.3)	11.1 (9.6, 13.2)	0.871
Parish	1647	16.0 (10.0, 22.3)	15.8 (11.4, 25.2)	0.710

Table S7: Outbreak windows and fitting windows used in fitting the major plague epidemics. See [Methods](#).

Source	Outbreak Year	Outbreak Window		Fitting Window	
		start	end	start	end
Husting wills	1348	15 Jan 1348	15 Dec 1349	20 Jan 1348	13 Apr 1349
Husting wills	1361	15 Jan 1361	15 Dec 1361	04 Feb 1361	08 Jul 1361
Husting wills	1368	01 Jan 1368	01 Jan 1369	31 Jan 1368	26 Jul 1368
Husting wills	1375	15 Jan 1375	15 Dec 1375	25 Jan 1375	21 Jul 1375
London parish	1563	04 Jun 1563	15 Jan 1564	04 Jun 1563	08 Oct 1563
London bills	1563	05 Jun 1563	14 Jan 1564	19 Jun 1563	01 Oct 1563
Canterbury wills	1563	05 Jun 1563	14 Jan 1564	08 Jun 1563	14 Oct 1563
London bills	1593	17 Mar 1593	22 Dec 1593	17 Mar 1593	11 Aug 1593
Canterbury wills	1593	17 Mar 1593	22 Dec 1593	16 Jun 1593	31 Oct 1593
London parish	1593	19 Mar 1593	25 Dec 1593	11 Jun 1593	17 Sep 1593
London bills	1603	17 Mar 1603	22 Dec 1603	16 Jun 1603	08 Sep 1603
Canterbury wills	1603	17 Mar 1603	22 Dec 1603	18 Mar 1603	13 Oct 1603
London parish	1603	19 Mar 1603	25 Dec 1603	19 Mar 1603	10 Sep 1603
London bills	1625	24 Dec 1624	15 Dec 1625	02 Jun 1625	25 Aug 1625
Canterbury wills	1625	24 Dec 1624	15 Dec 1625	15 Jun 1625	14 Sep 1625
London parish	1625	25 Dec 1624	18 Dec 1625	11 Jun 1625	20 Aug 1625
London parish	1665	25 Dec 1664	18 Dec 1666	25 Dec 1664	24 Sep 1665
London bills	1665	28 Dec 1664	18 Dec 1666	13 Jun 1665	26 Sep 1665
Canterbury wills	1665	28 Dec 1664	18 Dec 1666	28 Dec 1664	27 Sep 1665

Table S8: The start and end dates for the fitting windows used in fitting the minor plague epidemics. See [Methods](#).

Source	Outbreak Year	Outbreak Window		Fitting Window	
		start	end	start	end
London parish	1578	25 Dec 1577	23 Apr 1581	25 Dec 1577	08 Oct 1578
London bills	1578	26 Dec 1577	20 Apr 1581	26 Dec 1577	09 Oct 1578
Canterbury wills	1578	26 Dec 1577	20 Apr 1581	07 Jan 1578	22 Nov 1578
London bills	1581	27 Apr 1581	18 Jan 1582	01 Jun 1581	05 Oct 1581
Canterbury wills	1581	27 Apr 1581	18 Jan 1582	27 Apr 1581	14 Jun 1581
London parish	1581	30 Apr 1581	15 Jan 1582	30 Apr 1581	08 Oct 1581
London parish	1582	22 Jan 1582	22 Jan 1583	22 Jan 1582	29 Oct 1582
London bills	1582	25 Jan 1582	24 Jan 1583	25 Jan 1582	25 Oct 1582
Canterbury wills	1582	25 Jan 1582	24 Jan 1583	25 Jan 1582	04 Jul 1582
London parish	1606	25 Dec 1605	04 Jun 1607	25 Dec 1605	17 Sep 1606
London bills	1606	26 Dec 1605	04 Jun 1607	26 Dec 1605	09 Oct 1606
Canterbury wills	1606	26 Dec 1605	04 Jun 1607	30 Dec 1605	21 Feb 1607
London bills	1607	11 Jun 1607	04 Feb 1608	11 Jun 1607	01 Oct 1607
Canterbury wills	1607	11 Jun 1607	04 Feb 1608	11 Jun 1607	20 Nov 1607
London parish	1607	11 Jun 1607	05 Feb 1608	11 Jun 1607	08 Oct 1607
London bills	1608	11 Feb 1608	23 Feb 1609	07 Apr 1608	07 Oct 1608
Canterbury wills	1608	11 Feb 1608	23 Feb 1609	11 Feb 1608	08 May 1608
London parish	1608	12 Feb 1608	26 Feb 1609	12 Feb 1608	24 Sep 1608
London bills	1609	02 Mar 1609	08 Jun 1609	02 Mar 1609	04 May 1609
Canterbury wills	1609	02 Mar 1609	08 Jun 1609	04 Mar 1609	28 May 1609
London parish	1609	05 Mar 1609	04 Jun 1609	05 Mar 1609	16 Apr 1609
London parish	1609.5	11 Jun 1609	26 Feb 1610	11 Jun 1609	01 Oct 1609
London bills	1609.5	15 Jun 1609	01 Mar 1610	15 Jun 1609	28 Sep 1609
Canterbury wills	1609.5	15 Jun 1609	01 Mar 1610	15 Jun 1609	07 Jul 1609
London parish	1610	05 Mar 1610	18 Dec 1610	05 Mar 1610	20 Aug 1610
London bills	1610	08 Mar 1610	20 Dec 1610	08 Mar 1610	06 Sep 1610
Canterbury wills	1610	08 Mar 1610	20 Dec 1610	08 Mar 1610	29 Jun 1610
London bills	1630	24 Dec 1629	16 Dec 1630	01 Apr 1630	05 Aug 1630
Canterbury wills	1630	24 Dec 1629	16 Dec 1630	28 Dec 1629	03 Dec 1630
London parish	1630	25 Dec 1629	18 Dec 1630	25 Dec 1629	06 Aug 1630
London bills	1636	24 Dec 1635	14 Dec 1637	05 May 1636	07 Oct 1636
Canterbury wills	1636	24 Dec 1635	14 Dec 1637	24 Dec 1635	29 May 1636
London parish	1636	25 Dec 1635	11 Dec 1637	25 Dec 1635	15 Oct 1636
London parish	1639	18 Dec 1639	05 Mar 1641	18 Dec 1639	10 Sep 1640
London bills	1639	19 Dec 1639	04 Mar 1641	23 Apr 1640	18 Sep 1640
Canterbury wills	1639	19 Dec 1639	04 Mar 1641	19 Dec 1639	03 Dec 1640
London bills	1641	11 Mar 1641	10 Mar 1642	15 Apr 1641	30 Sep 1641
Canterbury wills	1641	11 Mar 1641	10 Mar 1642	11 Mar 1641	17 Feb 1642
London parish	1641	12 Mar 1641	12 Mar 1642	12 Mar 1641	24 Sep 1641
London bills	1642	17 Mar 1642	09 Feb 1643	17 Mar 1642	06 Oct 1642
Canterbury wills	1642	17 Mar 1642	09 Feb 1643	17 Mar 1642	22 May 1642
London parish	1642	19 Mar 1642	12 Feb 1643	19 Mar 1642	01 Oct 1642
London bills	1643	16 Feb 1643	01 Mar 1644	16 Feb 1643	12 Oct 1643
London parish	1643	19 Feb 1643	04 Mar 1644	19 Feb 1643	05 Nov 1643
London parish	1644	04 Mar 1644	19 Mar 1645	04 Mar 1644	13 Aug 1644
London bills	1644	07 Mar 1644	20 Mar 1645	07 Mar 1644	11 Oct 1644
London parish	1645	26 Mar 1645	29 Jan 1646	26 Mar 1645	20 Aug 1645
London bills	1645	27 Mar 1645	29 Jan 1646	05 Jun 1645	11 Sep 1645
London bills	1646	05 Feb 1646	18 May 1647	09 Apr 1646	10 Sep 1646
London parish	1646	05 Feb 1646	21 May 1647	05 Feb 1646	03 Sep 1646
London parish	1647	21 May 1647	11 Dec 1647	21 May 1647	15 Oct 1647
London bills	1647	25 May 1647	14 Dec 1647	25 May 1647	14 Sep 1647

9 Supplementary figure cited in the main text

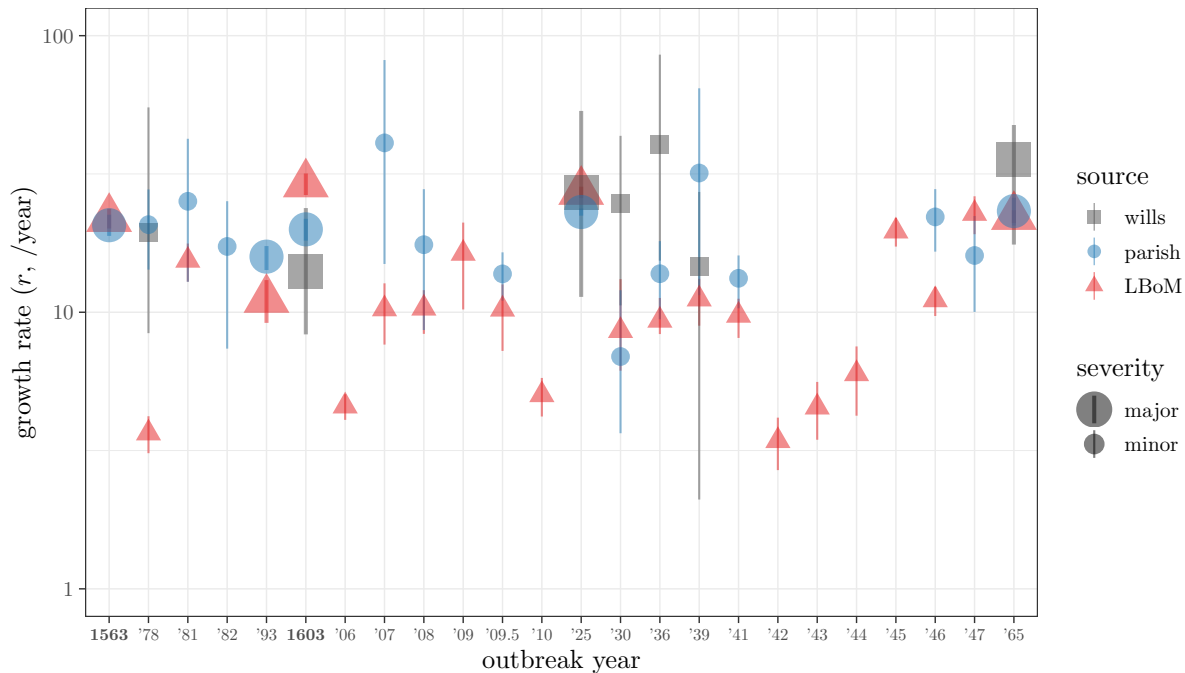


Figure S8: Growth rate estimates for all the late epoch (1540–1680) London plague epidemics. The growth rates shown for the major epidemics are the same as those in the right panel of [Figure 3](#).

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