

1	Supplementary materials for Assessing the accuracy of kernel-fitting	
2	and projections of spatial risk at key early timepoints in outbreaks	
3	Simin Lee ^{1,*} , Christopher M. Baker ² , Emily Sellens ³ , Mark A. Stevenson ¹ , Meryl Theng ¹ Andrew C.	
4	Breed ³ , Sharon E. Roche ³ , Simon M. Firestone ¹	
5	¹ Melbourne Veterinary School, Faculty of Science, The University of Melbourne, Parkville, VIC 3010,	
6	Australia.	
7	² School of Mathematics and Statistics, Faculty of Science, The University of Melbourne, Parkville, VIC	
8	3010, Australia.	
9	³ Australian Government Department of Agriculture, Fisheries and Forestry, Canberra 2600, Australia.	
10	Correspondence should be addressed to Simin Lee; simin.lee1@student.unimelb.edu.au	
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A. Descriptive analysis of the 2001 outbreak of foot-and-mouth disease in the United Kingdom

In most affected regions, the number of outbreak cases continued to increase during the first four weeks, followed by a gradual decline after reaching a peak (**Figure S1**). Cumbria experienced the largest FMD outbreak in 2001, which lasted for about 200 days. The other four regions experienced relatively small outbreaks, with peak case numbers not exceeding 10. North Yorkshire showed a relatively low and sporadic pattern of FMD occurrence.

The spatial patterns of FMD spread during the first four weeks of the outbreak varied across regions (**Figure S2**). In Cumbria, transmission between farms intensified early, forming dense clusters from the outset. In contrast, Devon, Dumfries and Galloway, and Durham began to show increasing numbers of infected premises in weeks 2 and 3, with spatial clustering becoming more evident over time. Meanwhile, North Yorkshire experienced only a small number of sporadic cases. Overall, during the early weeks of the outbreak, FMD predominantly spread through local transmission, with the speed and extent of spread differing by region. These patterns suggest that the spatial dissemination of FMD was strongly influenced by proximity to existing infected premises (IPs), demonstrating a consistent trend of geographically limited spread in the initial phase of the outbreak.

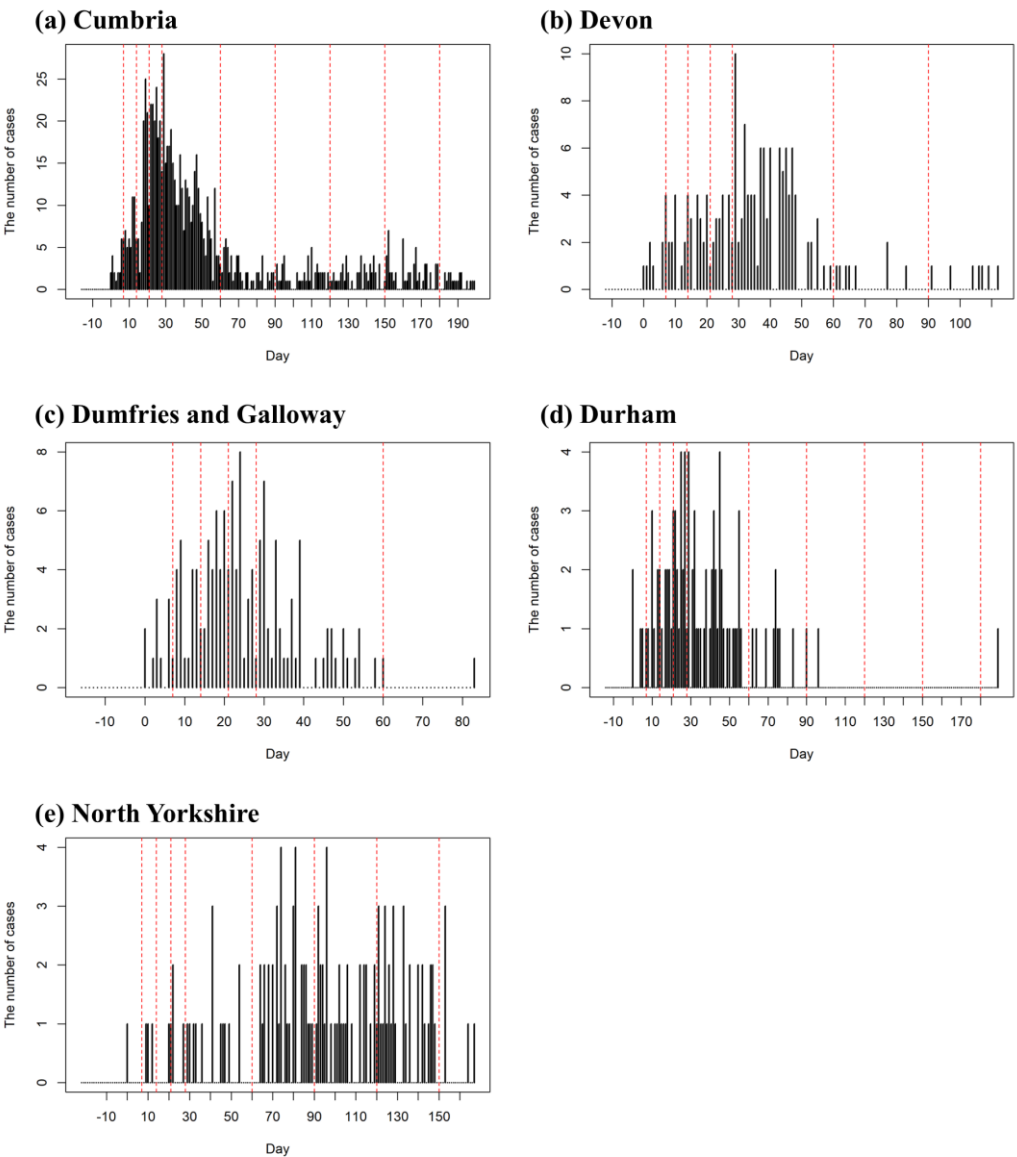


Figure S1. Epidemic curves for (a) Cumbria, (b) Devon, (c) Dumfries and Galloway, (d) Durham, and (e) North Yorkshire. The first notification date for each region is set as day 0. The number of cases is calculated based on the notification date to FMD. Vertical dashed lines represent the specific timepoints for each region (i.e., from left to right: day 7, 14, 21, 28, 60, 90, etc.).

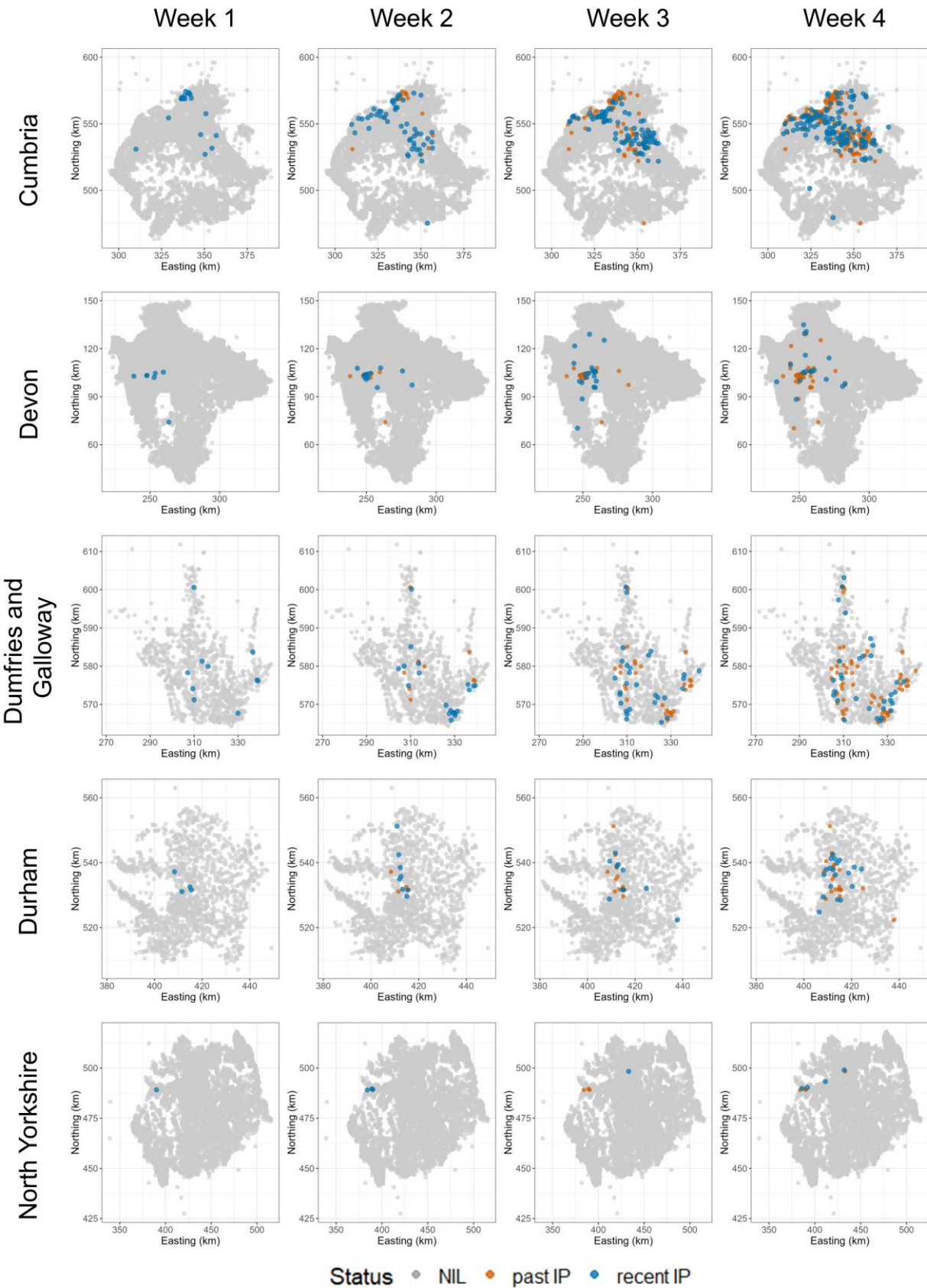


Figure S2. Outbreak maps for the first four weeks, shown in weekly intervals in Cumbria, Devon, Dumfries and Galloway, Durham, and North Yorkshire. Blue dots indicate infected premises (IPs) notified during the corresponding week, while orange dots represent all IPs notified prior to that week.

B. Materials and methods

Section 1. Details of required data and an example

The data required for the analysis includes the coordinates of each premises and two observed dates for infected premises. For calculating Euclidean distances between premises, it is recommended to use projected coordinates instead of latitude and longitude. Two unobserved dates (i.e., ‘the exposure date’ and ‘the infectious onset date’) are back-calculated from the clinical onset date using the latent and incubation periods (1).

Table S1. An example of dataset

ID	X coordinate (meters)	Y coordinate (meters)	Status	Clinical onset date	Depopulation date
1	386600	512900	Infected	01/03/2001	04/03/2001
2	386450	513520	Susceptible	NA	NA
...	...	...	...	...	...

The example data and a R script used in the study are available on GitLab (<https://gitlab.unimelb.edu.au/sllee2/kernel-estimation>). The R script includes the process of kernel estimation, calculating relative infection pressure, and visualising it on a map.

Section 2. Maximum likelihood estimation equation for estimating transmission kernel parameters.

The appropriate parameter values were estimated through the following process (2). The infection pressure of a susceptible premises j at day t was calculated as the sum of the kernels from all infectious premises I on that day (eq. (1)). $k(r_{ij})$ denotes the transmission rate from an infectious premises i to a susceptible premises j , dependent on the distance r_{ij} separating them.

$$\lambda_j(t) = \sum_{i \in I} k(r_{ij}) \quad \text{eq. (1)}$$

The likelihood function (L) is calculated as the product of the probabilities that: (i) a premises m in the set M which remain unexposed until the exposed time $t_{\text{exposure},m}$, (ii) a premises m in the set M which become infected is exposed at $t_{\text{exposure},m}$, (iii) a premises n in the set N which do not become infected throughout the entire period, and (iv) a dangerous contact premises or a susceptible premises o in the set O which do not become infected until the depopulation time $t_{\text{depopulation},o}$ (eq. (2)).

$$\begin{aligned}
 L = & \prod_{m \in M} P_{\text{not_exposed},m} (t_{\text{start}} \sim (t_{\text{exposure},m} - 1)) \\
 & \cdot P_{\text{exposed},m} (t_{\text{exposure},m}) \\
 & \times \prod_{n \in N} P_{\text{not_exposed},n} (t_{\text{start}} \sim t_{\text{end}}) \\
 & \times \prod_{o \in O} P_{\text{not_exposed},o} (t_{\text{start}} \sim (t_{\text{depopulation},o} - 1))
 \end{aligned} \quad \text{eq. (2)}$$

The probability that a premises m remains unexposed from t_{start} to t_{end} , denoted $P_{not_exposed,m}(t_{start} \sim t_{end})$, and the probability that a premises m is exposed at $t_{exposure}$, denoted $P_{exposed,m}(t_{exposure,m})$, were calculated using a Poisson process with the infection pressure (eqs. (3) and (4)).

$$P_{not_exposed,m}(t_{start} \sim t_{end}) = e^{-\sum_{t=t_{start}}^{t_{end}} \lambda_m(t)} \quad eq.(3)$$

$$P_{exposed,m}(t_{exposure,m}) = 1 - e^{-\lambda_m(t_{exposure,m})} \quad eq.(4)$$

Therefore, eq. (2) can be expressed as eq. (5).

$$L = \prod_{m \in M} e^{-\sum_{t=t_{start}}^{(t_{exposure,m}-1)} \lambda_m(t)} (1 - e^{-\lambda_m(t_{exposure,m})}) \times \prod_{n \in N} e^{-\sum_{t=t_{start}}^{t_{end}} \lambda_n(t)} \times \prod_{o \in O} e^{-\sum_{t=t_{start}}^{(t_{depopulation,o}-1)} \lambda_o(t)} \quad eq.(5)$$

To reduce computational complexity, the likelihood function (L) was transformed into a log-likelihood function ($\ln(L)$), and parameter values were estimated by maximising this function, i.e., by minimising the negative log-likelihood function.

$$\ln(L) = \sum_{m \in M} \ln(1 - e^{-\lambda_m(t_{exposure,m})}) - \sum_{m \in M} \sum_{t=t_{start}}^{(t_{exposure,m}-1)} \lambda_m(t) - \sum_{n \in N} \sum_{t=t_{start}}^{t_{end}} \lambda_n(t) - \sum_{o \in O} \sum_{t=t_{start}}^{(t_{depopulation,o}-1)} \lambda_o(t) \quad eq.(6)$$

C. Determining the earliest point at which the overall transmission kernel could be estimated

The best-fitting transmission kernel equation, based on estimation using the entire outbreak dataset in each of the five regions, was consistently the power law type 2 kernel (**Figure S3**). In Cumbria and Devon, the power law type 2 was consistently selected as the best fit from 7 days post-notification in the region through to the end of the outbreak. In Dumfries and Galloway, Durham, and North Yorkshire, although other transmission kernel equation were occasionally selected as the best fit, the power-law type 2 kernel was consistently preferred in most cases. Even when an alternative kernel instead of power law type 2 was chosen, the shape of the alternative kernel curve did not differ noticeably from that of the best-fitting transmission kernel or the overall transmission kernel (**Figures S4, S5, and S6**).

At later timepoints (as more data became available), the shape of the best-fitting transmission kernel curve progressively resembled that of the kernel estimated from the full outbreak dataset for each cluster. Additionally, the 95% and 50% confidential intervals (CIs) of the estimated kernels became more precise (**Figure S5 and S6**). The first 60-day datasets from North Yorkshire did not support CI estimation for kernel parameters (**Figure S5(e)** and **Table S2**) due to low case numbers (<20 reported IPs cases; **Figure S1**). North Yorkshire had only a single IP reported during the first 7 days, making it impossible to estimate a transmission kernel based on the relationships between IPs. This highlights the importance of the number of outbreak cases for reliable transmission kernel estimation.

We compared the shape of the estimated transmission kernel curves to the overall transmission kernel curve. If an estimated kernel was positioned higher than the overall kernel, it was classified as an overestimation (i.e., indicating broader spatial spread of FMD). If lower, it was considered an underestimation (i.e., indicating more restricted spread of FMD). During the first two weeks, underestimation was observed in Cumbria and Dumfries and Galloway (**Figures S5(a) and S5(c)**). However, after this period, the best-fitting kernel curves closely approximated the overall kernel curve. In Devon and Durham, the best-fitting kernel curves were already closely aligned with the overall kernel as early as day 7 (**Figures S5(b) and S5(d)**). In North Yorkshire, the best-fitting transmission kernel overestimated the overall kernel on day 14, underestimated it between days 21 and 60, and closely matched the overall transmission kernel thereafter (**Figure S5(e)**). Overall, discrepancies between estimated and overall best-fitting transmission kernels were resolved within two weeks (**Figure S5**). By day 60, after the epidemic peak, the 95% and 50% CI envelopes of the estimated transmission kernels closely aligned with those of the overall transmission kernel curve (**Figures S1 and S5**).

The estimated 95%, 90%, and 75% risk distances showed substantial variability at early timepoints (i.e., day 7 and day 14), but gradually stabilized over time (**Figure S7**). This suggests that while the spatial spread of FMD was uncertain in the early stages, it later persisted within a more stable range. For Cumbria, the estimated risk distances consistently remained within 10 km at all time points, indicating that the infection primarily spread over relatively short distances. Devon and Durham also experienced wide 95% risk distance confidence intervals during the early stages (Days 7–14), suggesting initial uncertainty in the spread. However, from subsequent time points, both the estimated values and their CIs showed a consistent pattern aligning with the final estimates, indicating a stable trend. Notably, the estimates of 90% and 75% risk distances generally stayed within 10 km, exhibiting relatively small variability. In Dumfries and Galloway, although wide CIs were observed at all time points, the final estimates also exhibited significant uncertainty, which did not pose a major issue for interpretation. The 75% risk distance in this region remained consistently low throughout the entire period, suggesting that FMD transmission primarily occurred over very short distances. Conversely, in North Yorkshire, the 95%, 90%, and 75% risk distances were all estimated to be very small, less than 0.2 km, on Day 14. This indicates that local transmission

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during this period was extremely limited or occurred only over very close distances. However, from Day 21 onwards, the estimated risk distances increased, approaching their final estimates.

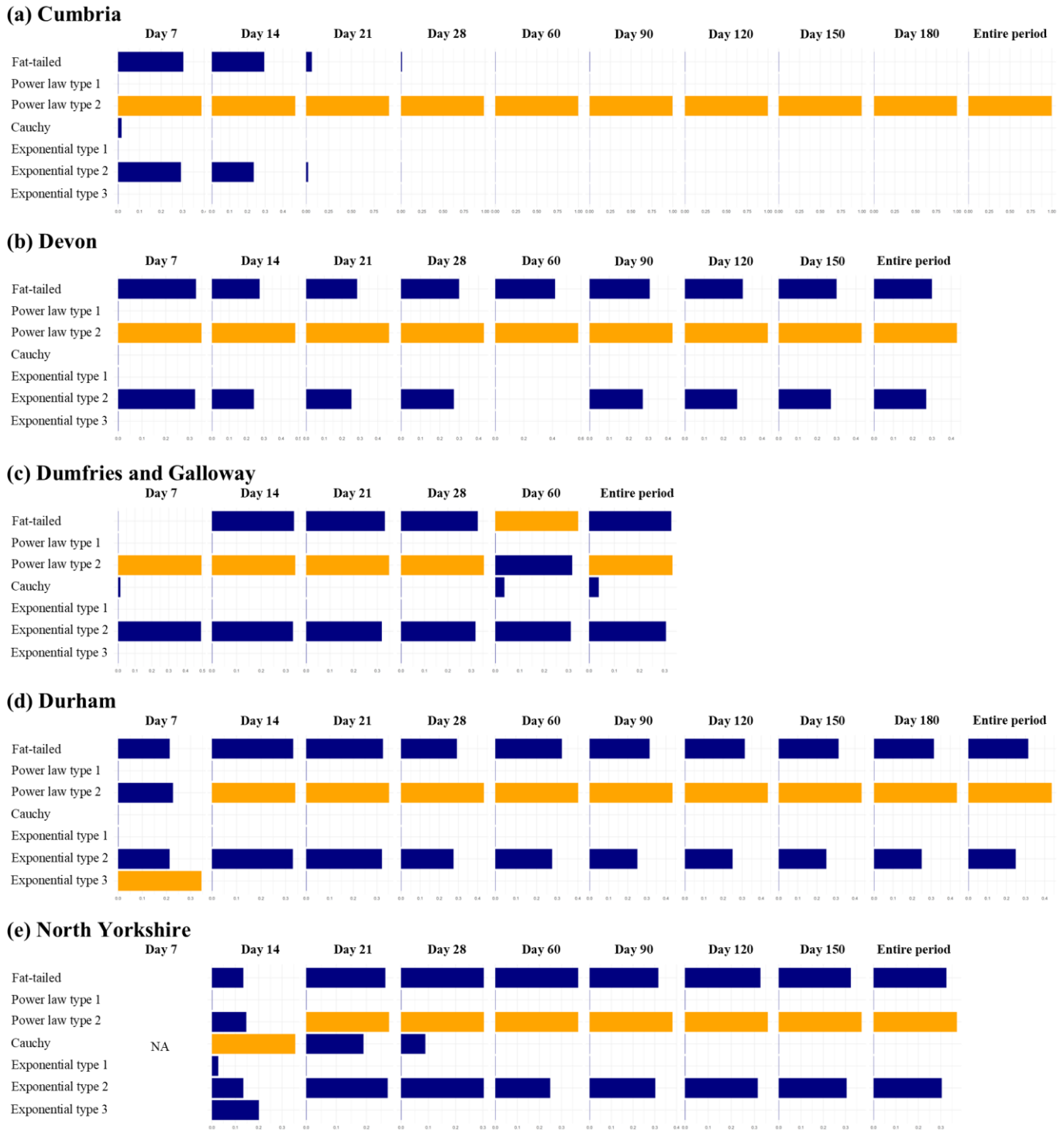


Figure S3. Weight plots of transmission kernels at each timepoint for (a) Cumbria, (b) Devon, (c) Dumfries and Galloway, (d) Durham, and (e) North Yorkshire. The days indicated on the plots represent the timepoint, calculated relative to the first detection date in each region. Entire period refers to the time span from the first detection date to the final depopulation event. The weights indicate the relative fit of each transmission kernel based on AIC values. The transmission kernel with the highest weight (orange) may be preferred over others (navy). In North Yorkshire, kernel estimation was not possible at day 7 due to the presence of only a single case.

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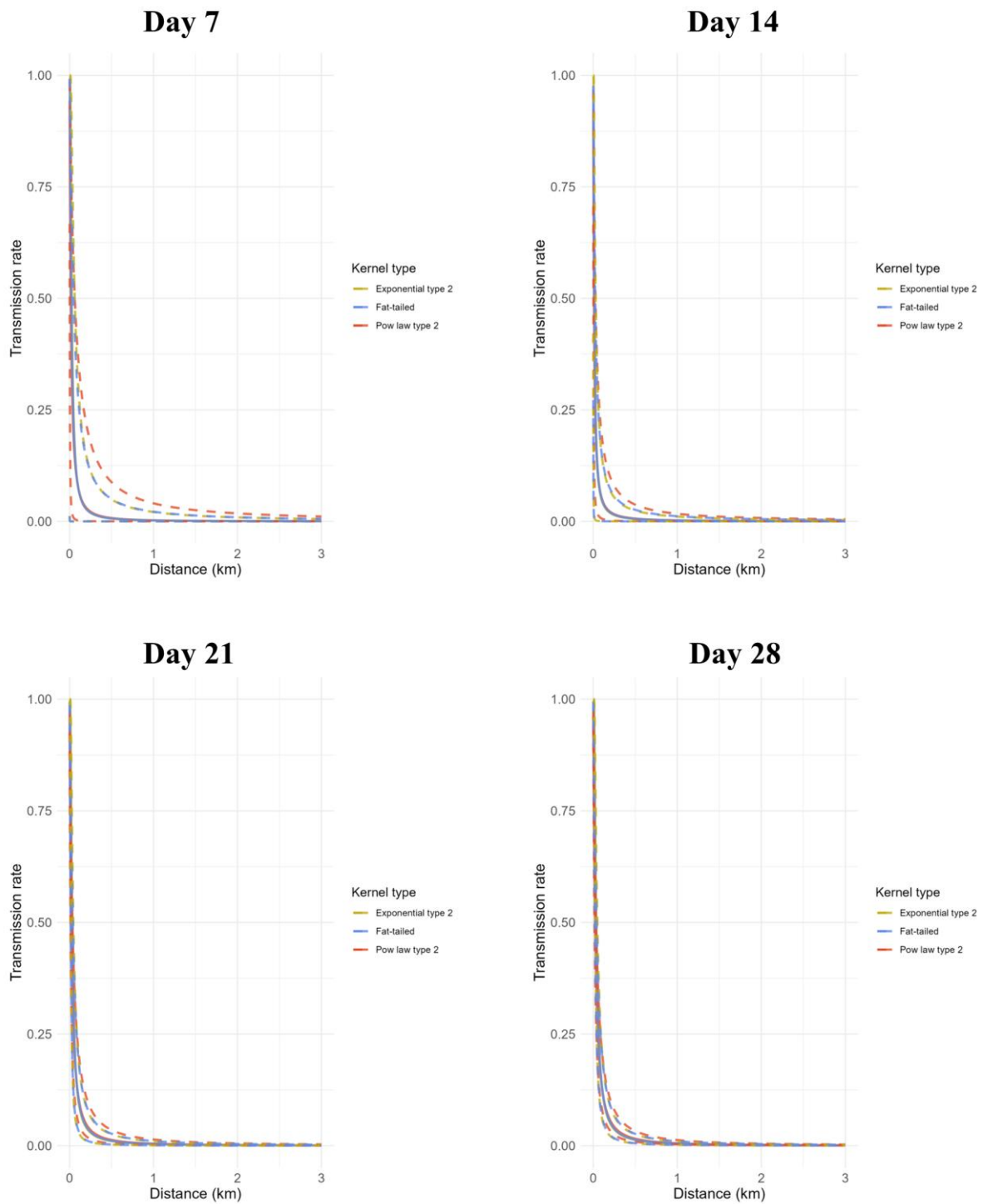


Figure S4(a). Plots of the candidate transmission kernels that could have been selected during the first month for Cumbria. Solid lines represent kernel estimates, while dashed lines indicate lower and upper limits of 95% confidential intervals (CI).

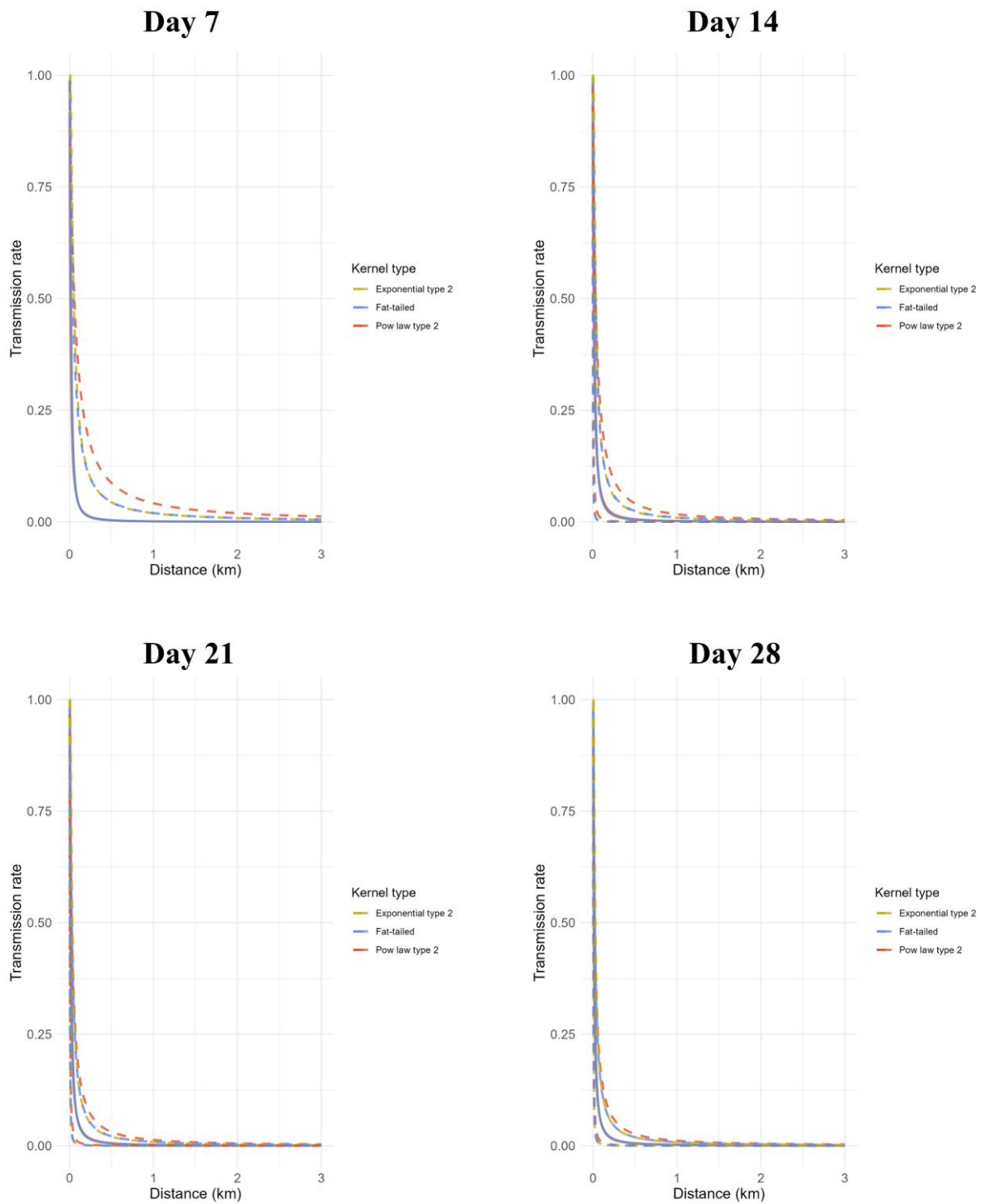


Figure S4(b). Plots of the candidate transmission kernels that could have been selected during the first month for Devon. Solid lines represent kernel estimates, while dashed lines indicate lower and upper limits of 95% confidential intervals (CI). If the 95% CIs for the kernel parameters cannot be estimated or are not visually distinguishable, the corresponding CIs for the transmission kernels are not displayed.

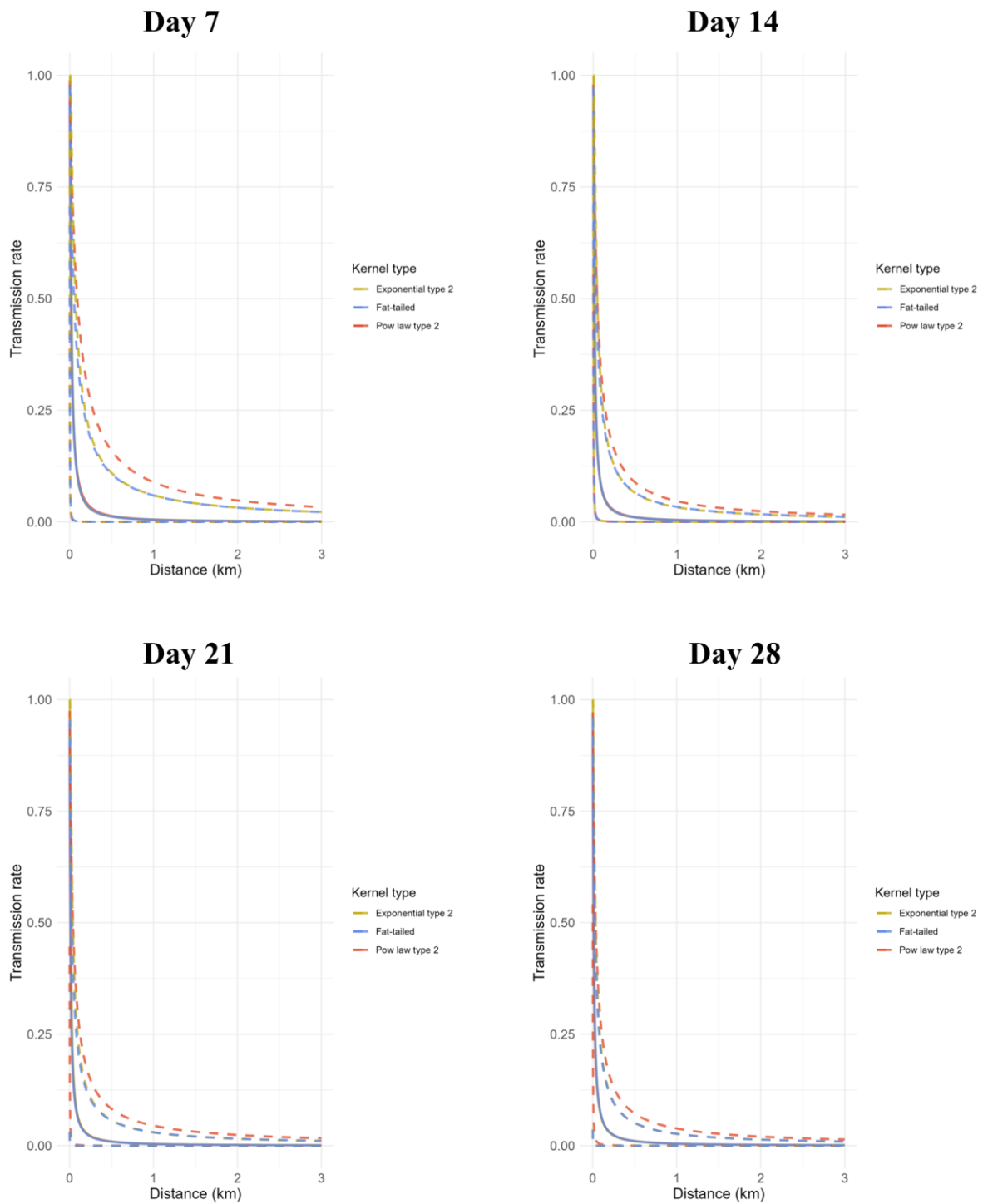


Figure S4(c). Plots of the candidate transmission kernels that could have been selected during the first month for Dumfries and Galloway. Solid lines represent kernel estimates, while dashed lines indicate lower and upper limits of 95% confidential intervals.

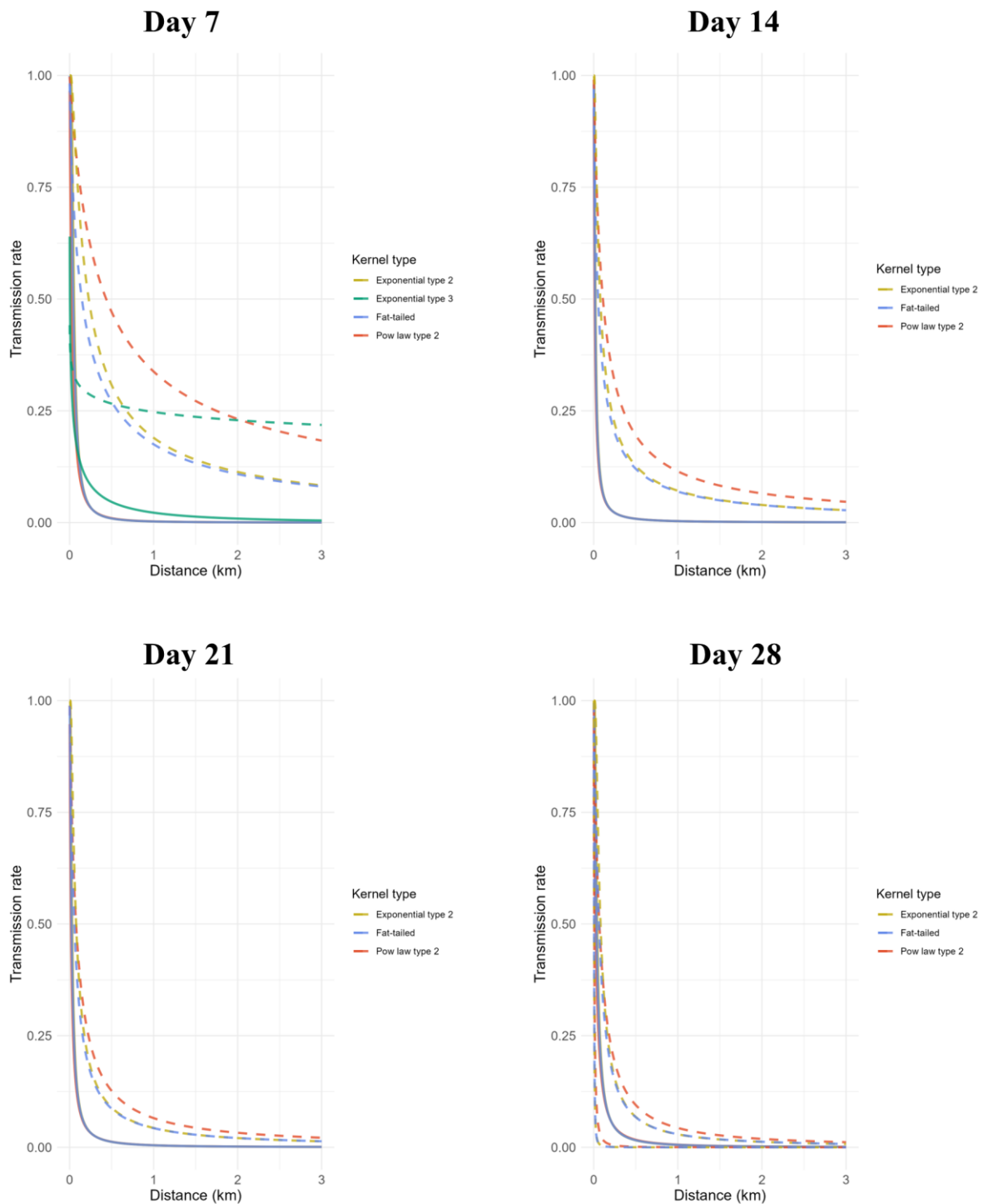
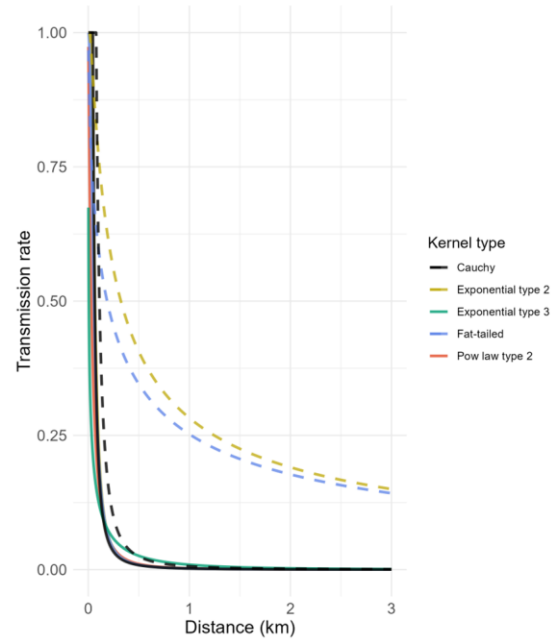


Figure S4(d). Plots of the candidate transmission kernels that could have been selected during the first month for Durham. Solid lines represent kernel estimates, while dashed lines indicate lower and upper limits of 95% confidential intervals (CI). If the 95% CIs for the kernel parameters cannot be estimated or are not visually distinguishable, the corresponding CIs for the transmission kernels are not displayed.

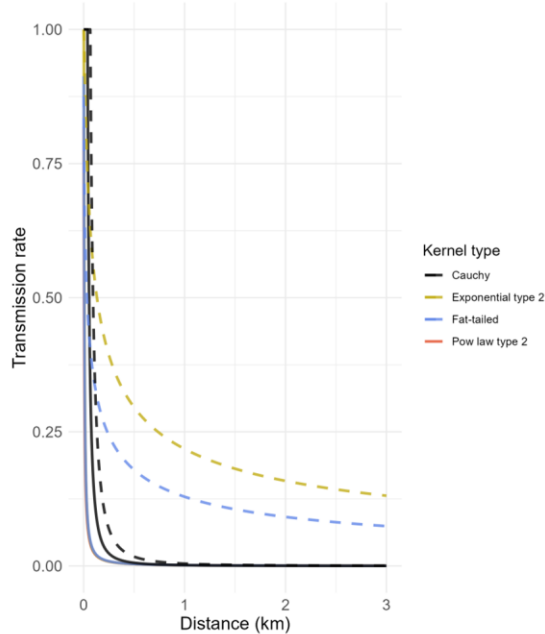
Day 7

N/A

Day 14



Day 21



Day 28

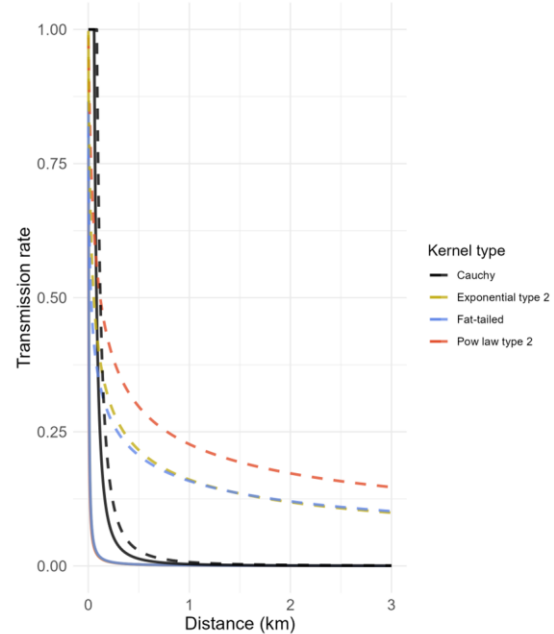


Figure S4(e). Plots of the candidate transmission kernels that could have been selected during the first month for North Yorkshire. Solid lines represent kernel estimates, while dashed lines indicate lower and upper limits of 95% confidential intervals (CI). If the 95% CIs for the kernel parameters cannot be estimated or are not visually distinguishable, the corresponding CIs for the transmission kernels are not displayed. Kernel estimation was not possible at day 7 due to the presence of only a single case.

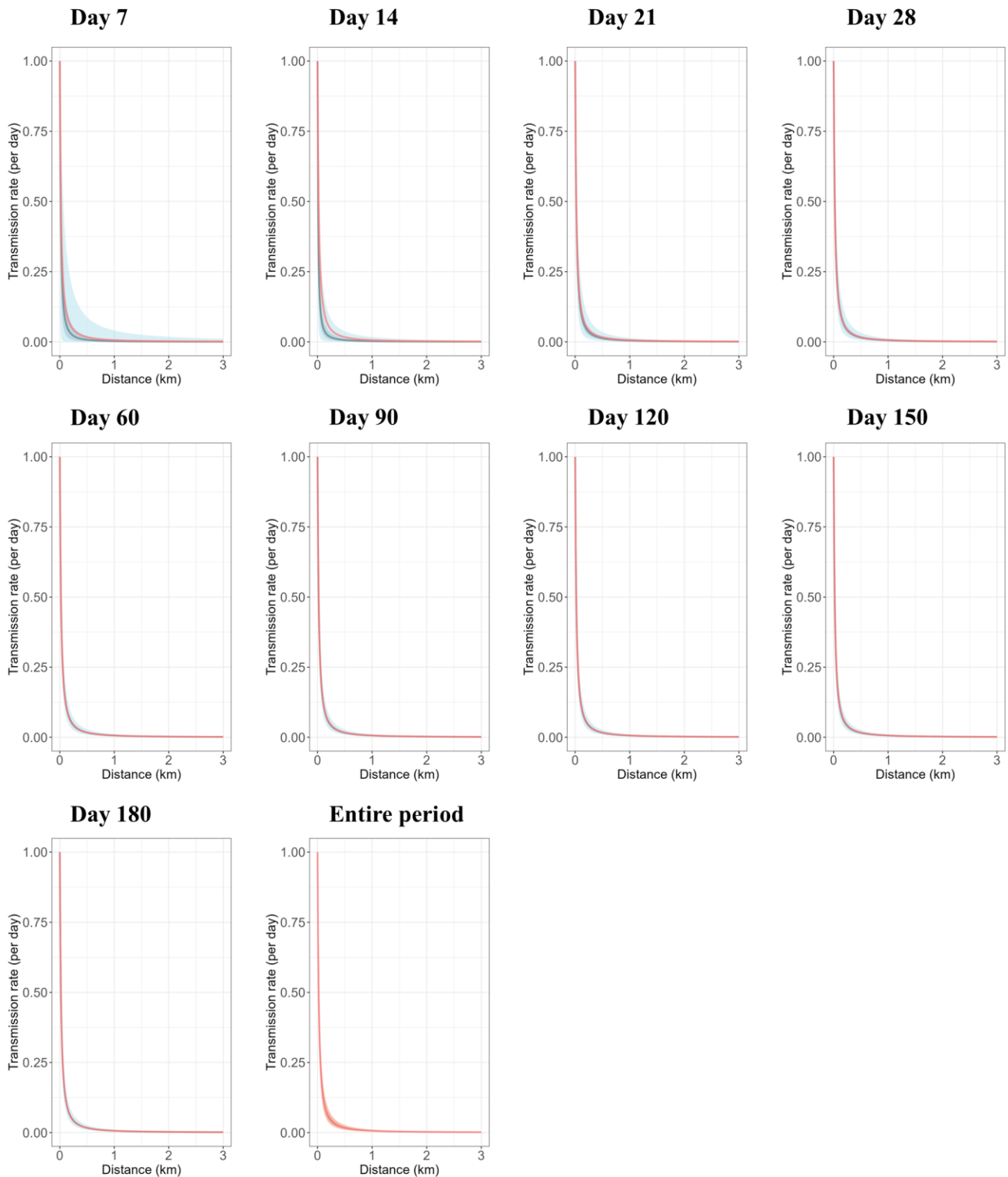


Figure S5(a). Plots of the best-fitting transmission kernel (blue line) and overall transmission kernel (red line) for each timepoint up to the end of the outbreak in Cumbria. The blue curve, along with the dark and light blue shaded areas, represents the best-fitting kernel estimated at the timepoint shown in each plot (day 0 = the first notification in each region), along with its 50% and 95% confidence intervals (CIs). The overall transmission kernel estimated using entire data is shown as a red curve, with its 50% and 95% CIs indicated by dark red and light red shading, respectively. The similarity between kernels was assessed by checking whether the overall transmission kernel curve falls within the CI envelopes of the best-fitting kernel.

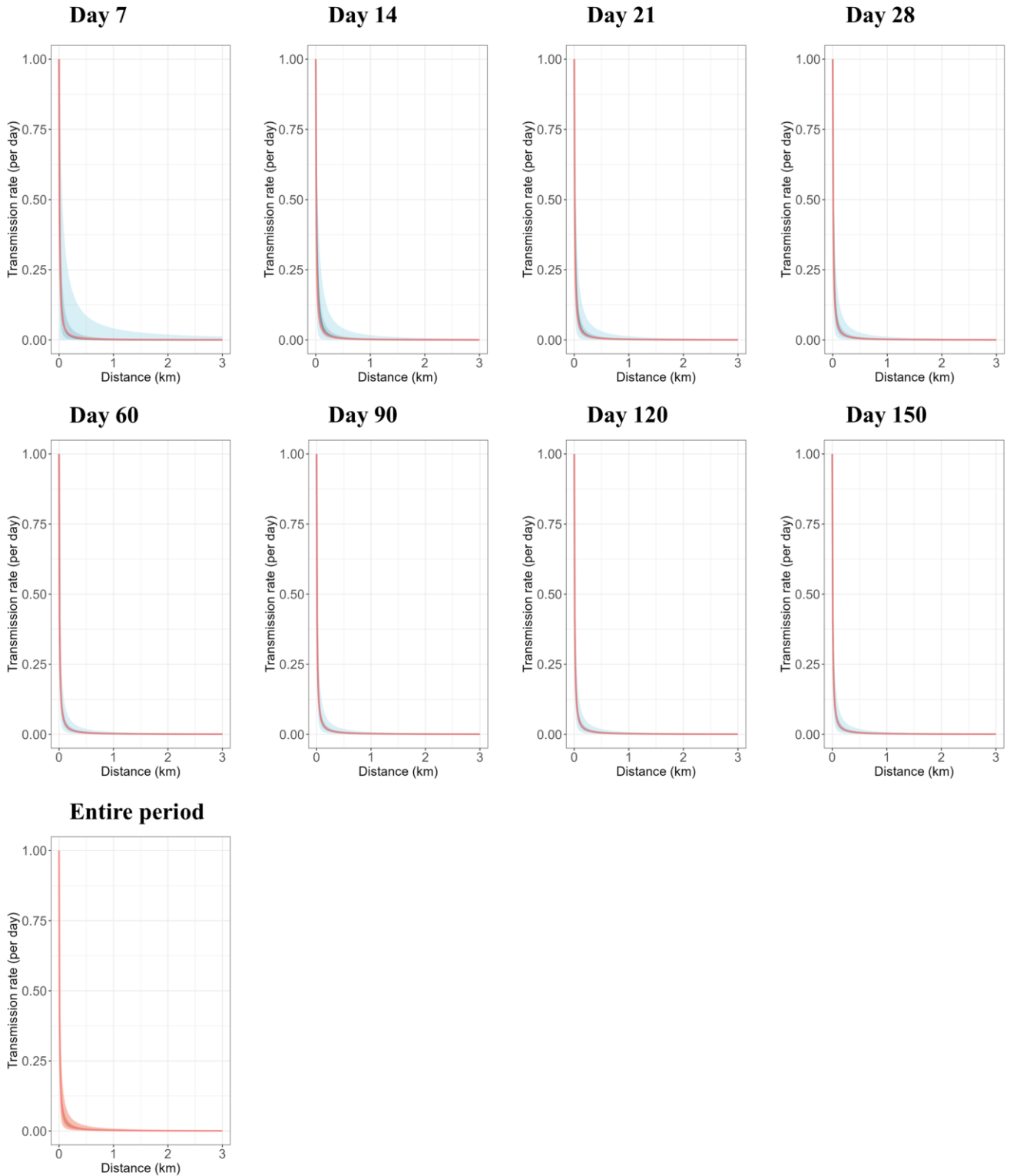


Figure S5(b). Plots of the best-fitting transmission kernel (blue line) and overall transmission kernel (red line) for each timepoint up to the end of the outbreak in Devon. The blue curve, along with the dark and light blue shaded areas, represents the best-fitting kernel estimated at the timepoint shown in each plot (day 0 = the first notification in each region), along with its 50% and 95% confidence intervals (CIs). The overall transmission kernel estimated using entire data is shown as a red curve, with its 50% and 95% CIs indicated by dark red and light red shading, respectively. The similarity between kernels was assessed by checking whether the overall transmission kernel curve falls within the CI envelopes of the best-fitting kernel.

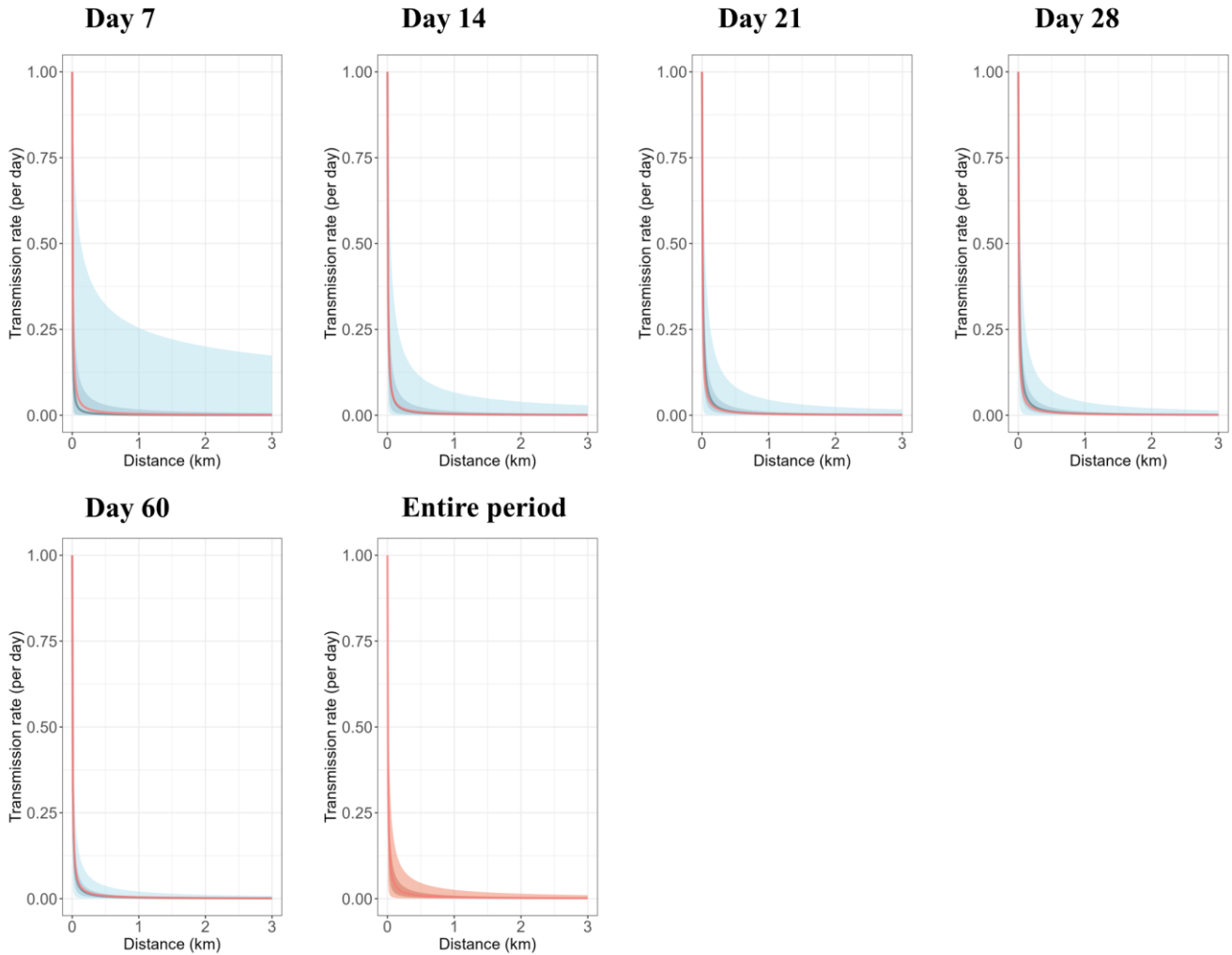


Figure S5(c). Plots of the best-fitting transmission kernel (blue line) and overall transmission kernel (red line) for each timepoint up to the end of the outbreak in Dumfries and Galloway. The blue curve, along with the dark and light blue shaded areas, represents the best-fitting kernel estimated at the timepoint shown in each plot (day 0 = the first notification in each region), along with its 50% and 95% confidence intervals (CIs). The overall transmission kernel estimated using entire data is shown as a red curve, with its 50% and 95% CIs indicated by dark red and light red shading, respectively. The similarity between kernels was assessed by checking whether the overall transmission kernel curve falls within the CI envelopes of the best-fitting kernel.

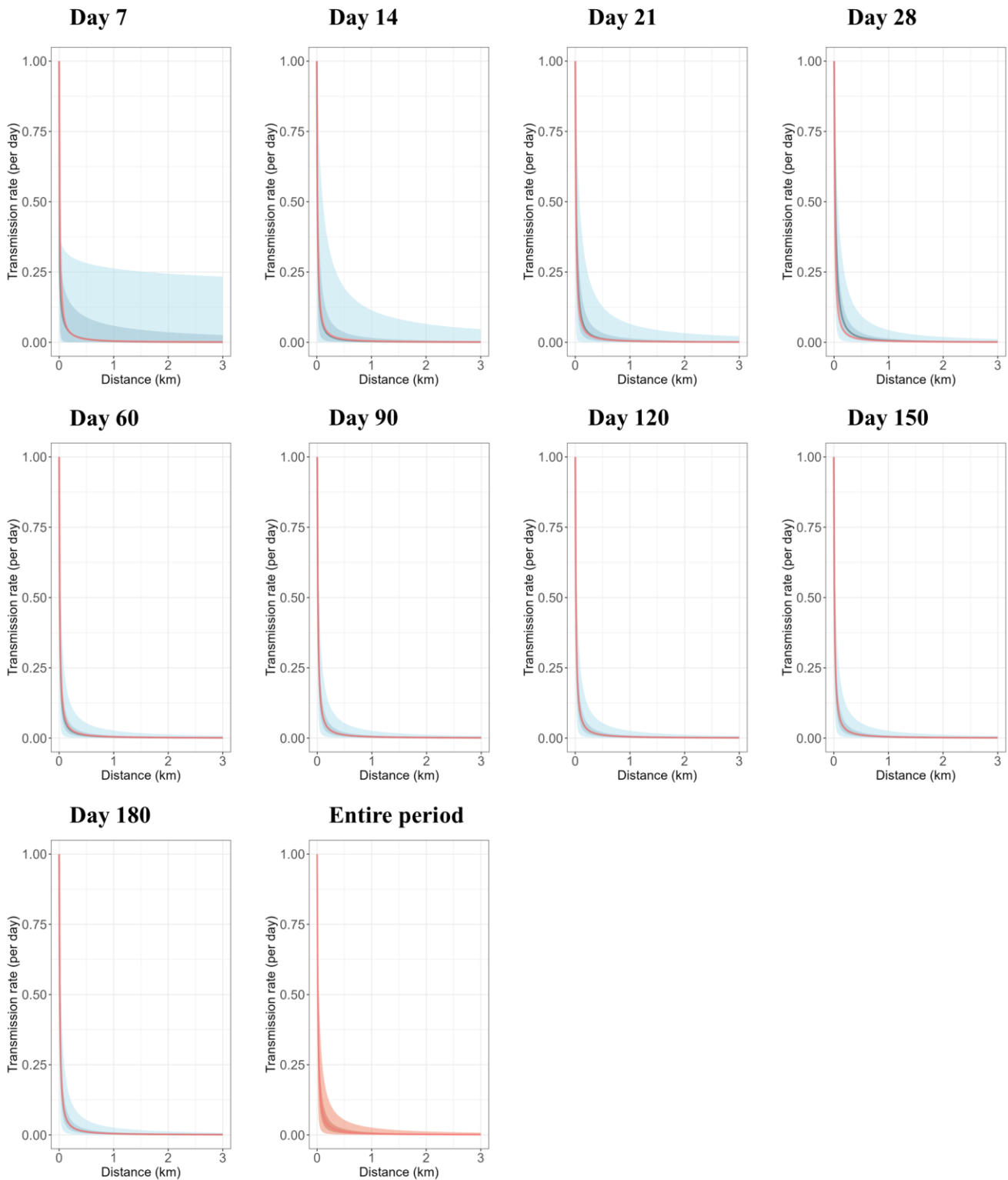


Figure S5(d). Plots of the best-fitting transmission kernel (blue line) and overall transmission kernel (red line) for each timepoint up to the end of the outbreak in Durham. The blue curve, along with the dark and light blue shaded areas, represents the best-fitting kernel estimated at the timepoint shown in each plot (day 0 = the first notification in each region), along with its 50% and 95% confidence intervals (CIs). The overall transmission kernel estimated using entire data is shown as a red curve, with its 50% and 95% CIs indicated by dark red and light red shading, respectively. The similarity between kernels was assessed by checking whether the overall transmission kernel curve falls within the CI envelopes of the best-fitting kernel.

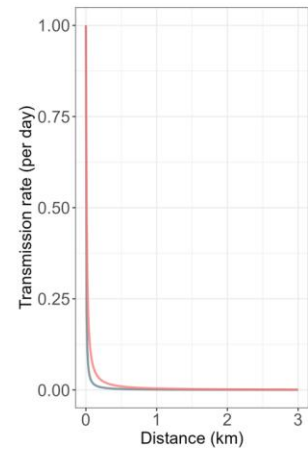
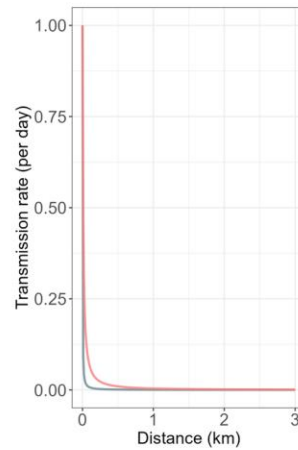
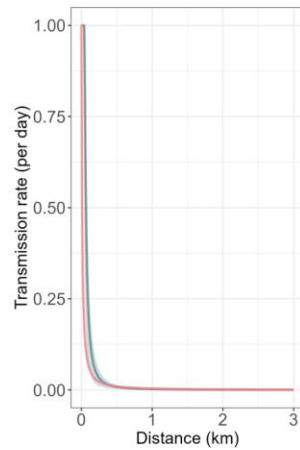
Day 7

Day 14

Day 21

Day 28

N/A

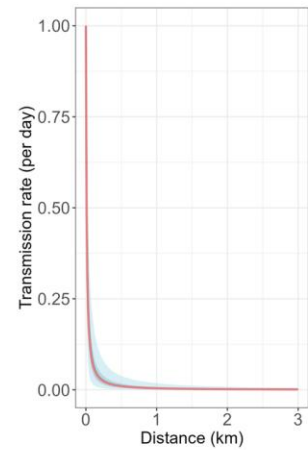
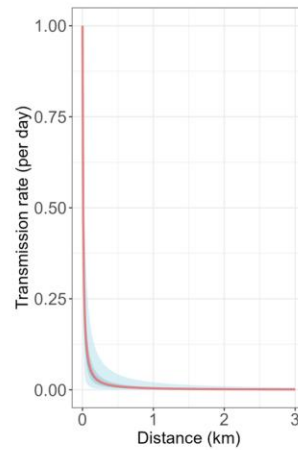
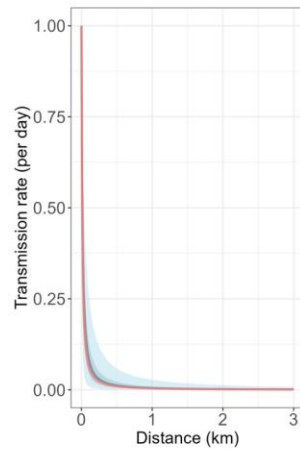
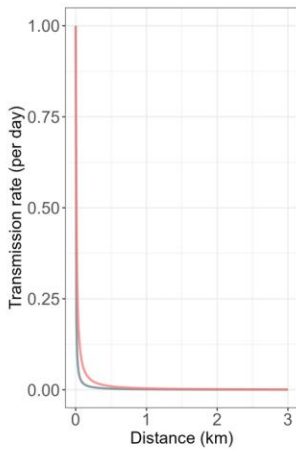


Day 60

Day 90

Day 120

Day 150



Entire period

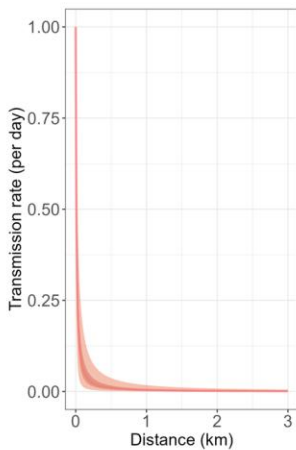


Figure S5(e). Plots of the best-fitting transmission kernel (blue line) and overall transmission kernel (red line) for each timepoint up to the end of the outbreak in North Yorkshire. The blue curve, along with the dark and light blue shaded areas, represents the best-fitting kernel estimated at the timepoint shown in each plot (day 0 = the first notification in each region), along with its 50% and 95% confidence intervals (CIs). The overall transmission kernel estimated using entire data is shown as a red curve, with its 50% and 95% CIs indicated by dark red and light red shading, respectively. The similarity between kernels was assessed by checking whether the overall transmission kernel curve falls within the CI envelopes of the best-fitting kernel. If 50% or 95% CIs for the kernel parameters cannot be estimated, the corresponding CIs for the transmission kernel are not displayed.

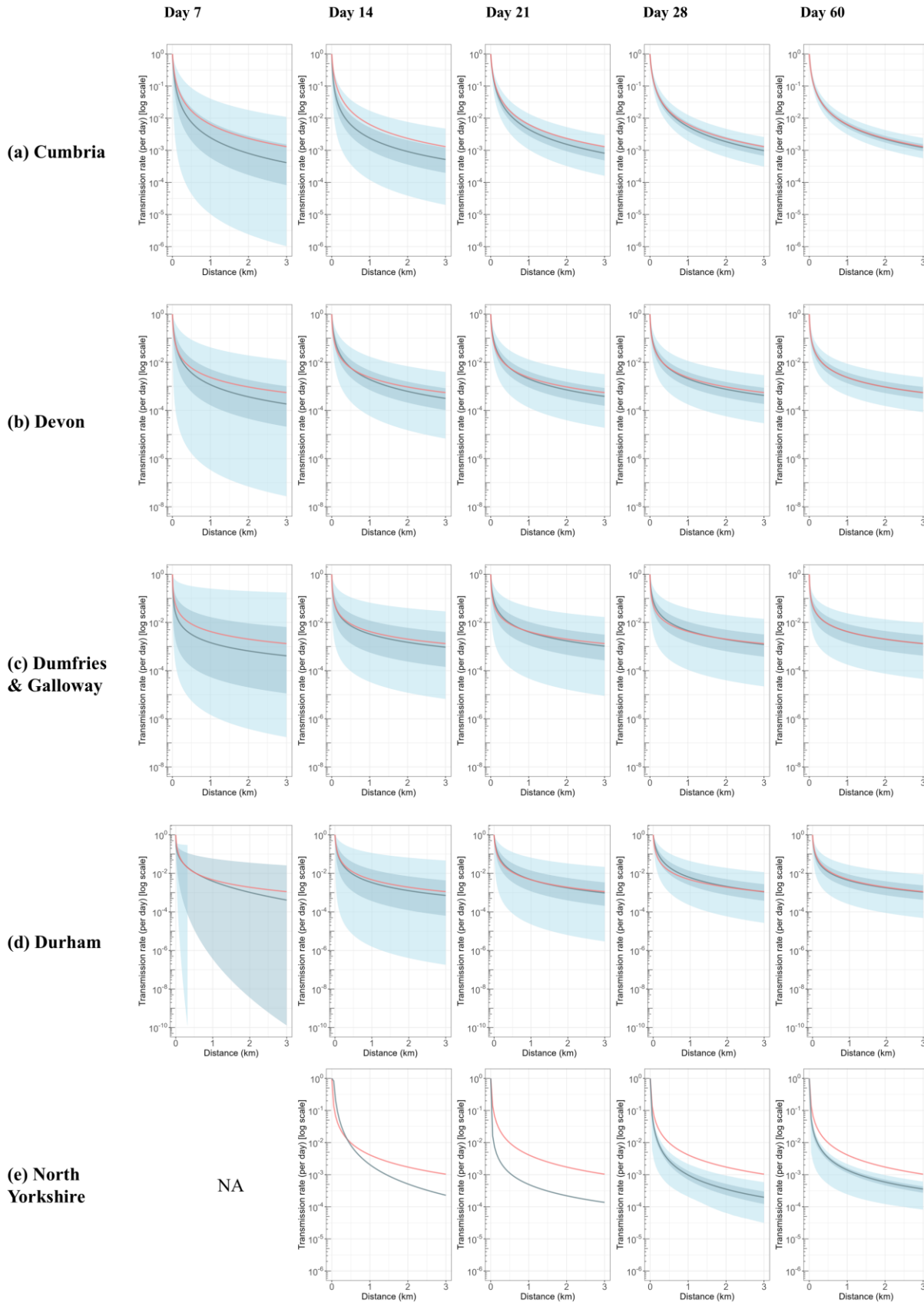


Figure S6. Comparison of the best-fitting and overall transmission kernels for (a) Cumbria, (b) Devon, (c) Dumfries and Galloway (d) Durham, and (e) North Yorkshire. The blue curve and associated dark and light blue shaded areas represent the best-fitting kernel and its 50% and 95% confidence intervals (CIs) estimated at each timepoint, respectively (day 0 = the first notification in each region). The red line represents the overall transmission kernel estimated using the full dataset. The y-axis is presented on a logarithmic scale for clarity.

Table S2. Types of the best-fitting transmission kernels and estimated parameter values along with their 95% and 50% confidence intervals (CIs) for each timepoint in Cumbria, Devon, Dumfries and Galloway, Durham, and North Yorkshire. All parameter values are rounded to three decimal places. If CIs could not be obtained during the maximum likelihood estimation, they were marked as NA.

(a) Cumbria							
Days	The best-fitting kernel type	Ψ (kernel power)	95% CIs	50% CIs	ρ_0 (kernel scale)	95% CIs	50% CIs
7	power law type 2	1.659	1.253-2.100	1.518-1.802	0.028	0.004-0.084	0.016-0.042
14	power law type 2	1.415	1.192-1.633	1.337-1.488	0.014	0.004-0.034	0.010-0.020
21	power law type 2	1.593	1.448-1.739	1.542-1.642	0.035	0.020-0.055	0.029-0.041
28	power law type 2	1.606	1.496-1.716	1.568-1.643	0.041	0.027-0.057	0.036-0.046
60	power law type 2	1.515	1.441-1.587	1.489-1.537	0.036	0.027-0.046	0.033-0.039
90	power law type 2	1.484	1.415-1.553	1.460-1.507	0.033	0.025-0.043	0.030-0.036
120	power law type 2	1.477	1.410-1.541	1.453-1.498	0.033	0.025-0.042	0.030-0.036
150	power law type 2	1.465	1.400-1.526	1.441-1.485	0.032	0.024-0.040	0.029-0.034
180	power law type 2	1.477	1.415-1.536	1.454-1.496	0.034	0.026-0.042	0.031-0.036
entire data	power law type 2	1.478	1.418-1.537	1.457-1.497	0.034	0.027-0.042	0.031-0.036
(b) Devon							
Days	The best-fitting kernel type	Ψ (kernel power)	95% CIs	50% CIs	ρ_0 (kernel scale)	95% CIs	50% CIs
7	power law type 2	1.695	1.172-2.294	1.514-1.880	0.019	0.002-0.071	0.010-0.032
14	power law type 2	1.673	1.384-1.986	1.571-1.774	0.024	0.008-0.056	0.017-0.033
21	power law type 2	1.540	1.318-1.766	1.462-1.615	0.018	0.006-0.039	0.013-0.024
28	power law type 2	1.460	1.263-1.644	1.388-1.519	0.015	0.005-0.030	0.011-0.019
60	power law type 2	1.329	1.194-1.453	1.280-1.370	0.011	0.005-0.019	0.008-0.013
90	power law type 2	1.323	1.193-1.448	1.278-1.366	0.011	0.005-0.019	0.008-0.013
120	power law type 2	1.328	1.197-1.450	1.281-1.369	0.011	0.005-0.019	0.008-0.013
150	power law type 2	1.328	1.197-1.450	1.281-1.369	0.011	0.005-0.019	0.008-0.013
entire data	power law type 2	1.328	1.197-1.450	1.281-1.369	0.011	0.005-0.018	0.008-0.013

(c) Dumfries and Galloway

Days	The best-fitting kernel type	Ψ (kernel power)	95% CIs	50% CIs	ρ_0 (kernel scale)	95% CIs	50% CIs
7	power law type 2	1.148	0.351-1.944	0.874-1.422	0.003	0.001-0.021	0.001-0.009
14	power law type 2	1.152	0.776-1.489	1.005-1.258	0.007	0.001-0.031	0.003-0.012
21	power law type 2	1.248	0.922-1.515	1.125-1.331	0.012	0.001-0.036	0.006-0.018
28	power law type 2	1.219	0.940-1.449	1.113-1.291	0.012	0.002-0.033	0.007-0.017
60	fat-tailed	1.050	0.850-1.249	0.981-1.118	0.005	0.001-0.013	0.003-0.008
entire data	power law type 2	1.054	0.847-1.261	0.983-1.125	0.006	0.001-0.014	0.003-0.008

(d) Durham

Days	The best-fitting kernel type	Ψ (kernel power)	95% CIs	50% CIs	ρ_0 (kernel scale)	95% CIs	50% CIs
7	exponential type 3	0.310	0.078-0.543	0.230-0.390	0.004	0.001-0.024	0.001-0.011
14	power law type 2	1.412	0.865-1.976	1.218-1.597	0.018	0.001-0.089	0.007-0.035
21	power law type 2	1.464	1.064-1.869	1.325-1.598	0.026	0.003-0.084	0.015-0.042
28	power law type 2	1.584	1.276-1.908	1.477-1.692	0.041	0.012-0.094	0.029-0.056
60	power law type 2	1.257	1.040-1.470	1.182-1.328	0.013	0.003-0.032	0.009-0.018
90	power law type 2	1.306	1.094-1.509	1.228-1.371	0.017	0.005-0.037	0.011-0.022
120	power law type 2	1.305	1.095-1.509	1.229-1.372	0.017	0.005-0.037	0.011-0.022
150	power law type 2	1.305	1.095-1.509	1.229-1.372	0.017	0.005-0.037	0.011-0.022
180	power law type 2	1.305	1.095-1.509	1.229-1.372	0.017	0.005-0.037	0.011-0.022
entire data	power law type 2	1.307	1.097-1.512	1.232-1.374	0.017	0.005-0.037	0.012-0.022

(e) North Yorkshire

Days	The best-fitting kernel type	Ψ (kernel power)	95% CIs	50% CIs	ρ_0 (kernel scale)	95% CIs	50% CIs
7	NA						
14	Cauchy	0.002	NA -0.006	0.001-0.003			
21	power law type 2	1.173	0.526-2.010	1.015-1.513	0.002	NA -0.077	0.001-0.019
28	power law type 2	1.227	0.402-1.996	0.943-1.486	0.004	NA -0.069	0.001-0.015
60	power law type 2	1.122	0.669-1.575	0.966-1.278	0.003	NA -0.013	0.002-0.007

90	power law type 2	1.372	1.155-1.583	1.296-1.443	0.020	0.006-0.047	0.014-0.028
120	power law type 2	1.254	1.078-1.425	1.194-1.313	0.012	0.004-0.028	0.009-0.017
150	power law type 2	1.291	1.133-1.441	1.235-1.341	0.015	0.006-0.030	0.011-0.019
entire data	power law type 2	1.269	1.116-1.418	1.217-1.320	0.013	0.005-0.027	0.010-0.018

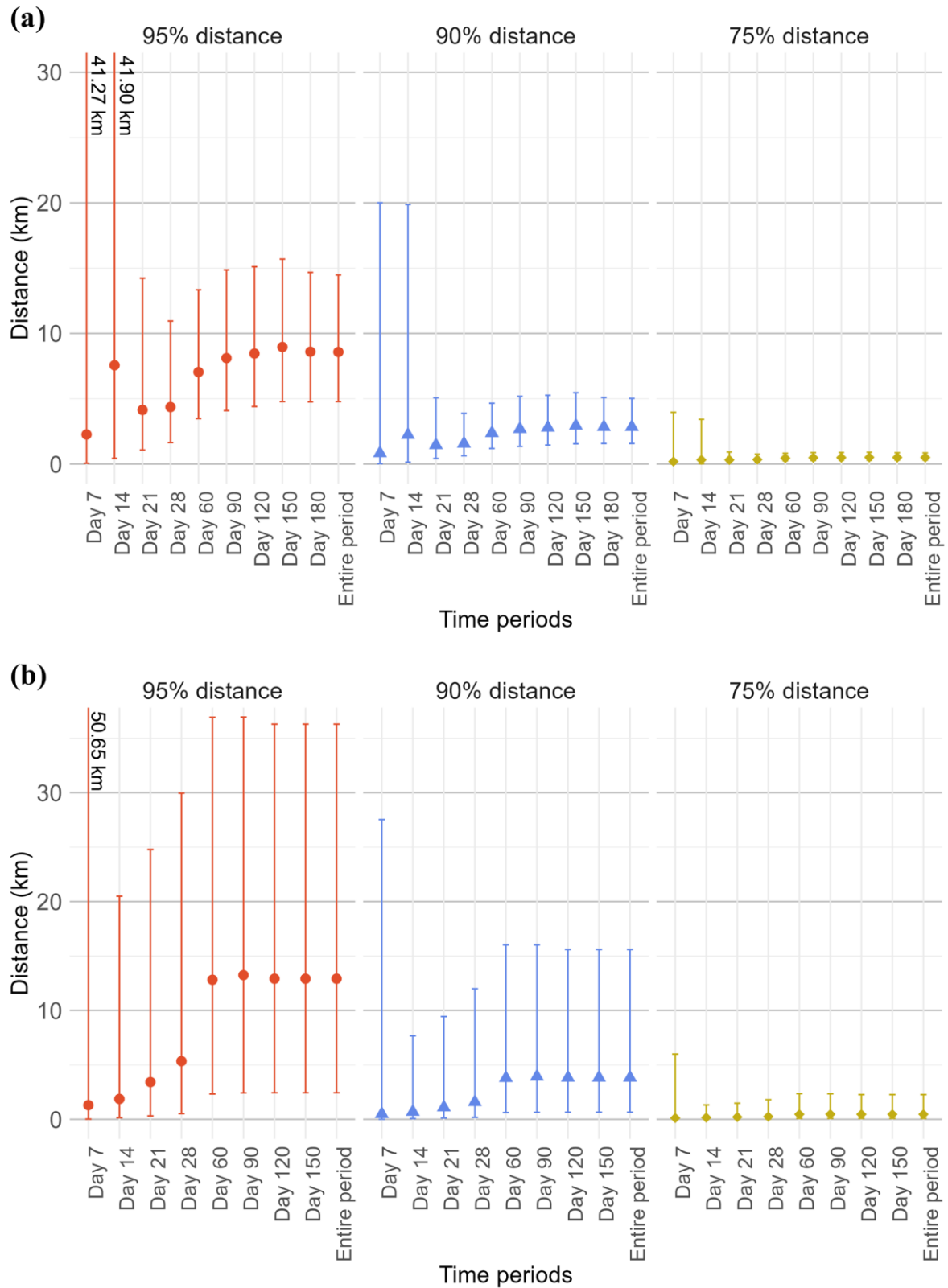


Figure S7. The estimated 95%, 90%, and 75% distances at each timepoint for (a) Cumbria and (b) Devon. The 95%, 90%, and 75% distances represent the radii within which 95%, 90%, and 75% of disease spread from a single infected premises are expected to occur. Shorter distances indicate that most transmissions occur over shorter ranges. When the 95% confidence intervals (CIs) of the estimates exceeded the y-axis range, the upper limit of the 95% CIs was recorded next to the corresponding cropped error bar.

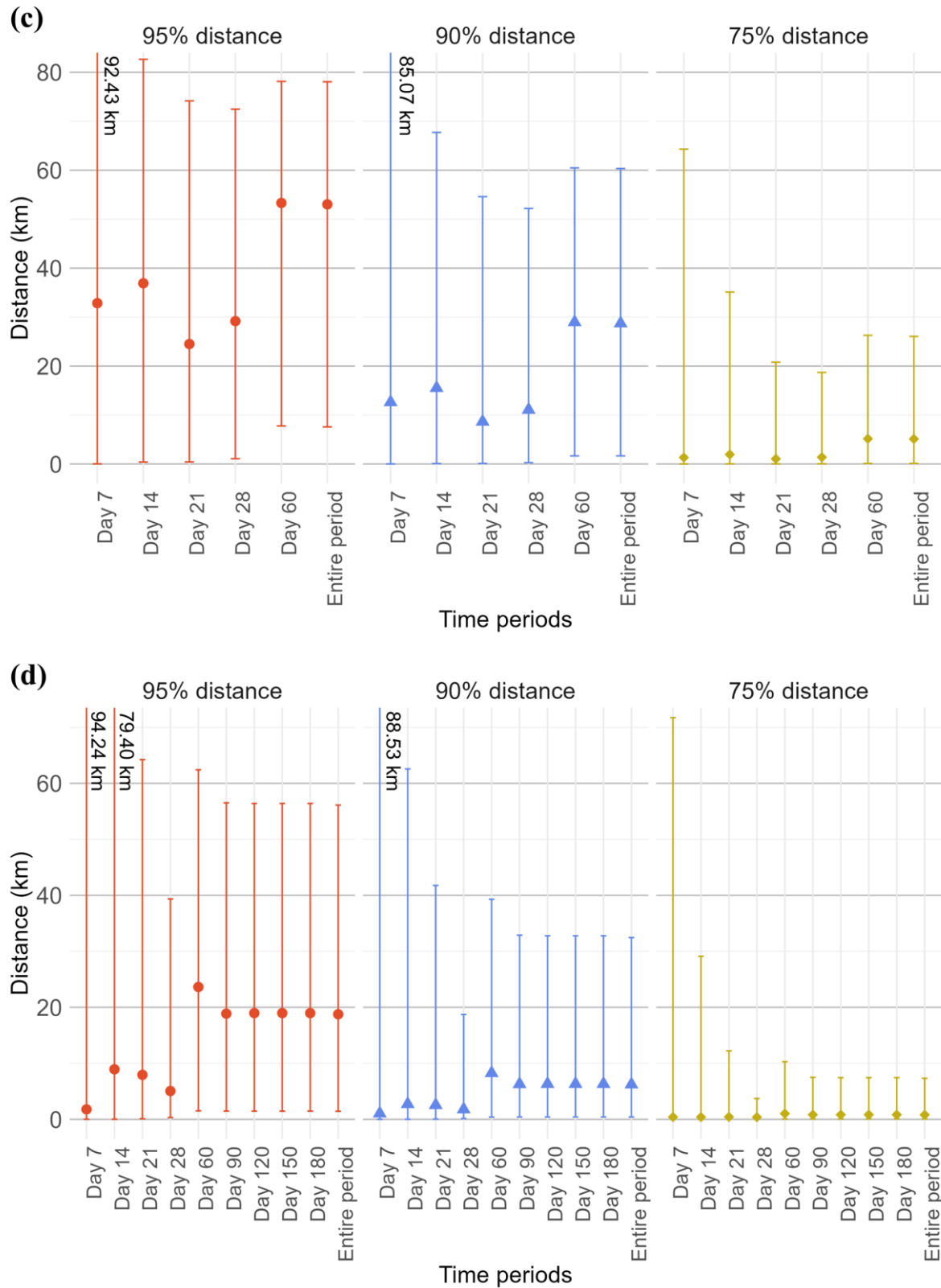


Figure S7. The estimated distance encompassing 95%, 90%, and 75% of the risk density at each timepoint for (c) Dumfries and Galloway and (d) Durham. The 95%, 90%, and 75% distances represent the radii within which 95%, 90%, and 75% of disease spread from a single infected premises are expected to occur. Shorter distances indicate that most transmissions occur over shorter ranges. When the 95% confidence intervals (CIs) of the estimates exceeded the y-axis range, the upper limit of the 95% CIs was recorded next to the corresponding cropped error bar.

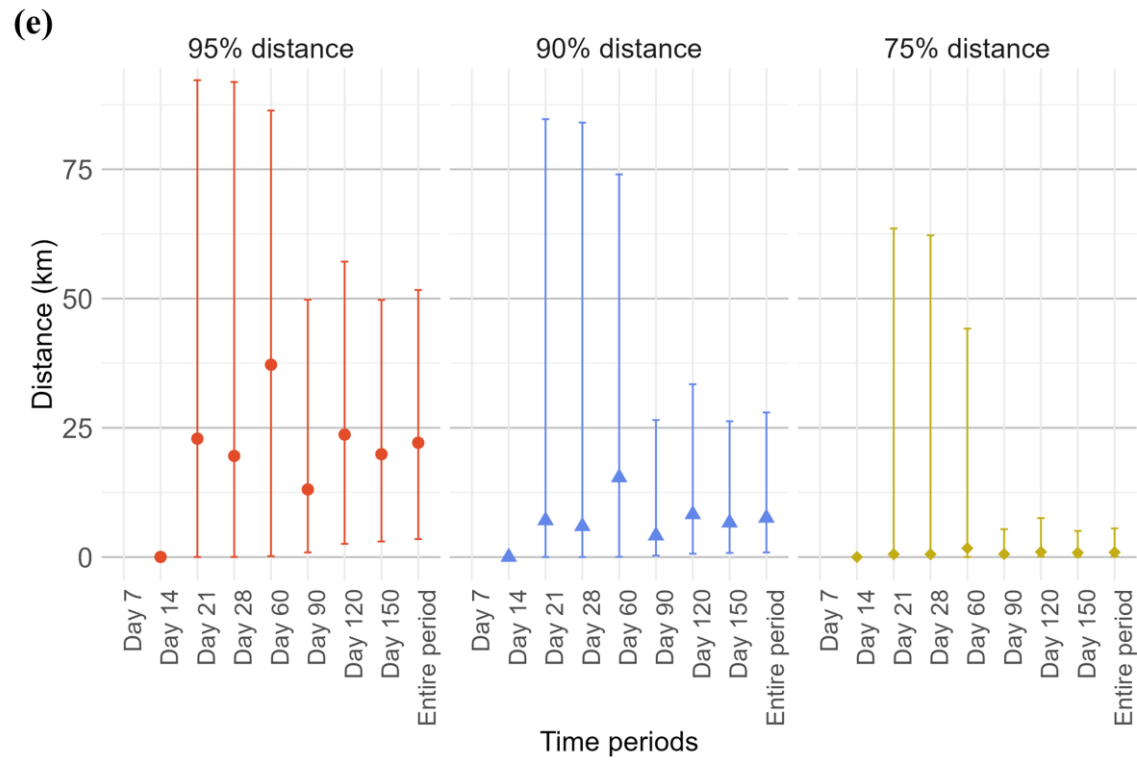


Figure S7. The estimated distance encompassing 95%, 90%, and 75% of the risk density at each timepoint for (e) North Yorkshire. The 95%, 90%, and 75% distances represent the radii within which 95%, 90%, and 75% of disease spread from a single infected premises are expected to occur. Shorter distances indicate that most transmissions occur over shorter ranges. Kernel estimation was not possible at day 7 due to the presence of only a single case.

D. Short-term projection of spatial risk using a kernel-derived infection pressure metric

Figures S8 and S9 illustrate the relative infection pressure of susceptible premises at each time point (day 7, 14, 21, and 28), calculated based on the locations of infectious premises (not culled yet at that moment). Figure S8 presents a classification of susceptible premises into quintiles of relative infection pressure, grouping premises within the same risk category. Figure S9 visualises susceptible premises spatially by generating contour lines based on infection pressure values, thereby identifying regions with similar risk levels. Across all regions, during the first four weeks, premises belonging to higher quintiles of relative infection pressure were more likely to become infected with FMD within the subsequent 7 days (see **Tables S3 and S4** for incidence risk ratios).

Table S3 presents a comparative assessment of predictive performance in Cumbria, the region with the largest outbreak. The comparison includes kernel-derived infection pressure, species-informed infection pressure incorporating livestock composition, and conventional zoning approaches (3 km and 10 km zones). The species-informed infection pressure accounts for the numbers of sheep, cattle, and pigs and was calculated following the approach proposed by Jewell *et al* (3). The infection pressure exerted by infectious premises i on susceptible j ($\lambda_{i \rightarrow j}(t)$) is calculated as follows:

$$\lambda_{i \rightarrow j}(t) = \beta \times (\text{sheep}_i^\chi + \zeta_1 \text{cattle}_i^\chi + \zeta_2 \text{pigs}_i^\chi) \times (\text{sheep}_j^\chi + \xi_1 \text{cattle}_j^\chi + \xi_2 \text{pigs}_j^\chi) \times k(r_{ij}),$$

where β denotes the background transmission rate, and ζ_1 and ζ_2 represent the relative infectivity of cattle and pigs, respectively, with sheep used as the reference species. Similarly, ξ_1 and ξ_2 represent the relative susceptibility of cattle and pigs, respectively. The parameter χ captures the nonlinear scaling of infectivity or susceptibility with respect to livestock population size. The term $k(r_{ij})$ denotes the best-fitting transmission kernel as a function of distance r_{ij} at the given time point. The parameters were estimated using maximum likelihood based only on data available up to each time point, following the procedure described in Section B.2. In addition, among competing kernel candidates, the kernel with the lowest AIC was selected as the best-fitting kernel. For Cumbria, across all time points (day 7, 14, 21, and 28), the power law type 2 kernel was consistently identified as the best-fitting model, consistent with the kernel-only estimation (**Figure S3**). However, the inclusion of species-related parameters increased the number of parameters to be estimated, resulting in substantially higher computational demand under the same computing environment.

Notably, the classification performance of kernel-derived infection pressure and species-informed infection pressure showed no substantial differences overall (**Figure S3**). At day 7, kernel-derived infection pressure appeared to more effectively discriminate premises that would become infected within the next 7 days. This may be due to the increased number of parameters in the species-informed model, which makes stable parameter estimation challenging when only limited early outbreak data are available. In contrast, at days 21 and 28, species-informed infection pressure tended to provide finer discrimination among low-risk premises. For example, among premises classified in the lowest 20% under the species-informed metric, only 1 infection (day 21) and 0 infections (day 28) were observed in the subsequent 7-day period. In comparison, kernel-derived infection pressure recorded 2 and 1 infections in the same quintile, respectively. These results suggest that while species-informed approaches may be advantageous for fine-scale risk stratification, the kernel-based approach is more practical in the early stages of an outbreak, where rapid risk assessment is required and data availability is limited.

Under conventional zoning, a substantial proportion of premises that became infected within the following 7 days were located within 10 km of infectious premises (**Figure S3**). However, many of these infected premises were located in the 3–10 km surveillance zone rather than the 3 km protection zone, where more

intensive control measures are typically implemented. Moreover, conventional zoning assigns the same risk category even when a susceptible premise is located near a single infectious premise, thereby failing to account for cumulative exposure from multiple infectious sources. As a result, its ability to differentiate risk levels is more limited compared with kernel-derived infection pressure, which explicitly integrates contributions from multiple infectious premises.

Kernel-derived infection pressure analysis indicated that most premises infected within the next 7 days belonged to the top 40% of relative infection pressure (**Tables S3 and S4**). As shown in **Figure S10**, the top 40% cutoff maintained high sensitivity, indicating a low false negative rate when used as a screening criterion. In contrast, the optimal threshold derived from Youden's J statistic was, except for one time point (Dumfries and Galloway, day 21), similar to or slightly higher than the top 40% cutoff. This suggests that increasing the cutoff could further improve specificity with minimal loss in sensitivity. However, such optimal thresholds are derived retrospectively and may have limited applicability in real-time outbreak settings. Therefore, in the early phase of an outbreak, a pragmatic cutoff such as the top 40% may provide a useful balance between sensitivity and operational feasibility.

Receiver operating characteristic results demonstrated that kernel-derived infection pressure had strong discriminatory ability for predicting future infection with FMD. This performance was substantially better than random classification, indicating that infection pressure is a useful predictor of future infection risk. These findings were also consistent with Cox proportional hazards models, which showed a significant positive association between infection pressure and subsequent infection risk (**Figures S11–S12**).

Although risk levels were evaluated using quintile-based categorisation in this study, threshold selection in practice may be adjusted depending on control objectives. In scenarios where the cost of missing infected premises is high, a broader definition such as the top 60% may be used to maximise case capture. Conversely, when resources are constrained, prioritising the top 20% or 40% may be more appropriate, with gradual expansion of coverage as required. Therefore, appropriate risk thresholds should be determined by considering national control capacity, available resources, and the severity of the outbreak situation.

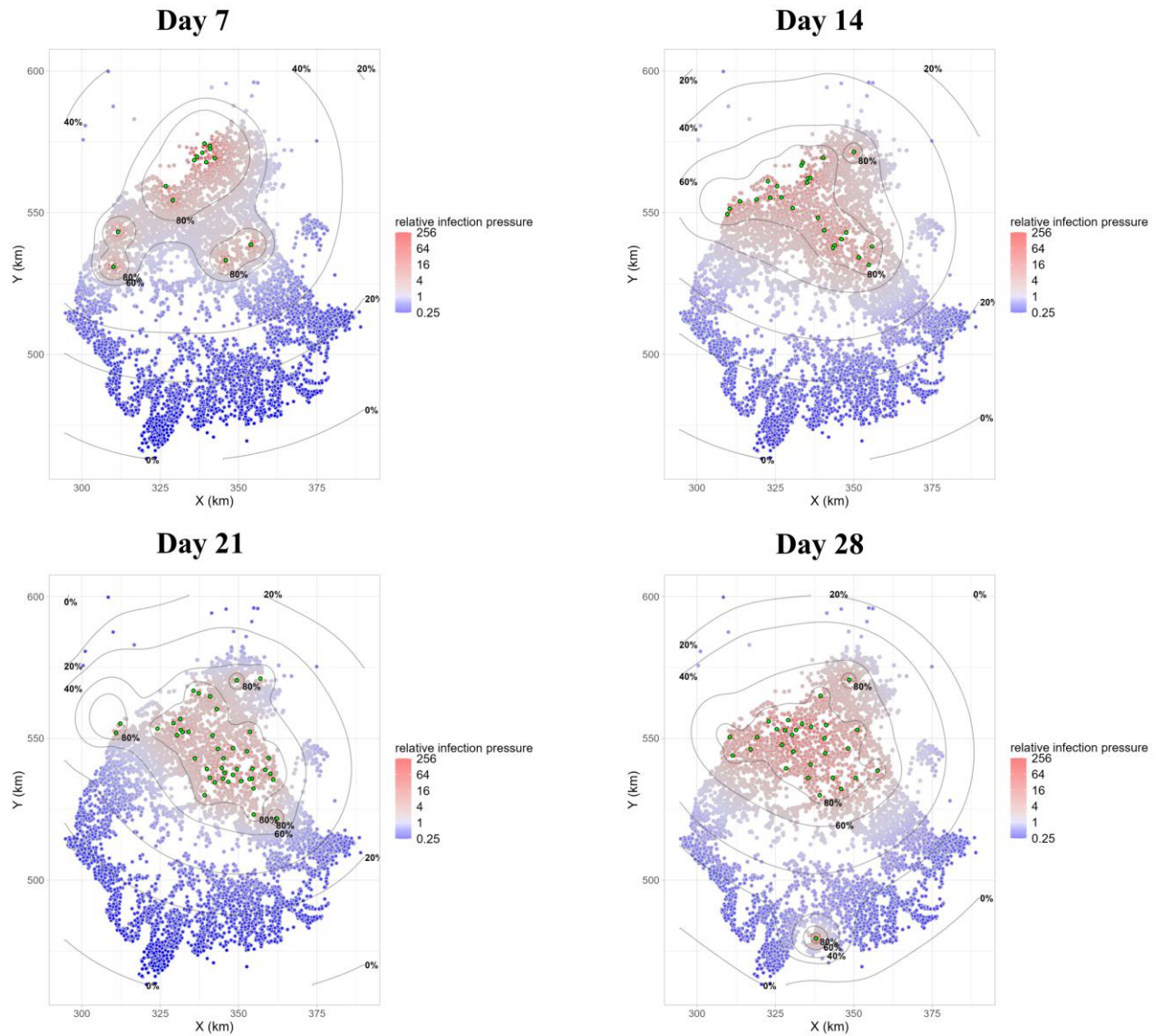


Figure S8(a). Maps of relative infection pressure calculated using the best-fitting transmission kernels at each timepoint (days 7, 14, 21, and 28) for Cumbria. Contour lines generated using thin-plate spline interpolation represent the boundaries between infection pressure quintiles (0%, 20%, 40%, 60%, and 80%), connecting locations with the same percentile rank of relative infection pressure. Premises are represented by circles, with green circles denoting infectious premises that had been confirmed as infected but had not yet been culled at the corresponding timepoint. Premises with relative infection pressure above one are shaded in a gradient of red, while those below one are shaded in a gradient of blue. A relative infection pressure value of 1 corresponds to the median infection pressure among susceptible premises at the corresponding timepoint.

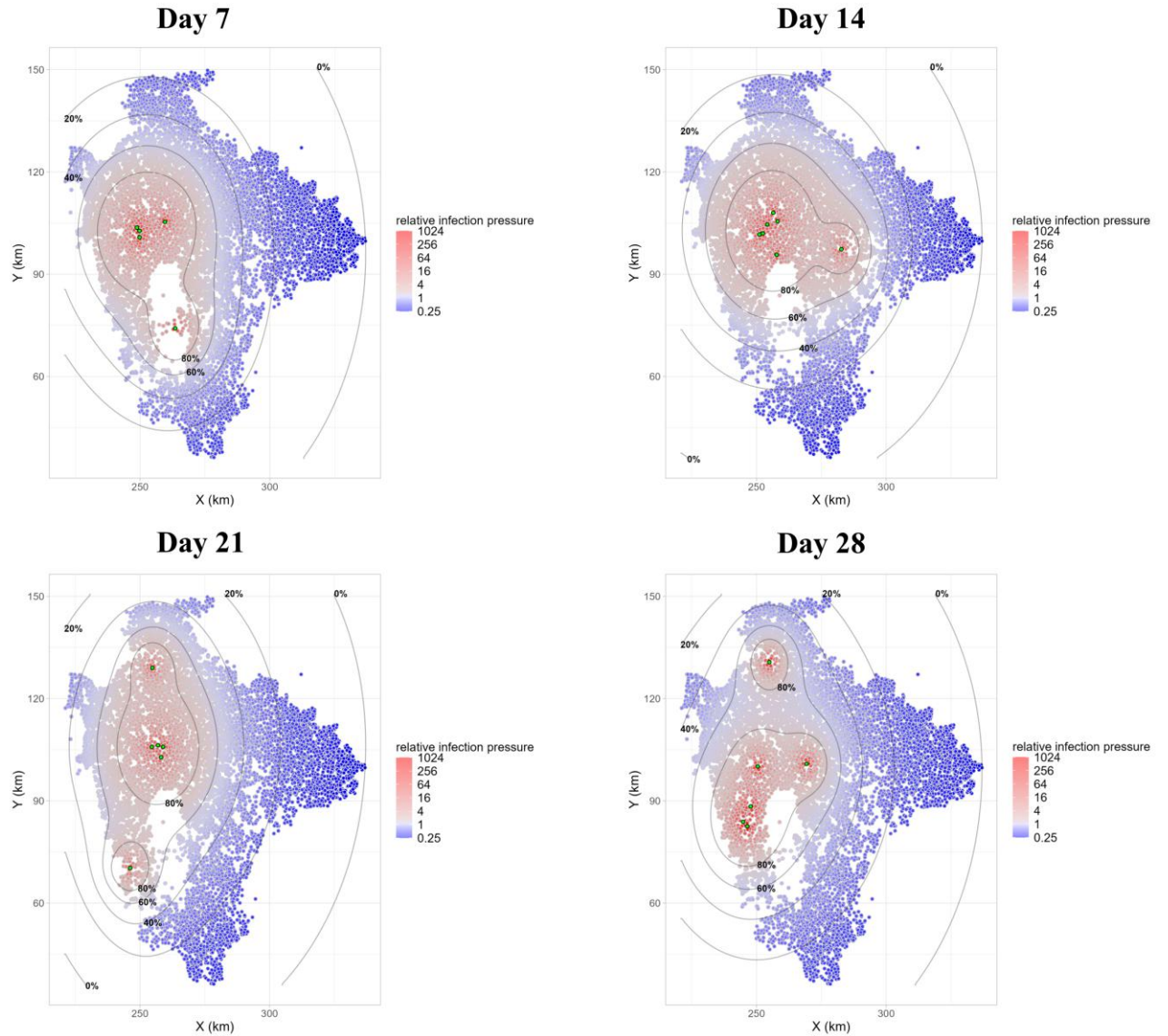


Figure S8(b). Maps of relative infection pressure calculated using the best-fitting transmission kernels at each timepoint (days 7, 14, 21, and 28) for Devon. Contour lines generated using thin-plate spline interpolation represent the boundaries between infection pressure quintiles (0%, 20%, 40%, 60%, and 80%), connecting locations with the same percentile rank of relative infection pressure. Premises are represented by circles, with green circles denoting infectious premises that had been confirmed as infected but had not yet been culled at the corresponding timepoint. Premises with relative infection pressure above one are shaded in a gradient of red, while those below one are shaded in a gradient of blue. A relative infection pressure value of 1 corresponds to the median infection pressure among susceptible premises at the corresponding timepoint.

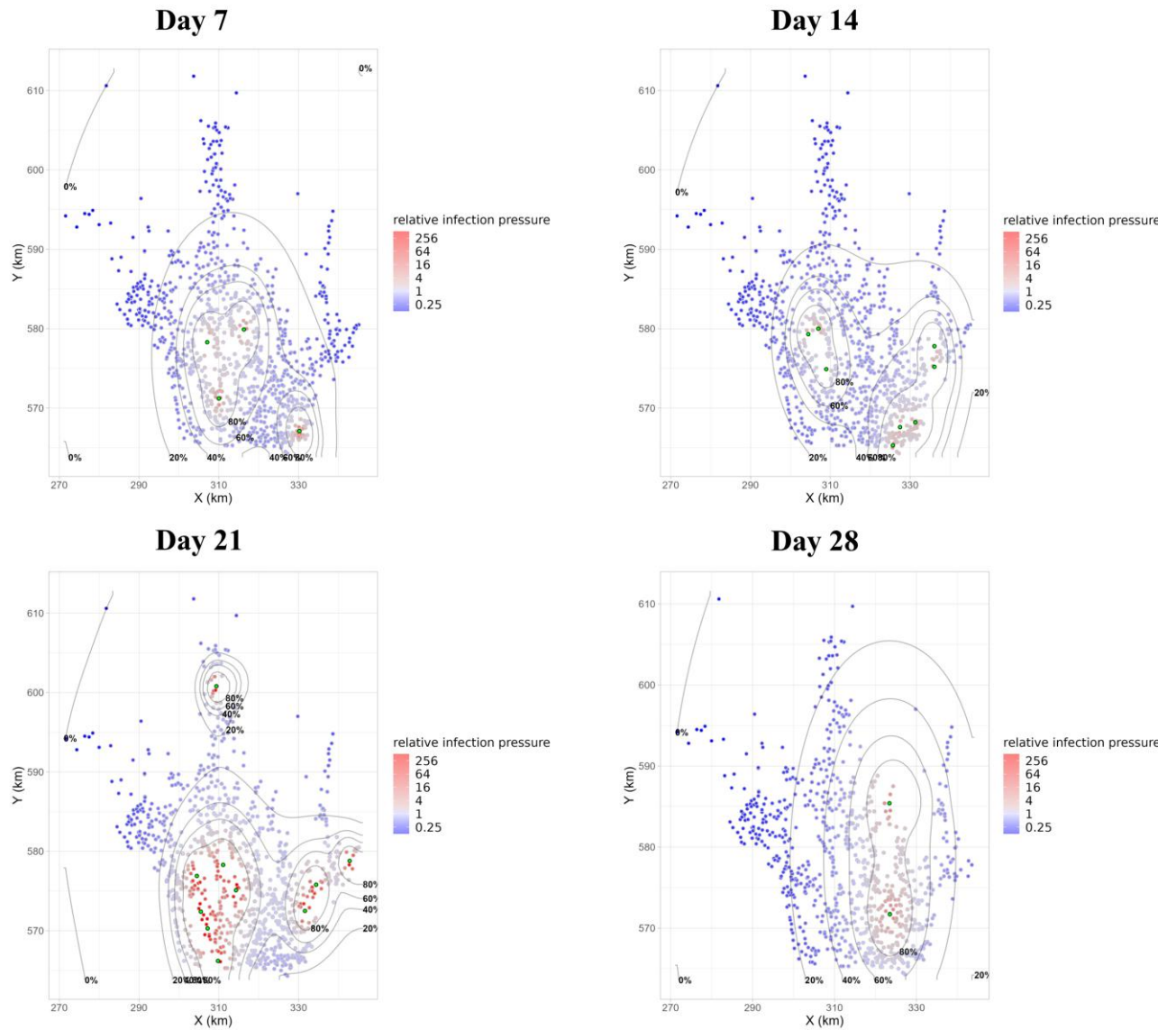


Figure S8(c). Maps of relative infection pressure calculated using the best-fitting transmission kernels at each timepoint (days 7, 14, 21, and 28) for Dumfries and Galloway. Contour lines generated using thin-plate spline interpolation represent the boundaries between infection pressure quintiles (0%, 20%, 40%, 60%, and 80%), connecting locations with the same percentile rank of relative infection pressure. Premises are represented by circles, with green circles denoting infectious premises that had been confirmed as infected but had not yet been culled at the corresponding timepoint. Premises with relative infection pressure above one are shaded in a gradient of red, while those below one are shaded in a gradient of blue. A relative infection pressure value of 1 corresponds to the median infection pressure among susceptible premises at the corresponding timepoint.

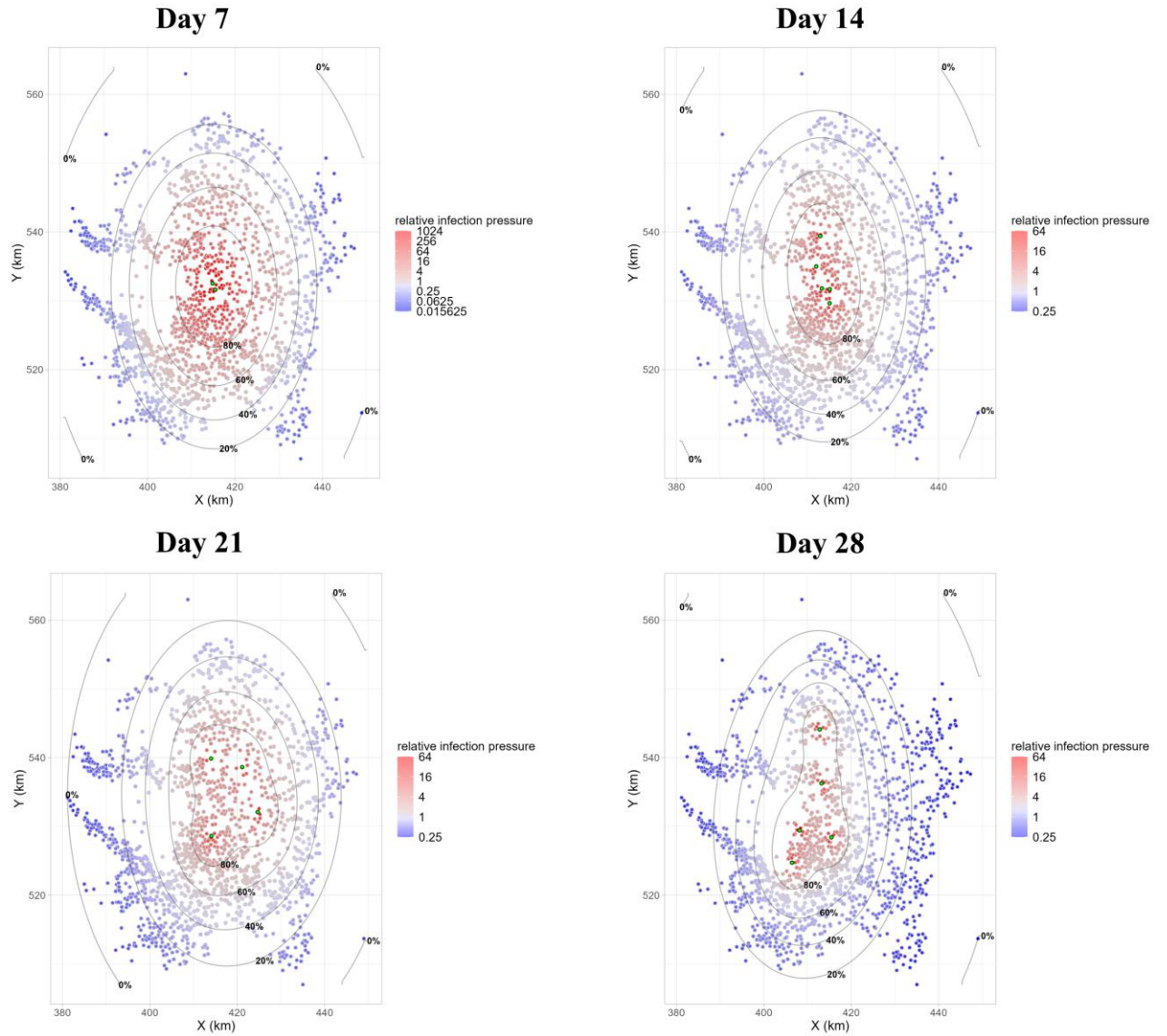


Figure S8(d). Maps of relative infection pressure calculated using the best-fitting transmission kernels at each timepoint (days 7, 14, 21, and 28) for Durham. Contour lines generated using thin-plate spline interpolation represent the boundaries between infection pressure quintiles (0%, 20%, 40%, 60%, and 80%), connecting locations with the same percentile rank of relative infection pressure. Premises are represented by circles, with green circles denoting infectious premises that had been confirmed as infected but had not yet been culled at the corresponding timepoint. Premises with relative infection pressure above one are shaded in a gradient of red, while those below one are shaded in a gradient of blue. A relative infection pressure value of 1 corresponds to the median infection pressure among susceptible premises at the corresponding timepoint.

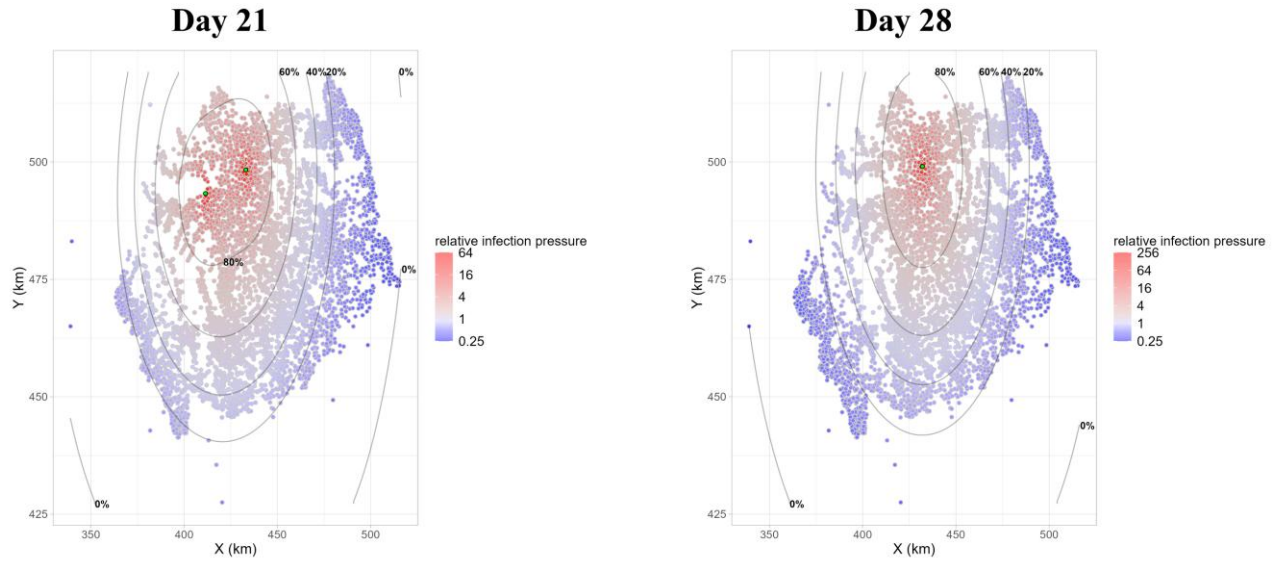


Figure S8(e). Maps of relative infection pressure calculated using the best-fitting transmission kernels at each timepoint (days 21 and 28) for North Yorkshire. Contour lines generated using thin-plate spline interpolation represent the boundaries between infection pressure quintiles (0%, 20%, 40%, 60%, and 80%), connecting locations with the same percentile rank of relative infection pressure. Premises are represented by circles, with green circles denoting infectious premises that had been confirmed as infected but had not yet been culled at the corresponding timepoint. Premises with relative infection pressure above one are shaded in a gradient of red, while those below one are shaded in a gradient of blue. A relative infection pressure value of 1 corresponds to the median infection pressure among susceptible premises at the corresponding timepoint.

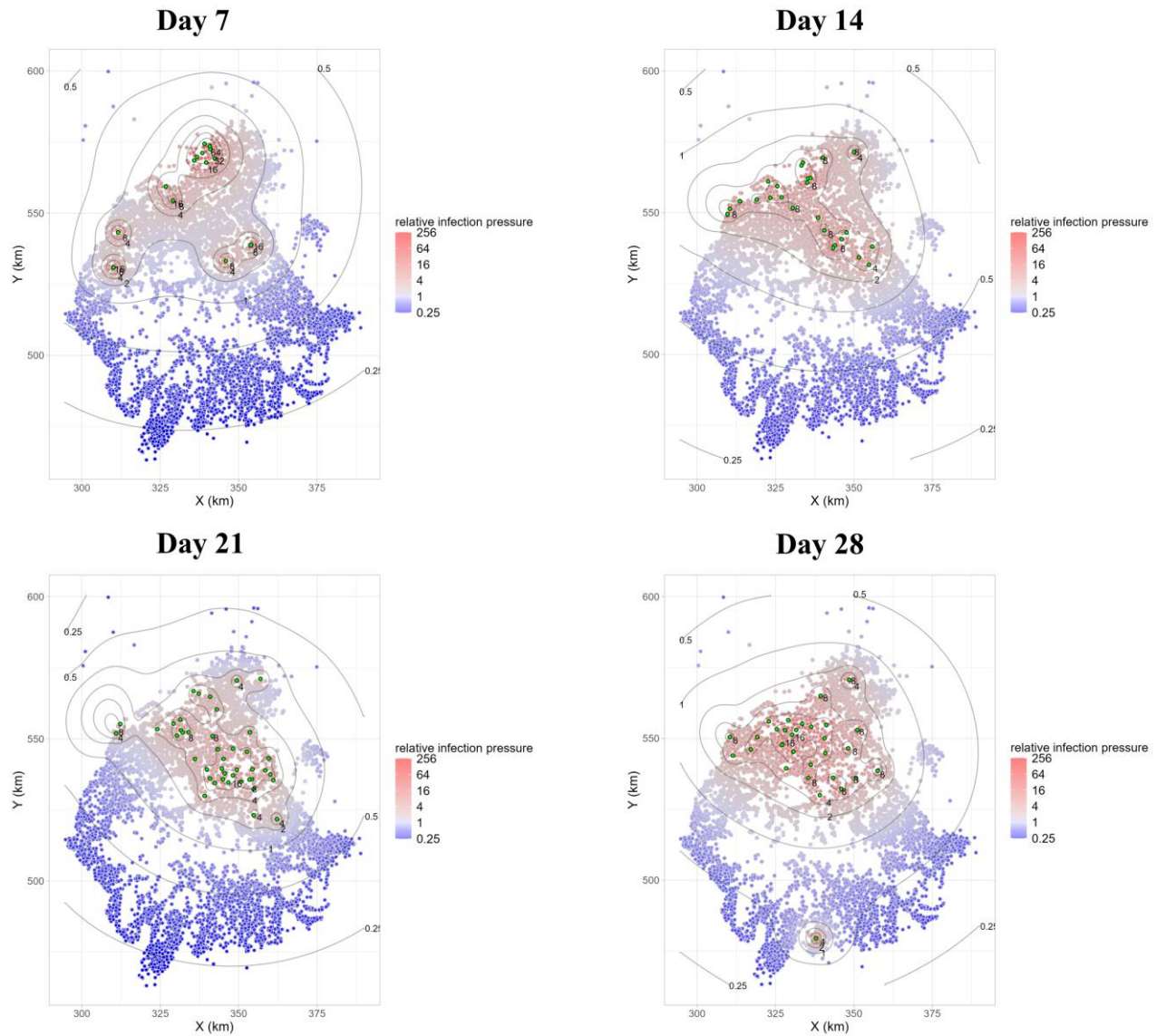


Figure S9(a). Maps of relative infection pressure calculated using the best-fitting transmission kernels at each timepoint (days 7, 14, 21, and 28) for Cumbria. Contour lines, generated using a thin-plate spline, connect locations with identical relative infection pressures. Premises are represented by circles, with green circles denoting infected premises (those with clinical signs onset but not yet depopulated) at the corresponding timepoint. Premises with relative infection pressure above one are shaded in a gradient of red, while those below one are shaded in a gradient of blue.

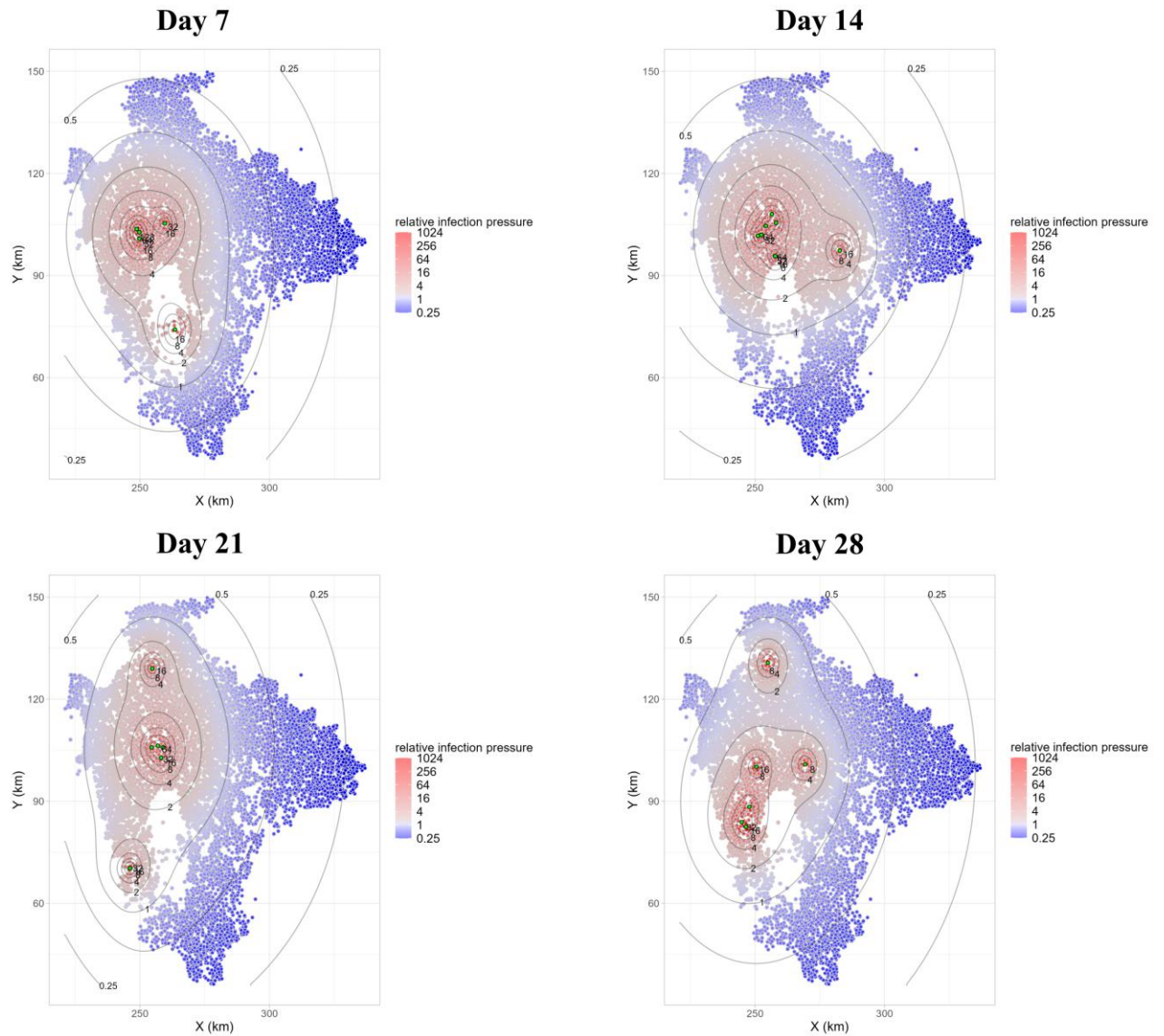


Figure S9(b). Maps of relative infection pressure calculated using the best-fitting transmission kernels at each timepoint (days 7, 14, 21, and 28) for Devon. Contour lines, generated using a thin-plate spline, connect locations with identical relative infection pressures. Premises are represented by circles, with green circles denoting infected premises (those with clinical signs onset but not yet depopulated) at the corresponding timepoint. Premises with relative infection pressure above one are shaded in a gradient of red, while those below one are shaded in a gradient of blue.

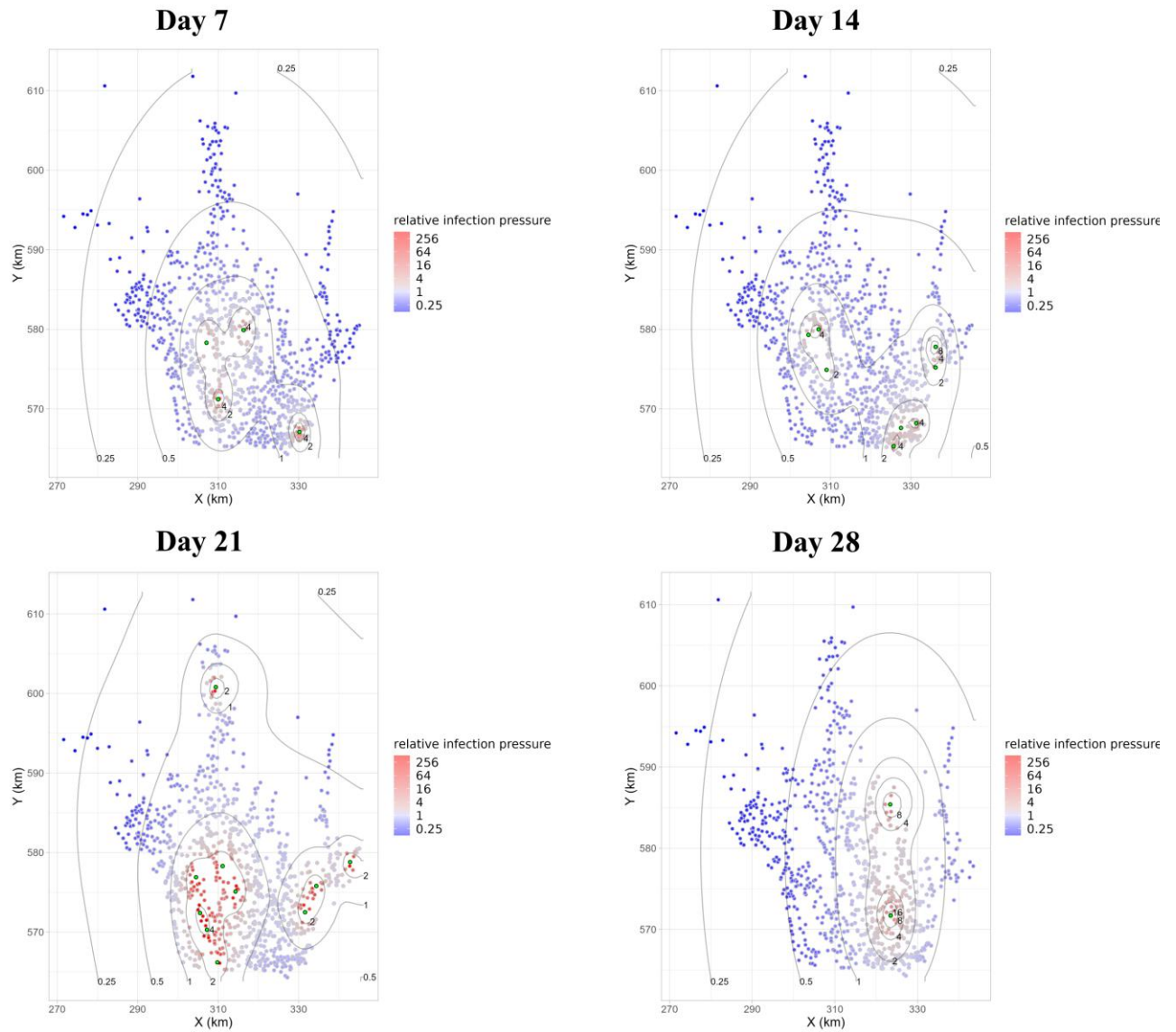


Figure S9(c). Maps of relative infection pressure calculated using the best-fitting transmission kernels at each timepoint (days 7, 14, 21, and 28) for Dumfries and Galloway. Contour lines, generated using a thin-plate spline, connect locations with identical relative infection pressures. Premises are represented by circles, with green circles denoting infected premises (those with clinical signs onset but not yet depopulated) at the corresponding timepoint. Premises with relative infection pressure above one are shaded in a gradient of red, while those below one are shaded in a gradient of blue.

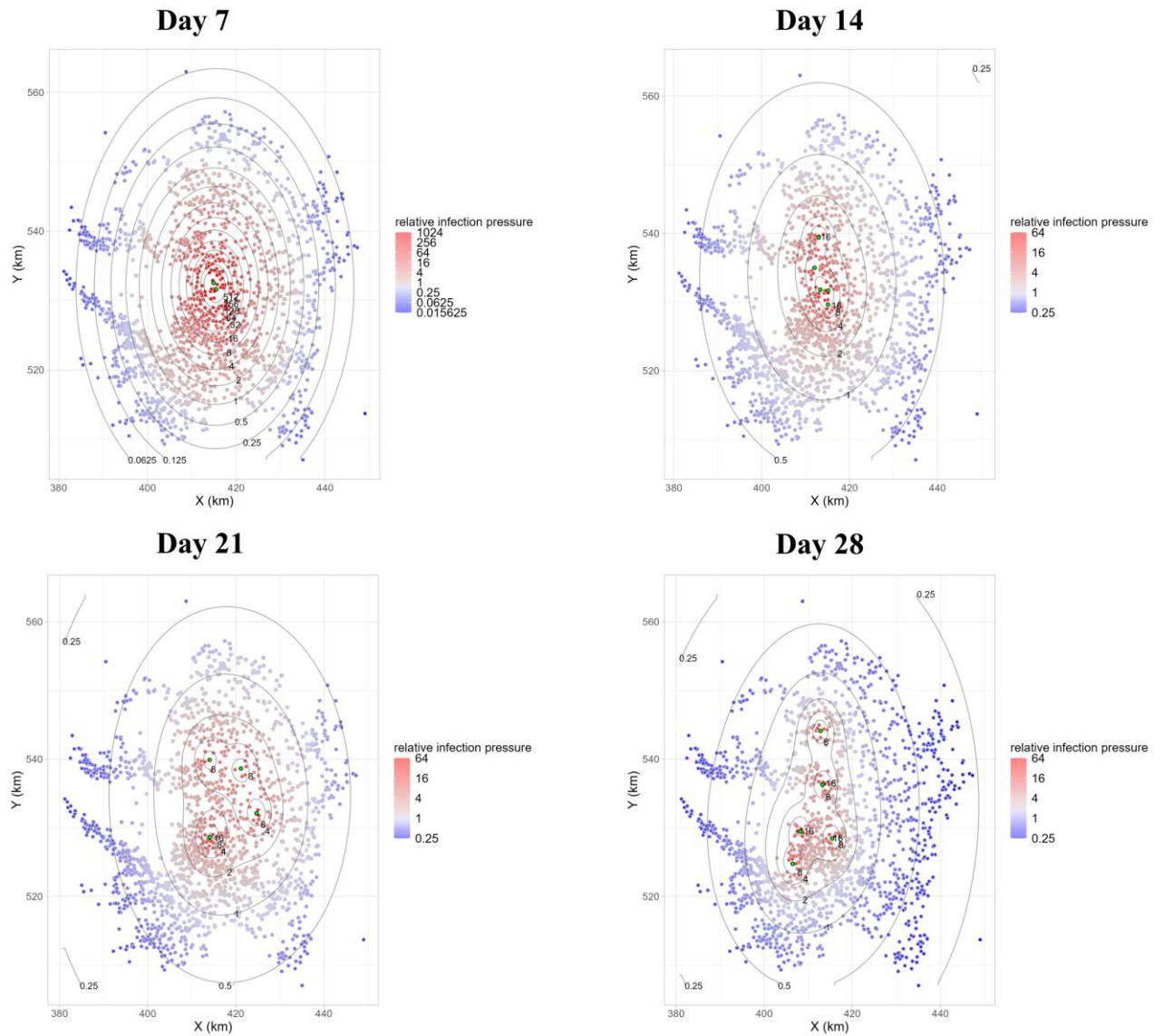


Figure S9(d). Maps of relative infection pressure calculated using the best-fitting transmission kernels at each timepoint (days 7, 14, 21, and 28) for Durham. Contour lines, generated using a thin-plate spline, connect locations with identical relative infection pressures. Premises are represented by circles, with green circles denoting infected premises (those with clinical signs onset but not yet depopulated) at the corresponding timepoint. Premises with relative infection pressure above one are shaded in a gradient of red, while those below one are shaded in a gradient of blue.

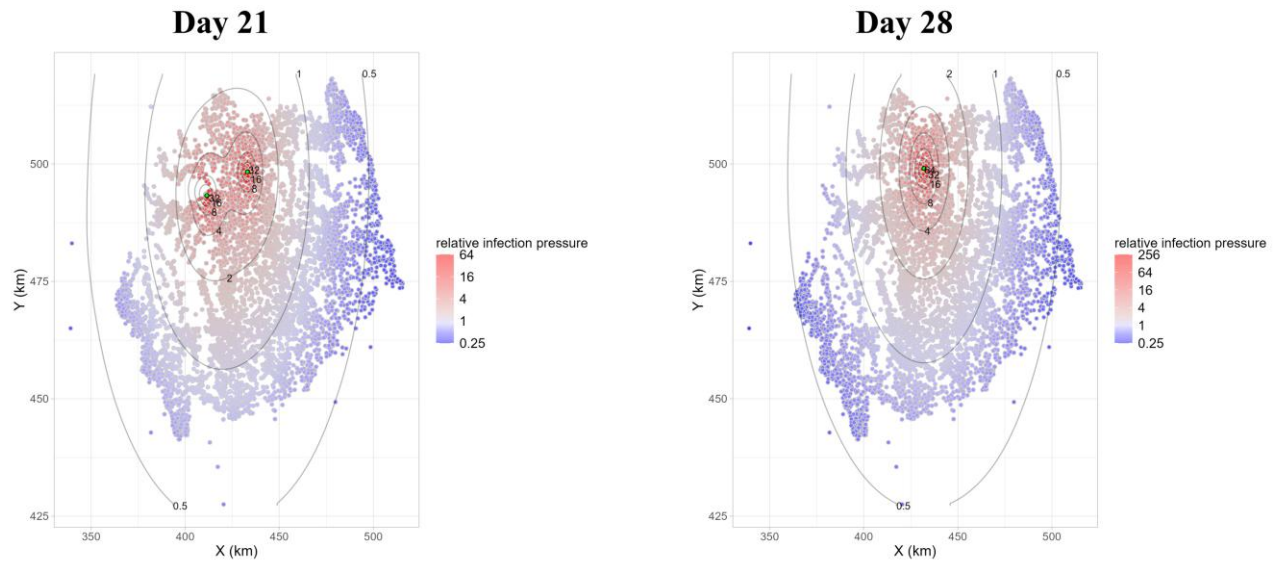


Figure S9(e). Maps of relative infection pressure calculated using the best-fitting transmission kernels at each timepoint (days 21 and 28) for North Yorkshire. Contour lines, generated using a thin-plate spline, connect locations with identical relative infection pressures. Premises are represented by circles, with green circles denoting infected premises (those with clinical signs onset but not yet depopulated) at the corresponding timepoint. Premises with relative infection pressure above one are shaded in a gradient of red, while those below one are shaded in a gradient of blue. For North Yorkshire, infection pressure could not be calculated at days 7 and 14 due to the absence of infected premises.

Table S3. Comparison of kernel-based, species-adjusted, and zoning risk indicators in relation to subsequent 7-day FMD incidence in Cumbria at days 7, 14, 21, and 28 of the outbreaks. Premises were ranked according to estimated infection pressure and grouped into quintiles. Premises were also classified according to the conventional distance-based control framework (<3 km, 3–10 km, and >10 km from an infected premises). Species-informed infection pressure incorporated species-specific infectivity and susceptibility in addition to the transmission kernel. For each infection pressure quintile and distance category, the occurrence of FMD during the subsequent 7-day period (based on estimated exposure dates) was assessed.

Day 7	Kernel-derived infection pressure			Species-informed Infection pressure ³			Conventional zoning (3km / 10km)			
Quintiles	Total	FMD infected (+) ¹	Incidence risk ratio ²	Total ⁴	FMD infected (+)	Incidence risk ratio	Distance	Total	FMD infected (+)	Incidence risk ratio ⁵
80~100%	1165	42	84.1 [5.2-1364.9]	1157	44	2.5 [1.5-4.4]	<3km	278	18	15.2 [7.9-29.1]
60~80%	1164	30	60.1 [3.7-982.2]	1156	7	0.4 [0.2-1.0]	≥3km & 10km	1561	40	6.0 [3.4-10.6]
40~60%	1165	3	6.0 [0.3-119.8]	1157	1	0.1 [0.0-0.5]				
20~40%	1164	0	0.0	1156	6	0.4 [0.2-0.9]				
0~20%	1165	0	1.0	1157	17	1.0	>10km	3958	17	1.0

Day 14	Kernel-derived infection pressure			Species-informed Infection pressure			Conventional zoning (3km / 10km)			
Quintiles	Total	FMD infected (+)	Incidence risk ratio	Total	FMD infected (+)	Incidence risk ratio	Distance	Total	FMD infected (+)	Incidence risk ratio
80~100%	1150	106	212.4 [13.2-3413.6]	1142	120	241.2 [15.0-3874.1]	<3km	546	68	78.9 [34.4-180.8]
60~80%	1150	32	64.1 [3.9-1046.1]	1142	22	45.0 [2.7-741.6]	≥3km & 10km	1406	70	31.5 [13.7-72.4]
40~60%	1150	4	8.0 [0.4-151.4]	1142	1	3.0 [0.1-73.6]				
20~40%	1150	2	4.0 [0.2-88.8]	1142	1	3.0 [0.1-73.6]				
0~20%	1151	0	1.0	1143	0	1.0	>10km	3799	6	1.0

Day 21	Kernel-derived infection pressure			Species-informed Infection pressure			Conventional zoning (3km / 10km)			
Quintiles	Total	FMD infected (+)	Incidence risk ratio	Total	FMD infected (+)	Incidence risk ratio	Distance	Total	FMD infected (+)	Incidence risk ratio
80~100%	1118	102	51.1 [12.6-206.4]	1110	99	66.3 [13.3-331.9]	<3km	756	77	35.7 [18.0-70.8]
60~80%	1118	38	19.0 [4.6-78.6]	1110	31	21.0 [4.1-107.8]	≥3km & 10km	1685	67	13.9 [7.0-27.8]
40~60%	1118	9	4.5 [1.0-20.8]	1110	20	13.7 [2.6-71.6]				
20~40%	1118	2	1.0 [0.1-7.1]	1110	2	1.7 [0.2-12.6]				
0~20%	1119	2	1.0	1110	1	1.0	>10km	3150	9	1.0

Day 28	Kernel-derived infection pressure			Species-informed Infection pressure			Conventional zoning (3km / 10km)			
Quintiles	Total	FMD infected (+)	Incidence risk ratio	Total	FMD infected (+)	Incidence risk ratio	Distance	Total	FMD infected (+)	Incidence risk ratio
80~100%	1078	78	78.1 [10.9-560.2]	1071	77	155.0 [9.6-2497.2]	<3km	722	38	23.6 [10.6-52.7]
60~80%	1078	16	16.0 [2.1-120.6]	1070	15	31.0 [1.9-517.9]				
40~60%	1078	3	3.0 [0.3-28.8]	1071	5	11.0 [0.6-198.7]	≥3km & 10km	1525	55	16.2 [7.4-35.5]
20~40%	1078	2	2.0 [0.2-22.1]	1070	3	7.0 [0.4-135.5]				
0~20%	1079	1	1.0	1071	0	1.0	>10km	3144	7	1.0

¹ Number of incident FMD cases within the next 7 days, excluding previously infected farms that were merely confirmed during this period.

² Incidence risk ratio calculated with the 0–20% group as the reference. The Haldane-Anscombe correction was used for zero-cell adjustments.

³ Infection pressure weighted by the on-farm populations of cattle, sheep, and pigs.

⁴ Farms raising only deer or goats were excluded, resulting in a lower total compared to the left column.

⁵ Incidence risk ratio for the conventional zoning calculated with the >10km group as the reference.

Table S4. Quintile-based analysis of estimated infection pressure and subsequent 7-day FMD incidence at days 7, 14, 21, and 28 of the outbreaks in (a) Devon, (b) Dumfries and Galloway, (c) Durham, and (d) North Yorkshire. Premises were ranked according to estimated infection pressure and grouped into quintiles. For each infection pressure quintile, the occurrence of FMD during the subsequent 7-day period (based on estimated exposure dates) was assessed.

(a) Devon

Quintiles	Day 7			Day 14		
	Total	FMD infected (+) ¹	Incidence risk ratio ²	Total	FMD infected (+)	Incidence risk ratio
80~100%	1743	14	28.0 [1.7-470.1]	1739	15	30.0 [1.8-502.0]
60~80%	1743	1	2.0 [0.1-59.6]	1739	3	6.0 [0.3-119.8]
40~60%	1743	1	2.0 [0.1-59.6]	1738	4	8.0 [0.4-151.4]
20~40%	1743	0	0.0	1739	0	0.0
0~20%	1743	0	1.0	1739	0	1.0

Quintiles	Day 21			Day 28		
	Total	FMD infected (+)	Incidence risk ratio	Total	FMD infected (+)	Incidence risk ratio
80~100%	1727	14	28.0 [1.7-470.1]	1715	14	28.0 [1.7-470.1]
60~80%	1727	11	22.0 [1.3-374.3]	1714	12	24.0 [1.4-406.4]
40~60%	1727	2	4.0 [0.2-88.7]	1714	2	4.0 [0.2-88.8]
20~40%	1727	1	2.0 [0.1-59.6]	1714	1	2.0 [0.1-59.7]
0~20%	1727	0	1.0	1715	0	1.0

(b) Dumfries and Galloway

Quintiles	Day 7			Day 14		
	Total	FMD infected (+)	Incidence risk ratio	Total	FMD infected (+)	Incidence risk ratio
80~100%	227	12	3.0 [1.0-9.2]	222	17	8.6 [2.0-36.7]
60~80%	227	3	0.8 [0.2-3.3]	221	6	3.0 [0.6-14.9]
40~60%	227	3	0.8 [0.2-3.3]	222	3	1.5 [0.3-9.0]
20~40%	227	4	1.0 [0.3-4.0]	219	4	5.1 [0.4-11.1]
0~20%	228	4	1.0	224	2	1.0

Quintiles	Day 21			Day 28		
	Total	FMD infected (+)	Incidence risk ratio	Total	FMD infected (+)	Incidence risk ratio
80~100%	213	5	1.3 [0.3-4.6]	195	5	5.0 [0.6-42.4]
60~80%	212	9	2.3 [0.7-7.2]	195	6	6.0 [0.7-49.4]
40~60%	212	5	1.3 [0.3-4.6]	195	1	1.0 [0.1-15.9]
20~40%	213	7	1.8 [0.5-5.9]	195	5	5.0 [0.6-42.4]
0~20%	213	4	1.0	195	1	1.0

(c) Durham

Quintiles	Day 7			Day 14		
	Total	FMD infected (+)	Incidence risk ratio	Total	FMD infected (+)	Incidence risk ratio
80~100%	345	8	8.0 [1.0-63.6]	343	12	24.1 [1.4-405.9]
60~80%	345	3	3.0 [0.3-28.7]	342	2	4.0 [0.2-88.9]
40~60%	345	0	0.0	342	0	0.0
20~40%	345	0	0.0	342	0	0.0
0~20%	345	1	1.0	343	0	1.0

Quintiles	Day 21			Day 28		
	Total	FMD infected (+)	Incidence risk ratio	Total	FMD infected (+)	Incidence risk ratio
80~100%	340	17	34.1 [2.1-565.4]	332	6	6.0 [0.7-49.6]
60~80%	339	2	4.02 [0.18-88.9]	332	1	1.0 [0.1-15.9]
40~60%	340	1	2.0 [0.1-59.6]	332	1	1.0 [0.1-15.9]
20~40%	339	0	0.0	332	1	1.0 [0.1-15.9]
0~20%	340	0	1.0	332	1	1.0

(d) North Yorkshire

Quintiles	Day 21			Day 28		
	Total	FMD infected (+)	Incidence risk ratio	Total	FMD infected (+)	Incidence risk ratio
80~100%	1212	2	2.0 [0.2-22.1]	1206	1	1.0 [0.1-16.0]
60~80%	1212	1	1.0 [0.1-16.0]	1206	0	0.0
40~60%	1212	0	0.0	1206	1	1.0 [0.1-16.0]
20~40%	1212	0	0.0	1206	0	0.0
0~20%	1213	1	1.0	1207	1	1.0

¹ Number of incident FMD cases within the next 7 days, excluding previously infected farms that were merely confirmed during this period.

² Incidence risk ratio calculated with the 0–20% group as the reference. The Haldane-Anscombe correction was used for zero-cell adjustments.

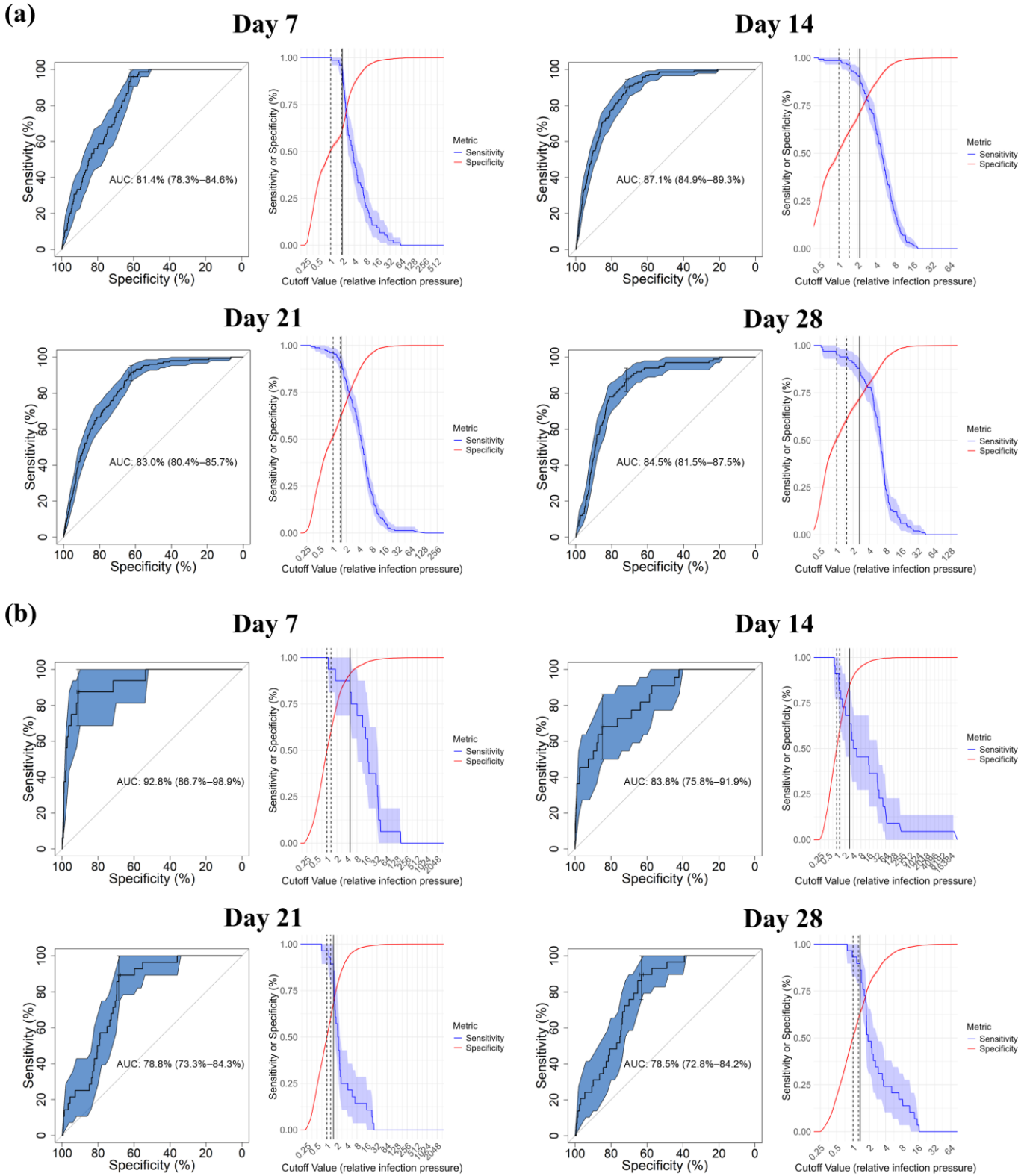


Figure S10. Receiver operating characteristic (ROC) curves with their areas under the curve and graphs displaying sensitivity (blue line) and specificity (red line) across different cut-off values for predicting FMD infection within the next 7 days in (a) Cumbria and (b) Devon. The diagonal dashed line on the ROC curves represents the performance of the random guessing. In the sensitivity and specificity graphs, the left and right vertical dashed line indicates a median and top 40% cutoff, respectively, while the vertical solid line indicates the optimal cut-off value based on Youden's statistic.

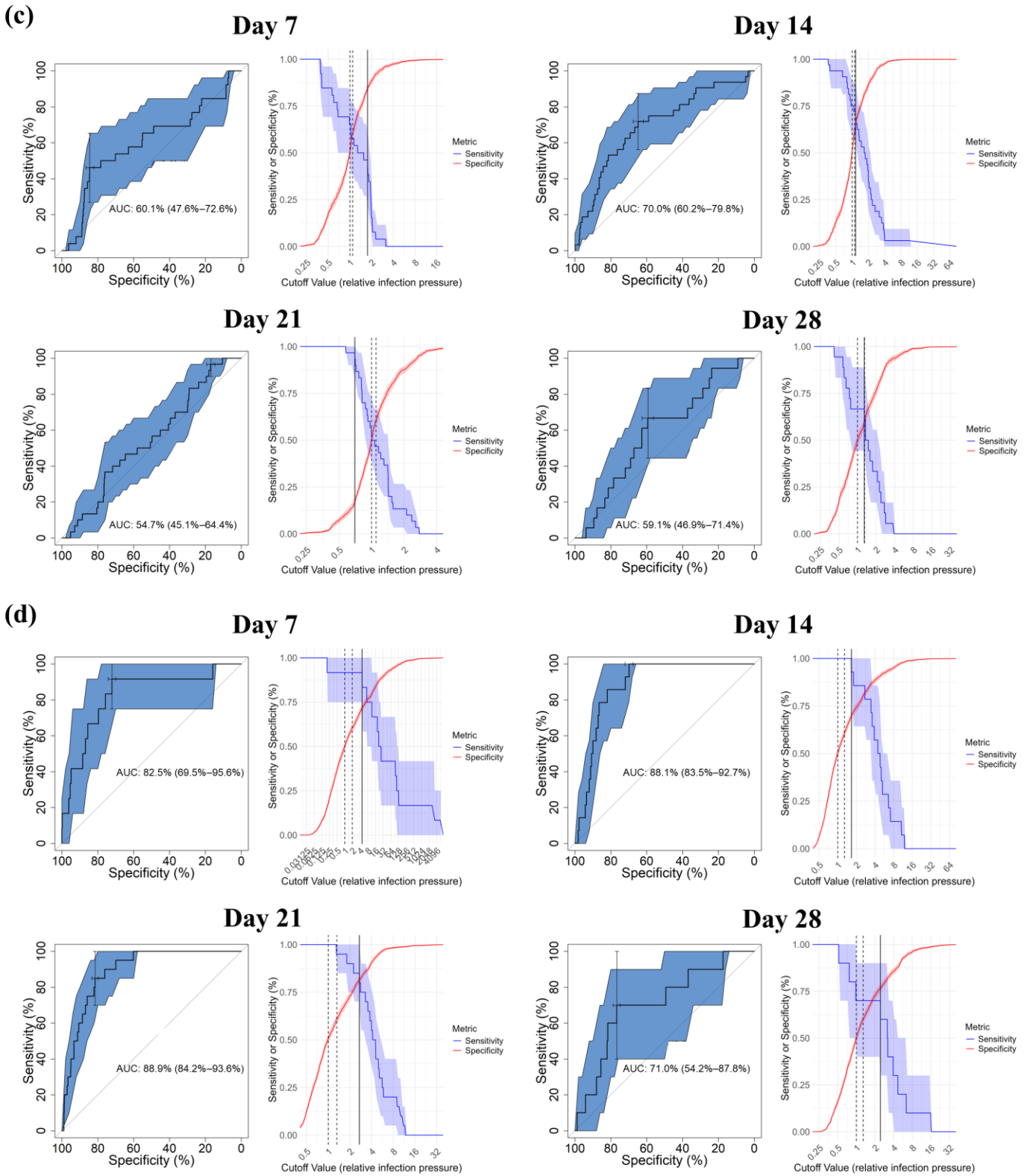
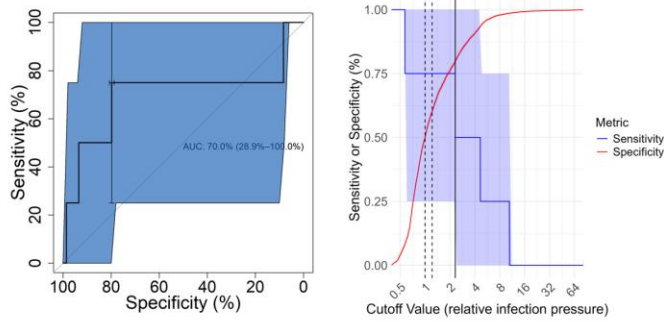


Figure S10. Receiver operating characteristic (ROC) curves with their areas under the curve and graphs displaying sensitivity (blue line) and specificity (red line) across different cut-off values for predicting FMD infection within the next 7 days in (c) Dumfries and Galloway and (d) Durham. The diagonal dashed line on the ROC curves represents the performance of the random guessing. In the sensitivity and specificity graphs, the left and right vertical dashed line indicates a median and top 40% cutoff, respectively, while the vertical solid line indicates the optimal cut-off value based on Youden's statistic.

(e)

Day 21



Day 28

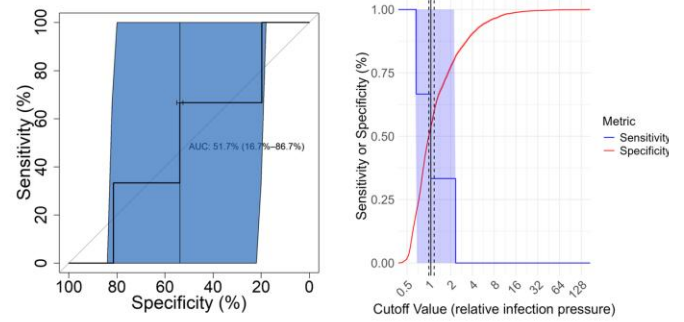


Figure S10(e). Receiver operating characteristic (ROC) curves with their areas under the curve and graphs displaying sensitivity (blue line) and specificity (red line) across different cut-off values for predicting FMD infection within the next 7 days in North Yorkshire. The diagonal dashed line on the ROC curves represents the performance of the random guessing. In the sensitivity and specificity graphs, the left and right vertical dashed line indicates a median and top 40% cutoff, respectively, while the vertical solid line indicates the optimal cut-off value based on Youden's statistic.

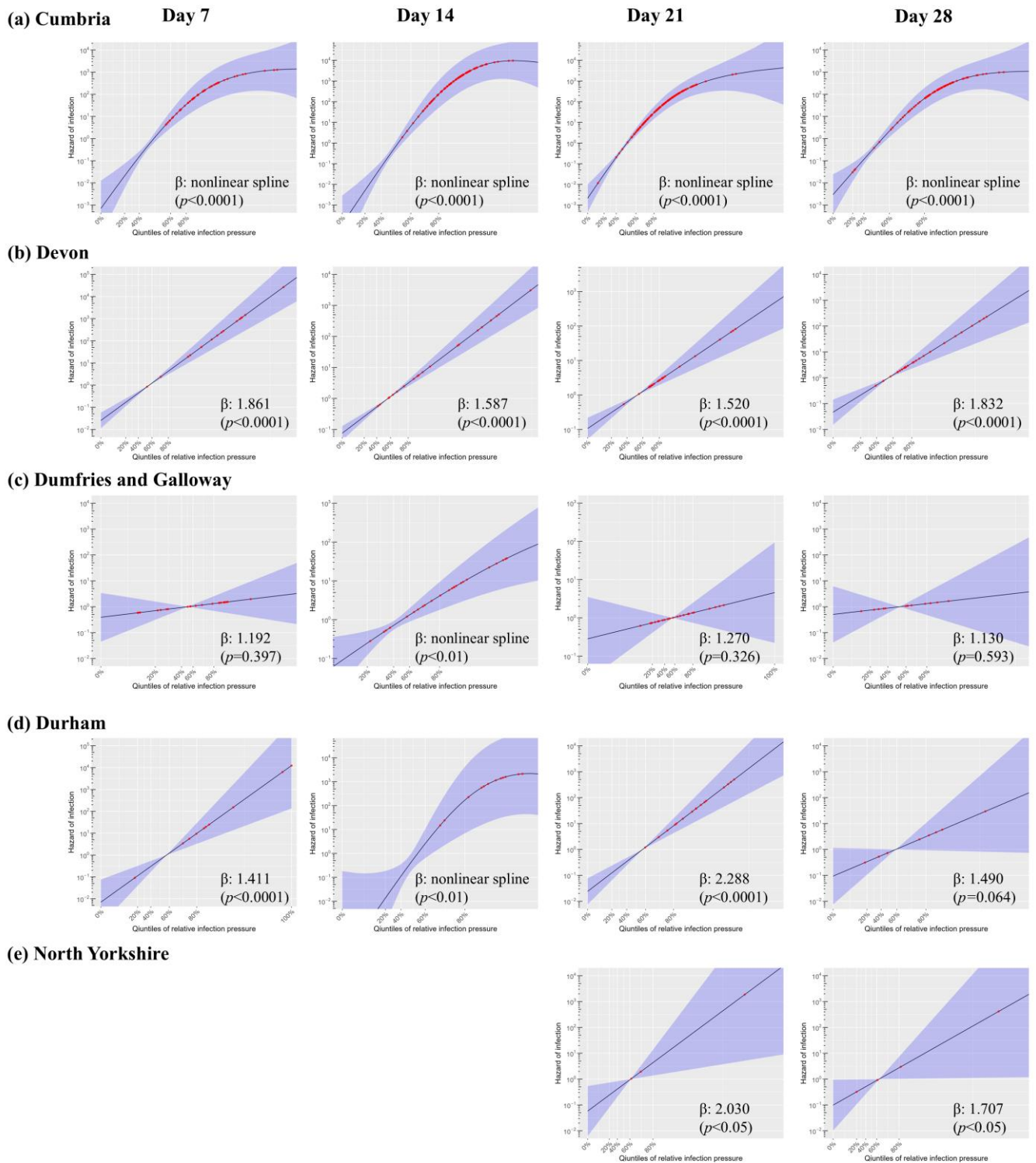


Figure S11. The crude relationship between hazard of infection and infection pressure of susceptible premises at each timepoint (day 7, 14, 21, and 28) for (a) Cumbria, (b) Devon, (c) Dumfries and Galloway, (d) Durham, and (e) North Yorkshire. The blue shaded areas represent the 95% confidence intervals. Relative infection pressure on the x-axis is shown as quintiles. Red points indicate the infection pressures of premises infected to FMD within 7 days following each timepoint and their corresponding infection hazards calculated using the Cox proportional hazard model. The exponential of coefficient β (hazard ratio) corresponding to relative infection pressure from the Cox proportional hazard model and its significance are displayed in the bottom right corner.

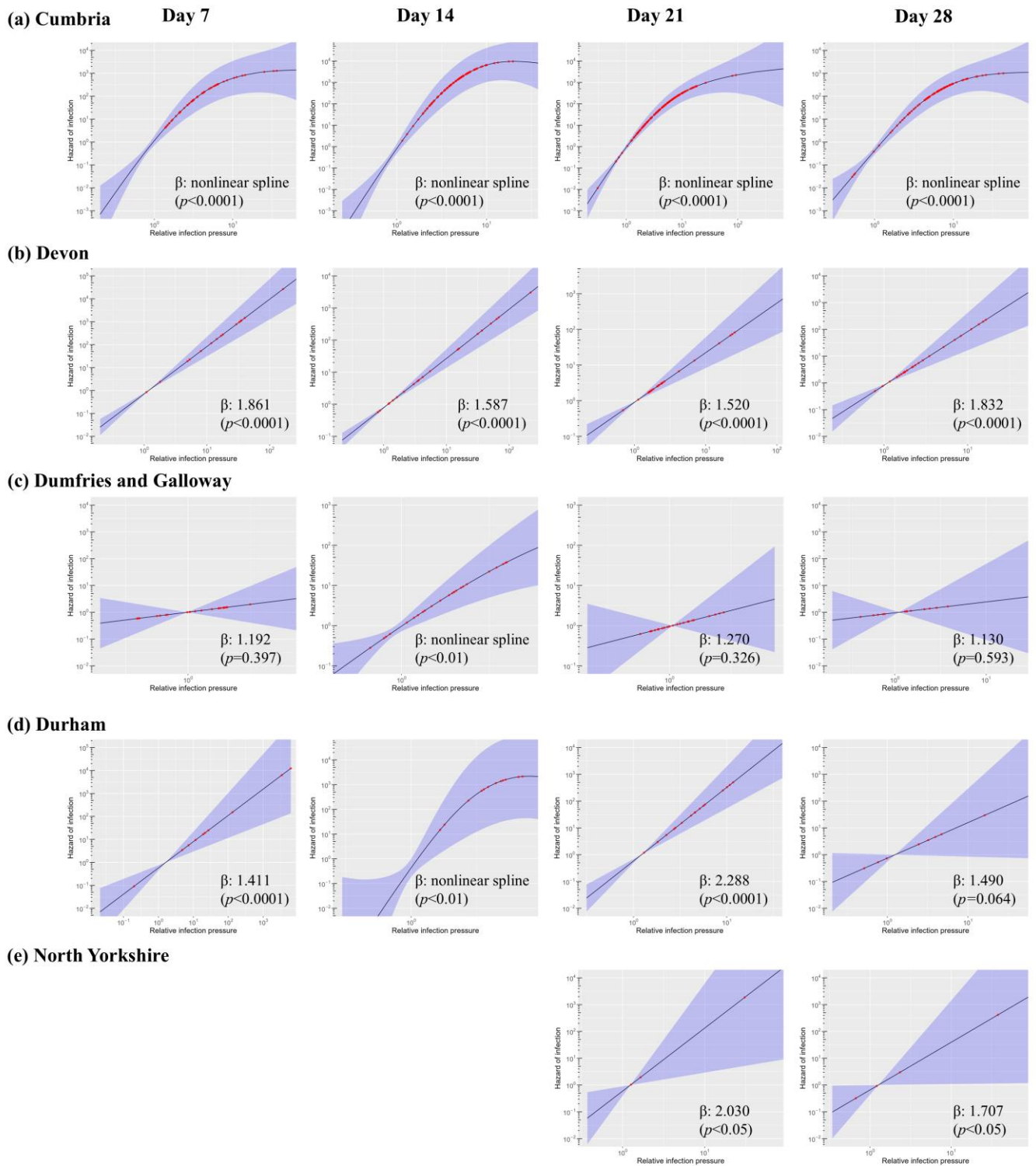


Figure S12. The crude relationship between hazard of infection and infection pressure of susceptible premises at each timepoint (day 7, 14, 21, and 28) for (a) Cumbria, (b) Devon, (c) Dumfries and Galloway, (d) Durham, and (e) North Yorkshire. The blue shaded areas represent the 95% confidence intervals. Red points indicate the infection pressures of premises infected to FMD within 7 days following each timepoint and their corresponding infection hazards calculated using the Cox proportional hazard model. The exponential of coefficient β (hazard ratio) corresponding to relative infection pressure from the Cox proportional hazard model and its significance are displayed in the bottom right corner.

Reference

1. Yadav S, Stenfeldt C, Branán MA, Moreno-Torres KI, Holmstrom LK, Delgado AH, Arzt J. Parameterization of the Durations of Phases of Foot-And-Mouth Disease in Cattle. *Frontiers in Veterinary Science*. 2019;6:263.
2. Chanchaidechachai T, de Jong MCM, Fischer EAJ. Spatial model of foot-and-mouth disease outbreak in an endemic area of Thailand. *Preventive Veterinary Medicine*. 2021;195:105468.
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