

S2. Appendix. Methods

Verification

In code verification, we conducted unit testing – all processes and functions were tested individually before incorporating into the main simulation code. For example, we tested creating bubbles of care homes in a simple ABM in which care home agents only had one state variable that defined the identity number of the bubble to which the care homes belonged. This test confirmed the number of care homes per bubble was as intended in the conceptual model before implementing the code in the full simulation. We also performed tracing of randomly chosen agents of each type via the simulation output and used the built-in debugger, bottom-up testing, stress testing, and regression testing for verification.

White-box validation

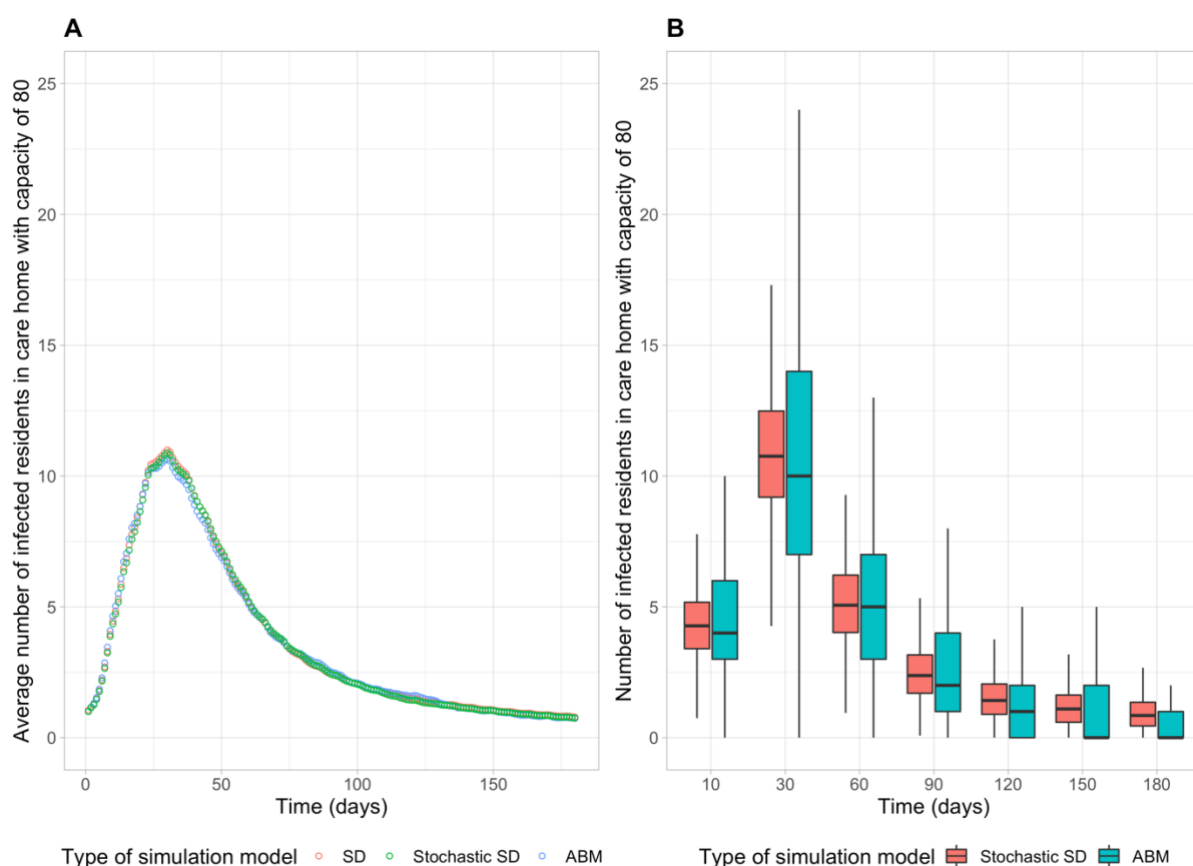


Fig S2-1. Comparisons of results generated from parallel system dynamics [SD], stochastic SD, and agent-based [ABM] models

The figure describes the time series of Covid-19 prevalence among residents in care home with capacity of 80 residents (1,000 simulations per scenario). Base-case parameters are used. Interventions implemented in the care home include testing upon admission of residents, no visitation, hand hygiene and using PPE, social distancing, isolation of symptomatic/confirmed residents, and weekly testing of staff. Simulations are seeded with one infected resident.

Box-plot: lower hinge: 25% quantile; lower whisker: smallest observation greater than or equal to lower hinge – 1.5×IQR; middle: median; upper hinge: 75% quantile; upper whisker: largest observation less than or equal to upper hinge + 1.5×IQR). Note: IQR – interquartile range.

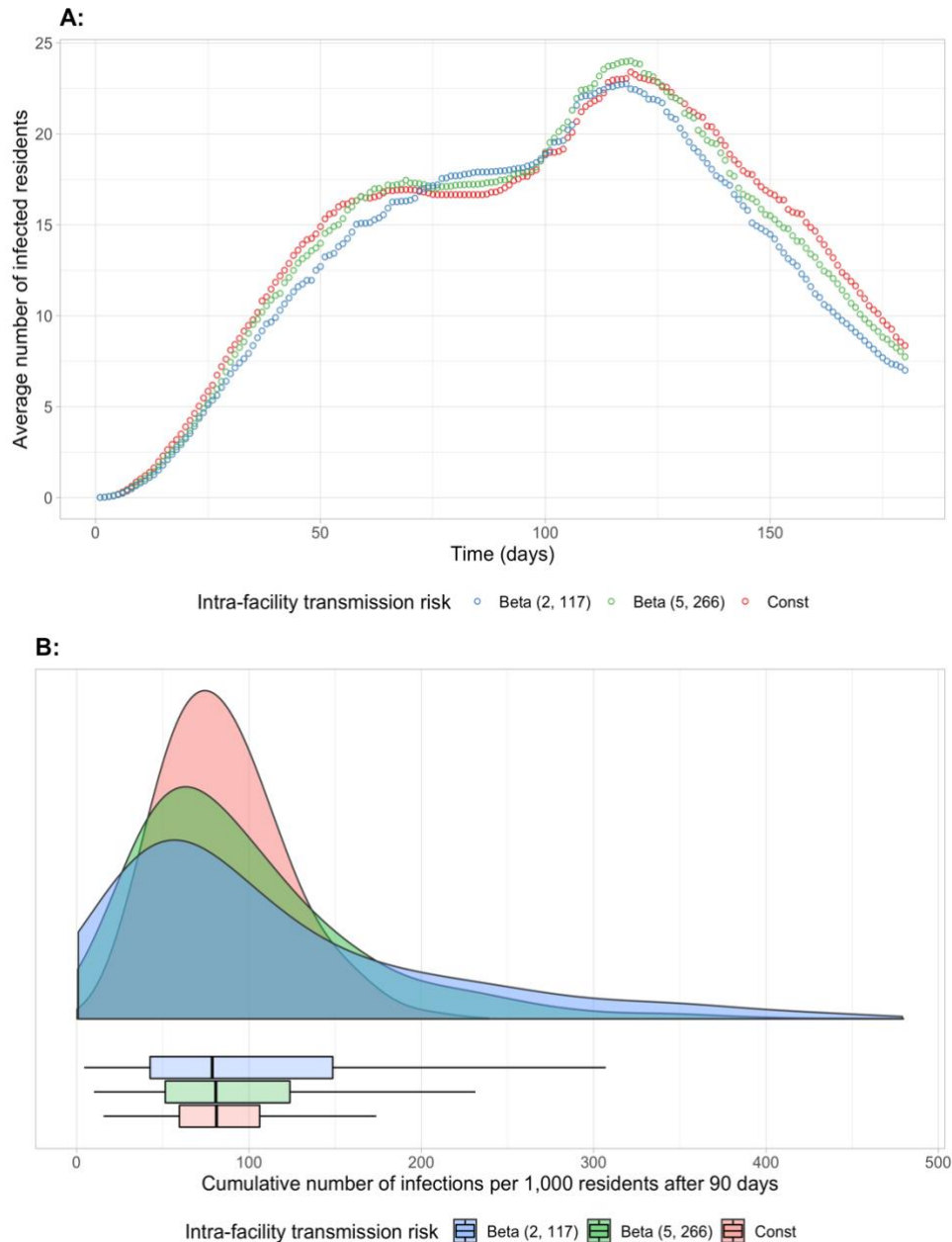


Fig S2-2. Time series of Covid-19 prevalence among residents

(A) and cumulative number of infected residents after 90 days (B) with different values of intra-facility transmission risk. The figure describes the model outcomes for network B in three scenarios: The intra-facility per-contact transmission risk is

i/ "Const": homogeneous across care homes (0.02);

ii/ heterogeneous across care homes and drawn from Beta distribution (5, 266);

iii/ heterogeneous and drawn from Beta distribution (2, 117).

No intervention in bank/agency staff is implemented. Bank/agency staff comprises 10% of total staff. Other parameters have the base-case values. Boxplot: middle – median; lower hinge – 25% quantile; upper hinge – 75% quantile; lower whisker = smallest observation greater than or equal to lower hinge - 1.5 * IQR; upper whisker = largest observation less than or equal to upper hinge + 1.5 * IQR.

Literature review

We searched PubMed, the WHO Covid-19 database, and medRxiv on the 25th June 2021, with the search terms (“COVID-19” OR “SARS-CoV-2” OR “coronavirus”) AND (“care home*” OR “LTCF*” OR “long term care” OR “nursing home*”) AND (“staff*” OR “healthcare worker*” OR “outbreak*”). These searches returned 306 studies, of which five examined the impact of staff working across multiple care homes on the inter-facility transmission or the impact of care home characteristics including resident population size and staff-to-resident ratio on the risk of outbreak occurrence. In addition to these searches, we identified relevant information from daily COVID-19 data for Scottish and English care homes. Table S2-1 below listed the studies to which we compared our modelling results.

Table S2-1. Relevant studies for black-box validation identified from a systematic search

Baister M, McTaggart E, McMenemy P, Megiddo I, Kleczkowski A. COVID-19 in Scottish care homes: A metapopulation model of spread among residents and staff. <i>medRxiv</i> . 2021:2021.2008.2024.21262524. (Added on the 30 th August)
Burton JK, Bayne G, Evans C, et al. Evolution and impact of COVID-19 outbreaks in care homes: population analysis in 189 care homes in one geographic region. <i>medRxiv</i> . 2020:2020.2007.2009.20149583.
Green R, Tulloch JSP, Tunnah C, et al. COVID-19 testing in outbreak free care homes: What are the public health benefits? <i>The Journal of hospital infection</i> . 2021.
Ladhani SN, Chow JY, Janarthanan R, et al. Increased risk of SARS-CoV-2 infection in staff working across different care homes: enhanced CoVID-19 outbreak investigations in London care Homes. <i>Journal of Infection</i> . 2020.
Scottish Government. Coronavirus (COVID-19): daily data for Scotland. https://www.gov.scot/publications/coronavirus-covid-19-daily-data-for-scotland/ Published 2020. Accessed 25 June, 2021.
Shallcross L, Burke D, Abbott O, et al. Factors associated with SARS-CoV-2 infection and outbreaks in long-term care facilities in England: a national cross-sectional survey. <i>The Lancet Healthy Longevity</i> . 2021;2(3):e129-e142.

S3. Appendix. Additional modelling results

Table S3-1. Risk of infection in residents and staff in various usage levels of bank/agency staff

Experiment scenario	Average usage level of bank/agency staff	RR of infection for residents in care homes using bank/agency staff to care homes not using bank/agency staff		RR of infection in bank/agency staff to permanent staff		RR of outbreaks in care homes using bank/agency staff to care homes not using bank/agency staff	
		Compliance to weekly PCR testing among bank/agency staff					
		0%	80%	0%	80%	0%	80%
Different networks							
A (Heterogeneous size & staff-to-resident ratio)	5%	1.68 (1.64 – 1.73)	1.14 (1.12 – 1.17)	1.34 (1.29 – 1.38)	1.28 (1.24 – 1.32)	2.43 (2.30 – 2.56)	1.64 (1.54 – 1.73)
	10%	2.65 (2.57 – 2.72)	1.28 (1.25 -1.31)	1.55 (1.52 – 1.58)	1.35 (1.32 – 1.38)	3.76 (3.58 – 3.96)	1.83 (1.73 – 1.94)
	15%	3.73 (3.63 – 3.84)	1.43 (1.39 – 1.47)	1.72 (1.69 – 1.75)	1.42 (1.39 – 1.45)	4.71 (4.48 – 4.95)	2.19 (2.08 – 2.32)
	20%	5.17 (5.03 – 5.30)	1.64 (1.60 – 1.68)	1.98 (1.95 – 2.01)	1.48 (1.46 – 1.51)	5.64 (5.37 – 5.92)	2.48 (2.35 – 2.61)
B (Homogeneous size & staff-to-resident ratio)	5%	1.65 (1.61 – 1.69)	1.14 (1.12 – 1.16)	1.33 (1.29 – 1.37)	1.29 (1.25 – 1.33)	2.62 (2.48 – 2.76)	1.25 (1.17 – 1.33)
	10%	2.54 (2.45 – 2.61)	1.28 (1.25 – 1.31)	1.52 (1.49 – 1.55)	1.33 (1.30 – 1.36)	4.36 (4.14 – 4.59)	1.82 (1.72 -1.93)
	15%	3.72 (3.62 – 3.82)	1.49 (1.45 – 1.53)	1.72 (1.69 – 1.75)	1.45 (1.42 – 1.48)	5.84 (5.56 – 6.13)	2.38 (2.25 – 2.52)
	20%	5.07 (4.94 – 5.21)	1.66 (1.57 – 1.69)	1.98 (1.95 – 2.01)	1.48 (1.45 – 1.50)	6.87 (6.55 – 7.21)	2.83 (2.68 – 2.98)
Heterogeneous intra-facility transmission risk drawn from a distribution (Network A)							
Beta (5, 266)	5%	1.75 (1.66 – 1.85)	1.17 (1.12 – 1.23)	1.43 (1.39 – 1.48)	1.32 (1.29 – 1.36)	2.03 (1.92 – 2.13)	1.34 (1.27 – 1.42)
	10%	2.64 (2.51 – 2.78)	1.28 (1.22 – 1.35)	1.62 (1.58 – 1.65)	1.38 (1.35 – 1.41)	3.00 (2.85 – 3.14)	1.50 (1.42 – 1.59)
	15%	3.80 (3.62 – 4.00)	1.56 (1.48 -1.64)	1.84 (1.80 – 1.87)	1.56 (1.52 – 1.59)	3.80 (3.63 – 3.98)	1.95 (1.85 – 2.06)
	20%	5.02 (4.79 – 5.27)	1.69 (1.60 -1.78)	2.06 (2.02 – 2.10)	1.59 (1.56 – 1.62)	4.51 (4.31 – 4.72)	2.11 (2.00 – 2.22)
Beta (2, 117)	5%	1.65 (1.53 – 1.78)	1.15 (1.06 – 1.24)	1.64 (1.58 – 1.69)	1.53 (1.49 – 1.57)	1.90 (1.80 – 2.00)	1.35 (1.27 – 1.43)
	10%	2.34 (2.17 – 2.52)	1.21 (1.13 – 1.29)	1.76 (1.71 – 1.80)	1.60 (1.56 – 1.64)	2.61 (2.48 – 2.74)	1.48 (1.40 – 1.56)
	15%	3.12 (2.90 – 3.35)	1.37 (1.27 – 1.49)	1.91 (1.87 – 1.95)	1.61 (1.56 – 1.66)	3.21 (3.06 – 3.36)	1.68 (1.59 – 1.77)
	20%	3.99 (3.73 – 4.28)	1.71 (1.57 – 1.85)	2.12 (2.08 – 2.16)	1.75 (1.71 – 1.79)	3.85 (3.67 – 4.03)	2.02 (1.92 – 2.13)

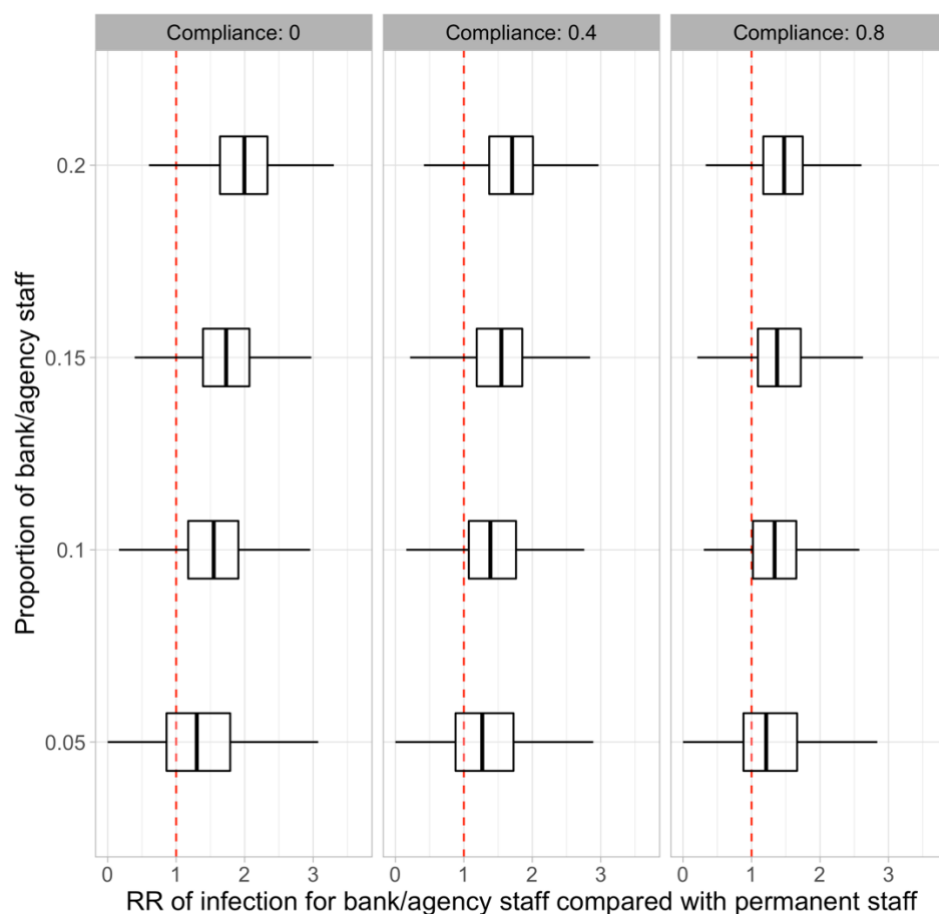


Fig S3-1. Relative risk [RR] of infection for bank/agency staff with different compliance rates to weekly PCR testing to permanent staff in care homes using bank/agency staff

Compliance to weekly testing among permanent staff is 80%. Results are for 1,000 simulations in each scenario. Boxplot: middle – median; lower hinge – 25% quantile; upper hinge – 75% quantile; lower whisker = smallest observation greater than or equal to lower hinge - 1.5 * IQR; upper whisker = largest observation less than or equal to upper hinge + 1.5 * IQR

S4. Appendix. Results of sensitivity and uncertainty analyses

Table S4-1. Output from Partial Rank Correlation Coefficient analyses

Parameter	Cumulative number of infected residents		Relative risk of infection in bank/agency staff to permanent staff	
	PRCC	p-value	PRCC	p-value
Community incidence	0.68	3.81E-45	0.17	6.06E-316
IFR for residents	-0.01	2.77E-02	0.01	1.75E-01
IFR for staff	0.00	7.18E-01	0.00	9.04E-01
Average resident- resident contact rate	0.12	1.21E-165	0.05	1.43E-26
Average staff-staff contact rate	0.07	9.16E-51	0.05	6.76E-31
Average staff-resident contact rate	0.69	5.25E-83	0.47	1.12E-58
Staff turnover	0.00	6.66E-01	0.00	3.65E-01
Resident leaving rate	0.00	4.12E-01	0.00	3.21E-01
Probability of symptomatic in infected residents	-0.14	3.32E-231	-0.12	3.60E-149
Probability of symptomatic in infected staff	-0.30	1.55E-10	-0.12	1.13E-149
Per-contact transmission probability	0.91	1.79E-241	0.77	1.50E-47
Pre-symptomatic time	0.58	7.96E-102	0.43	2.57E-104
Infectious time	0.06	1.50E-47	0.05	4.62E-27
Social distancing compliance rate	-0.10	2.57E-104	-0.10	1.75E-114
PCR sensitivity	0.00	8.68E-01	0.00	7.43E-01
Test turnaround time	0.07	3.45E-52	0.03	1.03E-11

A negative value indicates a negative correlation – increasing the parameter decreases the outcome. A positive value indicates a positive correlation – increasing the parameter increases the outcome. In PRCC analysis in general, the parameters with large PRCC values (>0.5 or <-0.5) and corresponding small p-values (<0.05) are deemed the most influential in the model.

The effect of the heterogeneity of resident population size was more significant than staff-to-resident ratio; whilst the latter had no impact on the risk of outbreak across care homes. Decreasing staff-to-resident ratio increased the number of contacts with residents per staff member as the average number of contacts with staff per resident remained the same. This is based on our model assumption that the number of contacts with staff per resident per day was maintained regardless of the staffing level as the overall care home workload does not change. Increasing the number of per-staff-member contacts with residents increased the force of infection in staff which in turn increased the force of infection in residents. However, decreasing staff-to-resident ratio reduced the risk of Covid-19 ingress as fewer staff members enter the care home each day. Overall, the staff-to-resident ratio had no impact on the risk of outbreak in care homes (Fig S4-1A). Our model assumption that staff-to-resident ratio did not affect the per-contact transmission risk or staff's compliance to other infection control measures may underestimate the impact of this parameter on the risk of outbreak in care homes. Larger care homes had an increased risk of Covid-19 ingress compared with smaller care homes (Figure S4-1B).

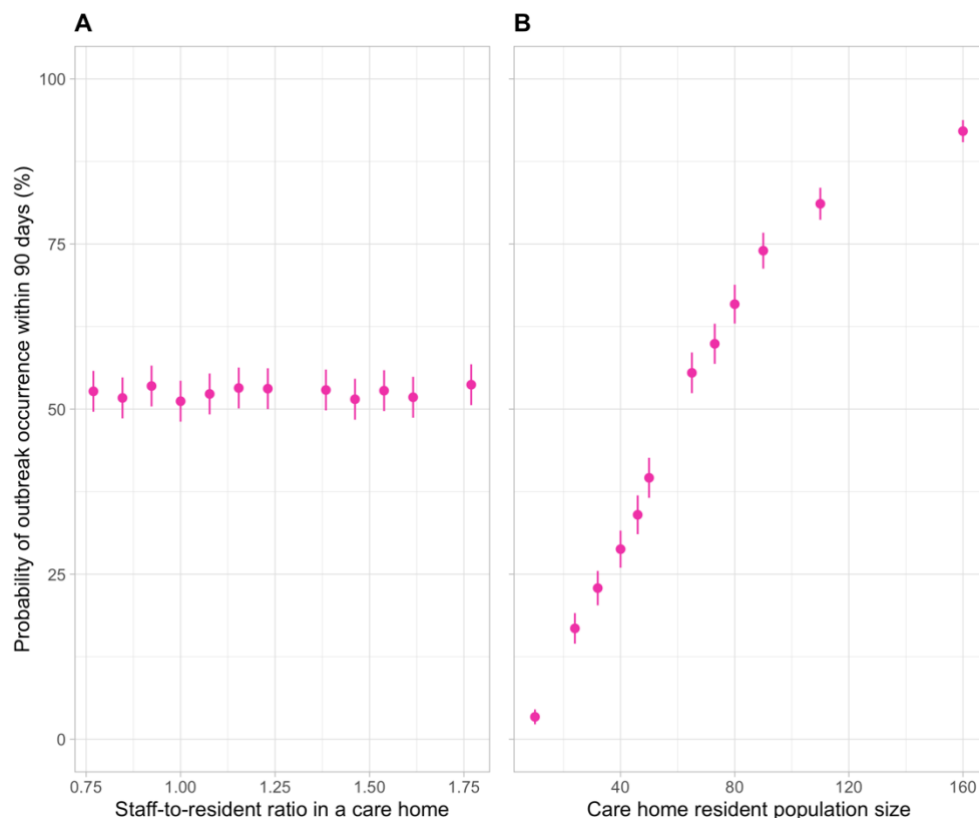


Fig S4-1. Impact of staff-to-resident ratio and resident population size on risk of outbreak

The plot describes the risk of outbreak occurrence within 90 days in individual care homes with

A: the same population size of 65 residents but different staff-to-resident ratios (network C).

B: different resident population size (network D).

The average intra-facility transmission risk in care homes is homogeneous. The average usage level of bank/agency staff is 10% of total staff. No intervention on bank/agency staff is implemented. The risk of outbreak occurrence (point) is the probability of simulations where outbreaks occur in 1,000 simulation for each scenario. Line range denotes the 95% CI of this outcome.