Multilayer network analysis of FMD transmission and containment among beef cattle farms

Chunlin Yi*, Qihui Yang & Caterina M. Scoglio

As a highly contagious livestock viral disease, foot-and-mouth disease poses a great threat to the beef-cattle industry. Direct animal movement is always considered as a major route for between-farm transmission of FMD virus. Sharing contaminated equipment and vehicles have also attracted increasing interests as an indirect but considerable route for FMD virus transmission. With the rapid development of communication technologies, information-sharing techniques have been used to control epidemics. In this paper, we built farm-level time-series three-layer networks to simulate the between-farm FMD virus transmission in southwest Kansas by cattle movements (direct-contact layer) and truck visits (indirect-contact layer) and evaluate the impact of information-sharing techniques (information-sharing layer) on mitigating the epidemic. Here, the information-sharing network is defined as the structure that enables the quarantine of farms that are connected with infected farms. When a farm is infected, its infection status is shared with the neighboring farms in the information-sharing network, which in turn become quarantined. The results show that truck visits can enlarge the epidemic size and prolong the epidemic duration of the FMD outbreak by cattle movements, and that the information-sharing technique is able to mitigate the epidemic. The mitigation effect of the information-sharing network varies with the information-sharing network topology and different participation levels. In general, an increased participation leads to a decreased epidemic size and an increased quarantine size. We compared the mitigation performance of three different information-sharing networks (random network, contact-based network, and distance-based network) and found the outbreak on the network with contact-based information-sharing layer has the smallest epidemic size under almost any participation level and smallest quarantine size with high participation. Furthermore, we explored the potential economic loss from the infection and the quarantine. By varying the ratio of the average loss of quarantine to the loss of infection, we found high participation results in reduced economic losses under the realistic assumption that culling costs are much greater than quarantine costs.

Foot-and-mouth disease (FMD) is a highly contagious livestock viral disease, which can lead to destructive economic losses. Several major outbreaks have occurred in the UK (2001), Netherlands (2001), Japan (2010), Uganda (2006) etc. The estimated losses of the FMD outbreak in the UK, 2001 amount to about Pound Sterling 3.1 billion; about 290,000 animals had been culled during the FMD outbreak occurred in Japan, 2010; a study estimated that one FMD outbreak constrained to Kansas US would result in an economic loss varying from US Dollar 43 to 706 million. Therefore, it is of great importance to understand the impacts of different FMD virus transmission routes on the outbreak and design control measures to prevent the spread of the disease in the livestock industries.

Moving infected animals and sharing contaminated equipment are considered two of the most common routes for between-farm infectious disease transmission. A number of researches have been conducted to explore the impacts of the different transmission routes on the spread of infectious diseases by building variant between-farm contact networks. Generally, the between-farm transmission routes can be described by two types of contact network—direct contact networks (DCN) which are formed by the movement of livestock between farms, and indirect contact networks (ICN) which are formed by the personnel visits, sharing transport vehicle and tools, etc. Instead of focusing on a single contact network, many studies combined the DCN and ICN into a two-layer network (D&ICN) to analyze the roles each transmission route plays in the disease spreading. Study showed that the porcine reproductive and respiratory syndrome virus transmitted by...
the D&ICN resulted in a larger outbreak compared with the situation when the virus was transmitted by DCN. Sharing haulage vehicles and animal product transport vehicles were found able to increase the contacts between farms by > 50% and accelerate the disease transmission. Study14 concluded that the indirect contacts through vehicles and operators were crucial to accurate predictions of the epidemic size. These results all highlighted the impacts of indirect contacts on the disease spread.

Thanks to the rapidly developed communication technology, mitigation strategies based on information sharing16 have become increasingly promising. Information sharing was primarily used as a method to improve supply chain resilience to disruptions for livestock production17,18. Recently, a number of scholars have used it to control the progressive epidemic16,19–21. In study16, an agent-based model was developed, where the FMD virus was spread through the D&ICN, the infected farms would inform their partners through the information-sharing network (ISN) and the informed farms would implement preventive measures to suppress the disease spreading. In their study, they assumed that all farms participated in the information-sharing system. However, Farmers’ willingness to participate in the information-sharing system depends on complicated factors such as risk attitudes, privacy, and transparency issues22,23. Therefore, efforts are still needed to investigate how participation levels will affect the effectiveness of information-sharing mitigation strategies.

In this paper, we generated a three-layer network including the direct-contact layer (cattle movements), the indirect-contact layer (truck visits), and the information-sharing layer to simulate the FMD virus transmission dynamics among beef-cattle farms in southwest Kansas (SW KS) and the effectiveness of the mitigation strategies based on the information-sharing method. Our goal is to investigate the potential impacts of the virus transmitted by cattle movement (direct contacts) and vehicle visits (indirect contacts) on the FMD outbreaks, and to assess how the information-sharing networks and the fraction of participation farms can affect the epidemic size. To our knowledge, there is no previous study constructing a three-layer network analysis on FMD involving information-sharing techniques. In addition, the influence of different participations in the information sharing are explored unprecedentedly. In this study, hypothetical FMD outbreaks were first simulated on a single-layer DCN (cattle-movement network), a two-layer D&ICN (cattle-movement layer and truck-visit layer), and a three-layer D&ICN (cattle-movement layer, truck-visit layer, and information-sharing layer) to assess the effects of each layer on the transmission of FMD virus among beef-cattle farms. We also investigated the impacts of different types of information-sharing layers and participation levels on the epidemic size and quarantine size. Furthermore, a sensitive analysis was conducted to explore the potential economic losses caused by the infection and quarantine to optimize the economy loss and control cost.

Materials and methods

Data. We extracted the weekly cattle movement records and the vehicle sharing records between July 1st 2019 and December 31st 2019 from the database24. The database provides comprehensive cattle trading records between premises and premises information in SW KS. Cattle trading records includes the identifiers for departure premises and destination premises, truck identifiers for every movement, headcount of cattle carried by truck, and transport date. The premises information includes the premises type (ranches, stockers, and feedlots) and the capacity which is the maximum number of cattle one can hold. In this study, 301 premises in different production type are involved, among which there are 18 ranches, 50 stockers, and 233 feedlots.

Multilayer network construction. To describe the FMD transmission routes by cattle movements and truck visits shown in Fig. 1, we construct a weekly series of weighted two-layer contact network based on the movement data. On top of the contact network, we add an information-sharing layer to simulate the influence of different information-sharing networks and the participation level on suppressing the epidemic. Thus, each network was formed by three independent layers as is shown in Fig. 2. The nodes with the same identifier on each layer represent the same premise; the edges within the layer represents the virus (contact layers) or information (information-sharing layer) transmission routes between premises. Direct-contact layer, indirect-contact layer, and information-sharing layer are presented as $L_{DC} = (V, E_{DC})$, $L_{IC} = (V, E_{IC})$, and $L_{IS} = (V, E_{IS})$, where $V$ represents the set of nodes, and $E_{i}$ represents the set of edges within layer $i$. In the direct-contact layer $L_{DC}$, every cattle movement is generated as a directed and weighted edge from the departure premise (node) pointing to the destination one, with the weight as the headcount of transported cattle. For the indirect-contact layer $L_{IC}$, the premises are connected if they are visited by the same truck in a week. Because the trucks usually return to the departure premises after transporting cattle, the edges within $L_{IC}$ are undirected. The weights on $E_{IS}$ are the number of visits between premises (“Supplementary information”).

We design three information-sharing layer $L_{IS}$ with different network structure but same network density. The first type is an Erdos Renyi random network25 with the same network density (0.0068) as the $L_{IS}$; the second...
The SQEIR model embedded in the multilayer network is simulated in the Generalized Epidemic Modeling Framework (GEMF), which was developed by the Network Science and Engineering group at Kansas State University. GEMF can numerically simulate spreading processes on static multilayer networks, and is available online at https://doi.org/10.1038/s41598-022-19981-0.
in MATLAB, R, Python, and C programming language. In this work, we further adapt GEMF toolbox in Matlab for simulating disease spreading on time-series multilayer networks.

**Impact of cattle movement, vehicle visits, and information sharing on disease spreading.** The hypothetical FMD spreading is simulated on a weekly-series of DCN, D&ICN, and multilayer network with contacts layers and information layer (DIC&ISN). Those different networks are formed by the $L_{DC}$, $L_{IC}$, and $L_{IS}$ we constructed in the previous section. For this simulation, the Erdos Renyi random network is used as the $L_{IS}$, and all premises participate in the information sharing system. The FMD virus is seeded in three randomly selected

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**Figure 3.** Node degree distributions of different networks.

**Figure 4.** SQEIR model transition process.
Impact of different information-sharing layers and premises participation on disease spreading. The idea behind the information sharing network is the following. Suppose that one farm discovers to have cattle infected with FMD. This farm will immediately go to isolation, following the state of Kansas procedure. At this point, this farm will inform its neighboring farms (the farms connected in the network are defined as neighboring farms) of its infection status. The neighboring farms will, in turn, go into a quarantine state, halting all movements of animals and trucks. Cattle in infected farms will be culled, while cattle in farms protected by quarantine, will return to normal conditions once the epidemic is contained. Three different types of the information-sharing layer are added individually to the contact networks. The hypothetical FMD spreading is simulated on the weekly-series of DIC&ISNs with different $L_{IS}$—the Erdos Renyi random information-sharing layer, the contact-based information-sharing layer, and the distance-based information-sharing layer. Different premises participations are also considered. We randomly activate 10–100% (with interval 10%) participation nodes and deactivate the rest in each $L_{IS}$, and simulate the hypothetical FMD spreading. Considering there are hubs (nodes with higher degree) in both contact networks, we rank the nodes by their node degrees and activate 10–100% (with interval 10%) participation of nodes with the highest degree, and simulate the FMD spread again. All the simulations are repeated 5000 times. The distributions of the final epidemic size and the quarantine size of the different participations are presented and evaluated.

Sensitivity analysis of the potential economic loss from the epidemic and quarantine. According to study\(^1\) the FMD infection can cause losses by reducing milk production, suppressing growth rate of live-stock, and culling the infected cattle. Considering that quarantined farms stop contact with other farms, which leads to economic losses as well, we proposed a loss function $l = xR + yQ (x > y)$, where $x$ is the average loss for one removed farm, $y$ is the average loss for one quarantined farm, $R$ is the number of the removed farms, and $Q$ is the number of the quarantined farms. To qualitatively analyze the potential loss from the epidemic and the quarantine, we rewrite the loss function as $\tilde{l} = \frac{R + yQ}{x}$, where the relative loss per quarantined farm $\tilde{y} = \frac{y}{x}$, and the relative total loss $\tilde{l} = \frac{1}{x}$. We vary the value of $\tilde{y}$ from 0 to 0.5 with step increment 0.05, and calculate $\tilde{l}$ of each $L_{IS}$ with different participation levels.

### Results and discussion

Impact of cattle movement, vehicle visits, and information sharing on disease spreading. The numbers of premises in different infection compartments and the distribution of the epidemic size based on three networks with different layers are shown in Fig. 5. The blue dash line, green dash line, and red solid line represent the number of premises in state E, I, and R versus time separately; the boxplots shows the distributions of the final epidemic size, where the red line in the box represents the median; the upper and lower edges of the box represent the 75% and 25% quartiles; the short lines outside the box are the adjacent (maximum and minimum without outliers); red plus signs are the outliers.

For the hypothetical FMD spreading simulations, the number of simulations producing additional infections on different networks are 1628 (32.56%) on DCN, 1799 (35.98%) on D&ICN, and 1770 (35.40%) on DIC&ISN. The reason for this low outbreak probability is the sparsity of the contact layers, in which there are often no links to or from the initial infected farms during simulation. Surprisingly, the increment of the outbreak probability (the fraction of simulations producing additional infections) on D&ICN from DCN is only 171 (3.42%) even if the average network density of truck-visit network is more than twice of the cattle-movement network. Two facts should be considered here. On the one hand, the indirect infection rate of the truck visit layer is much smaller than the direct infection rate. On the other hand, the number of truck visits is smaller than the number of cattle transported (normally several cattle transported by one truck), which means the weight of the truck visit layer is smaller than that of the cattle movement layer. Therefore, the pathogens are more likely to be transmitted by the cattle movements when the number of infections is small.

For those spread FMD, the average epidemic duration is 4.44 weeks on DCN (minimum 2 weeks and maximum 12 weeks), 8.29 weeks on D&ICN (minimum 2 weeks and maximum 22 weeks), and 6.89 weeks on DIC&ISN (minimum 2 weeks and maximum 18 weeks). As shown in Fig. 4d, the maximum and average epidemic duration of the box represent the 75% and 25% quartiles; the short lines outside the box are the adjacent (maximum and minimum without outliers); red plus signs are the outliers.

### Table 1. Description and value of the parameters in the model.

| Parameter | Description | Value | References |
|-----------|-------------|-------|------------|
| $\beta_{DC}$ | Infection rate of direct contact | 0.95 | 16 |
| $\beta_{IC}$ | Infection rate of indirect contact | 0.15 | 16 |
| $\lambda$ | Incubation rate | 0.83 | 16 |
| $\delta$ | Removing rate | 0.12 | 16 |
| $\alpha$ | Quarantine rate | 1 | Assumed |
| $\mu$ | Releasing rate | 0 | Assumed |

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size of spread FMD are 0.392 (118/301) and 0.040 (12/301) on DCN, 0.684 (206/301) and 0.261 (78.5/301) on D&ICN, and 0.449 (135/301) and 0.138 (41.6/301) on DIC&ISN. Our results show that the truck-visit layer not only prolong the average epidemic duration by 86%, but also enlarge the overall epidemic size by 554% on average and 74% on the maximum. Apparently, the truck visits greatly boost the disease transmission. Truck visits become increasingly effective for FMD transmission as the number of infected farms is increasing, although the infection rate and the weight for it are relatively small. The other important characteristics of the truck visit network like higher density and undirected links also contribute to spreading the disease to more farms. The random information-sharing layer has apparent impact on mitigating the epidemics of D&ICN with 17% shorter average duration and 47% smaller average epidemic size.

Impact of different information-sharing layers and premises participation on disease spreading. Figure 6 shows the maximums and average of the epidemic size and quarantine size versus participations when different $L_{IS}$ are applied. In this scenario, the participated farms are randomly selected. The solid lines in the figure represent the average while the dashed lines are the maximums; the red, blue, and green lines present the data from random $L_{IS}$, contact-based $L_{IS}$, and distance-based $L_{IS}$ separately. In general, the epidemic size decreases and the quarantine size increases when more farms participated in the information-sharing networks. The maximum and average epidemic size of the contact-based $L_{IS}$ is the smallest almost under any participation level, which means the contact-based $L_{IS}$ has the best performance on containing the disease spread. The quarantine size of the contact-based $L_{IS}$ is the largest when the participation is less than 50%, and the smallest when participation is greater than 60%. Based on the Eq. (1), infected farms is promoting the growth of quarantine while the quarantined farms is prohibiting the growth of infection in every three-layer networks. From the results, we can deduct that the contact-based $L_{IS}$ is able to make more farms quarantined under lower participation level to prohibit the infection more effectively than other two $L_{IS}$, and that the smaller epidemic size of contact-based $L_{IS}$ under higher participation level makes the quarantine size small.

In order to more effectively prohibit the disease spreading on the contact networks, we primarily include the farms with the highest node degrees into the information-sharing networks. The epidemic size and the quarantine size are shown in Fig. 7. Compare with the random participation, the performance of contact-based $L_{IS}$ on
containing epidemic size has an obvious improvement. Under 10% participation, the average epidemic size is 0.19, which is 20.8% decrease from 0.24 with random participation. The average epidemic size decreases to less than 0.1 when participation level is higher than 50%. However, different types of participations have little effect on epidemic size of the other two LIS and the quarantine size of all three LIS.

Sensitivity analysis of the potential economic loss from the epidemic and quarantine. The potential losses caused by the infection and the quarantine are displayed in Fig. 8. The x-axis represents the participation level ranging from 10 to 100%; y-axis represents the relative loss per quarantine farm $y$; the scaled color in each pixel represents the relative total loss $l$. Comparing the loss color map of three networks, the relative total loss $l$ with the contact-based LIS are mostly the smallest under any participation and quarantine loss $y$ pair. The smallest economic loss is always achieved in the upper right corner, which suggests that the more farms participated in the information-sharing network, the lower economic losses can be achieved, especially when the quarantine cost is much lower than infection (when $y$ is negligible).

The results in Fig. 9 show the range of the total loss under different participation or different quarantine loss $y$. The range of the total loss is taken as a measurement of the sensitivity between the total loss and the other variables. The ranges of the total loss under 10% participations are less than 3, which means the total loss is not sensitive to the relative quarantine loss $y$ under 10% participations. The range increases with the participation level, and decreases with the relative quarantine loss, which means the loss becomes more sensitive to quarantine...
loss $\gamma$ under greater participations, and less sensitive to the participations when the relative quarantine loss $\gamma$ grows. From Fig. 7, we know that quarantine size $Q$ is much smaller than epidemic size $R$ when the participation is low, so that $R$ is the dominant term in the loss calculation. The increase rate of the quarantine size is greater than the decrease rate of the epidemic size with participation level based on Fig. 7. The loss decreased from $R$ can be compensated by the increase in $Q$ especially when the relative quarantine loss $\gamma$ is large.

**Conclusions**

In this study, we firstly conducted hypothetical FMD spreads on a single-layer DCN, a two-layer D&ICN, and a three-layer DIC&ISN, where the results show that the FMD has larger epidemic size and long duration on the two-layer D&ICN than the single-layer DCN, and that the information-sharing layer is able to mitigate the spread of the disease. These results re-addressed the significant influence of the truck visits on the between-farm transmission of FMD virus, and revealed that truck-visit routes can greatly enlarge the outbreak epidemic size, but have limited influence on increasing the outbreak probability. Therefore, the regional animal disease control agencies should take actions to reduce direct-contact rate and control the cattle movements in the early stage of the epidemic to prevent the outbreak. For existing outbreaks, increasing truck sterilization frequency and limiting truck visits are useful policies to mitigate the epidemic size.

The information-sharing network is tested effective for epidemic mitigation. We compared the mitigating performance of three information-sharing networks with different topologies and participation levels. The contact-based network has the best performance on suppressing the epidemic size while maintaining low quarantine size especially when the farms with the highest degrees are participated. For all three information-sharing networks, increased participations result in decreased epidemic sizes but increased quarantine sizes. For contact-based ISN, the epidemic size decreases fastest, while the quarantine size increases slowest. A sensitive analysis is conducted.
to explore the potential economic losses caused by the infection and quarantine. We found that the losses with contact-based ISN is the smallest under any participation and relative quarantine loss pair, and that an increased participation level generally leads to a deceased economic loss when the quarantine costs are negligible ($\gamma < 0.3$).

The regional agencies could work on calling more farms to participate in the contact-based information-sharing network to ensure that the infection status of the farms is accessible to their business partners. In our results, an 80% participation level is able to display fairly good performance on reducing the economic losses. We focused on the beef-cattle industry in SW KS, but the implement of information-sharing network can be used by the whole livestock industry.

In this study, there are several limitations. First, the other indirect contacts, like personnel visits and air-borne are not considered. Another limit is we did not consider the auction market. Removing these limitations can be the subject of the future work, together with the determination of the optimal participation level.

Data availability
The datasets used and analyzed during the current study available from the corresponding author on reasonable request.

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References
1. Knight-Jones, T. J. & Rushton, J. The economic impacts of foot and mouth disease—What are they, how big are they and where do they occur? Prev. Vet. Med. 112(3–4), 161–173 (2013).
2. Thompson, D. et al. Economic costs of the foot and mouth disease outbreak in the United Kingdom in 2001. Revue Scientifique et Technique (Int. Office Epizootics) 21(3), 675–687 (2002).
3. Bouma, A. et al. The foot-and-mouth disease epidemic in The Netherlands in 2001. Prev. Vet. Med. 57(3), 155–166 (2003).
4. Muroya, N. et al. The 2016 foot-and-mouth disease epidemic in Japan. J. Vet. Med. Sci. 74(4), 399–404 (2012).
5. Balinda, S. N. et al. Prevalence estimates of antibodies towards foot-and-mouth disease virus in small ruminants in Uganda. Transbound. Emerg. Dis. 56(9–10), 362–371 (2009).
6. Pendell, D. L., Leatherman, J., Schroeder, T. C. & Alward, G. S. The economic impacts of a foot-and-mouth disease outbreak: A regional analysis. J. Agric. Appl. Econ. 39(1), 19–33 (2007).
7. Fèvre, E. M., Bronsvoort, B. M. C., Hamilton, K. A. & Cleaveland, S. Animal movements and the spread of infectious diseases. Trends Microbiol. 14(3), 125–131 (2006).
8. Porphyre, T., Bronsvoort, B. M. C., Gunn, G. J. & Correia-Gomes, C. Multilayer network analysis unravels haulage vehicles as a hidden threat to the British swine industry. Transb. Emerg. Diseases 67(3), 1231–1246 (2020).
9. VanderWaal, K. L. et al. Network analysis of cattle movements in Uruguay: Quantifying heterogeneity for risk-based disease surveillance and control. Prev. Vet. Med. 123, 12–22 (2016).
10. Rossi, G., Smith, R. L., Pongolini, S. & Bolzoni, L. Modelling farm-to-farm disease transmission through personnel movements: From visits to contacts, and back. Sci. Rep. 7(1), 1–11 (2017).
11. Nöremark, M., Frössling, J. & Lewerin, S. S. A survey of visitors on Swedish livestock farms with reference to the spread of animal diseases. BMC Vet. Res. 9(1), 1–10 (2013).
12. Bates, T. W., Thurmond, M. C. & Carpenter, T. E. Direct and indirect contact rates among beef, dairy, goat, sheep, and swine herds in three California counties, with reference to control of potential foot-and-mouth disease transmission. Am. J. Vet. Res. 62(7), 1121–1129 (2001).
13. Thakur, K. K. et al. Development of a network based model to simulate the between-farm transmission of the porcine reproductive and respiratory syndrome virus. Vet. Microbiol. 180(3–4), 212–222 (2015).

Figure 9. Range of the total loss under different participations and relative quarantine losses.
14. Bernini, A., Bolzoni, L. & Casagrandi, R. When resolution does matter: Modelling indirect contacts in dairy farms at different levels of detail. *PLoS ONE* **14**(10), e0223652 (2019).
15. Rossi, G. *et al.* The potential role of direct and indirect contacts on infection spread in dairy farm networks. *PLoS Comput. Biol.* **13**(1), e1005301 (2017).
16. Yang, Q. *et al.* Impact of truck contamination and information sharing on foot-and-mouth disease spreading in beef cattle production systems. *PLoS ONE* **15**(10), e0240819 (2020).
17. Viet, N. Q., Behdani, B. & Bloemhof, J. *The value of information in supply chain decisions: A review of the literature and research agenda.* *Comput. Ind. Eng.* **120**, 68–82 (2018).
18. Kim, M. & Chai, S. *The impact of supplier innovativeness, information sharing and strategic sourcing on improving supply chain agility: Global supply chain perspective.* *Int. J. Prod. Econ.* **187**, 42–52 (2017).
19. Granell, C., Gómez, S. & Arenas, A. *Dynamical interplay between awareness and epidemic spreading in multiplex networks.* *Phys. Rev. Lett.* **111**(12), 128701 (2013).
20. Zheng, C., Xia, C., Guo, Q. & Dehmer, M. *Interplay between SIR-based disease spreading and awareness diffusion on multiplex networks.* *J. Parallel Distrib. Comput.* **115**, 20–28 (2018).
21. Sahneh, F., Chowdhury, E., Brase, G. & Scoglio, C. *Individual-based information dissemination in multilayer epidemic modeling.* *Math. Model. Nat. Phenomena* **9**(2), 136–152 (2014).
22. Pappa, I. C., Iliopoulos, C. & Massouras, T. *What determines the acceptance and use of electronic traceability systems in agri-food supply chains?* *J. Rural. Stud.* **58**, 123–135 (2018).
23. Wiseman, L., Sanderson, J., Zhang, A. & Jakku, E. *Farmers and their data: An examination of farmers’ reluctance to share their data through the lens of the laws impacting smart farming.* *NJAS-Wageningen J. Life Sci.* **90**, 100301 (2019).
24. Yang, Q., Scoglio, C. & Gruenbacher, D. *EAGER: SSDIM: Data generation for the coupled system composed of the beef cattle production infrastructure and the transportation services infrastructure in Southern Kansas.* *Designsafe-CI.* https://doi.org/10.17603/DS2-3FT2-0441 (2019).
25. ErdHos, P. *et al.* *On the evolution of random graphs.* *Publ. Math. Inst. Hung. Acad. Sci.* **5**(1), 17–60 (1960).
26. Sahneh, F. D., Scoglio, C. & Van Mieghem, P. *Generalized epidemic mean-field model for spreading processes over multilayer complex networks.* *IEEE/ACM Trans. Netw.* **21**(5), 1609–1620 (2013).

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**Author contributions**

C.Y., Q.Y., and C.S. formulated the model; C.Y., Q.Y., and C.S. analyzed the data; C.Y., Q.Y., and C.S. developed the methodology; C.Y. developed the simulation tool; C.Y., Q.Y., and C.S. analyzed the results and contributed to the discussions; C.Y., Q.Y., and C.S. contributed to the writing. All authors reviewed the manuscript.

**Competing interests**

The authors declare no competing interests.

**Additional information**

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