Spatiotemporal Frameworks for Infectious Disease Diffusion and Epidemiology

Peter Congdon

School of Geography and Life Sciences Institute, Queen Mary University of London, Mile End, London E1 4NS, UK; p.congdon@qmul.ac.uk; Tel.: +44-207-882-8200

1. Background

Emerging infectious diseases, and the resurgence of previously controlled infectious disease (e.g., malaria, tuberculosis), are a major focus for public health concern, as well as providing challenges for establishing aetiology and transmission. Novel aspects affecting spread of infectious disease are factors such as globalisation, population growth, environmental change and antibiotic resistance [1].

Understanding the diffusion of infectious disease at population level in this context is of major importance in managing outbreaks of new or resurgent infectious disease. Infectious disease diffusion through space and time is an example of a broader class of spatiotemporal diffusion processes, involving movement across space and changing extent through time [2,3].

2. Diffusion Processes

With regard to infectious disease spread, spatiotemporal diffusion has been considered both for historic diseases, such as bubonic plague [4], and for recent infectious disease outbreaks such as the H1N1 pandemic, recurrent epidemics of dengue fever, and the spread of ebola [5]. Infectious disease spread among animals is subject to similar considerations [6]; up to a half of human infectious diseases have a zoonotic origin, that is, are transmitted from animals, with a higher proportion among emerging infectious diseases [7].

In the past, infectious disease diffusion was based primarily on contagious spread of the disease, but increasingly disease can spread quickly via transport links at regional and global scale, a process known as network diffusion [8]. Other principles may be paramount such as hierarchical spread from large cities to smaller towns, while impediments to spread (e.g., distance decay effects) are also relevant.

One may also consider co-dependence between infectious diffusion and other outcomes, such as malformation in newborns linked to zika virus infection in mothers. For example, [9] consider the dynamics of HIV sero-discordancy (one partner testing HIV seropositive, while the other testing HIV seronegative), and of sero-concordancy, as against HIV prevalence itself.

3. Analytic Methods

Analytic tools are of obvious importance in measuring and analysing disease diffusion. An established tradition in epidemiological research has been to use surveillance and spatiotemporal visualisation techniques. These are used to identify the spread of infectious disease outbreaks, provide early warnings [10], identify the source of infection [11], predict the eventual disease extent [12], or permit intervention to prevent further spread of the disease.

Geographic information system (GIS) methods and GIS-based simulation in particular have utility in describing and analysing spatiotemporal infectious disease patterns [13,14]. For example, [15] describes DengueME, an open source platform to simulate dengue disease, implemented over a GIS database. DengueME represents Aedes aegypti population dynamics, human demography and

mobility, urban landscape and dengue transmission mediated by human and mosquito encounters. Data mining applied to internet search and social media data is being increasingly applied [16].

A wide range of sophisticated mathematical and statistical techniques [17,18] have also been developed. These include measuring spatial and space-time clustering [19,20] to detect existing high risk areas or areas at risk of disease influx, while mathematical diffusion and epidemic models [21,22] focus especially on the time pattern of disease spread.

Incorporating spatial dependence for analysis at large scale geographies is important since environmental exposures, such as climate and land use, and other factors affecting transmission such as antibiotic resistance [14] and socio-economic status, are spatially dependent. So analyses that do not account for spatial dependence in exposures may overstate significance effects, whereas analysis allowing for spatial dependence will provide a better fit [23].

Illustrating application of such methods, Dong et al. [24] develop a predictive risk map for the distribution of the HN79 outbreak in China in 2013–2014, with spatial–temporal autocorrelation incorporated into logistic regression analysis along with environmental and climatic risk factors. By contrast, time dependence is the focus in the hybrid approach of Zhou et al. [25], combining autoregressive integrated moving average (ARIMA) and nonlinear autoregressive neural network (NARNN) models to forecast the prevalence of schistosomiasis. Li et al. [26] use space and space–time scan statistics and trajectory similarity analysis to establish differences in the location and evolution of new and retreated smear-positive TB patients. Adegboye and Adegboye [27] apply a dynamic transmission multivariate time series model to cutaneous leishmaniasis in Afghanistan, e.g., see [28], to evaluate the effects of three environmental layers as well as seasonality in the data. Furthermore, ecological niche modeling was used to study the geographically suitable conditions for cutaneous leishmaniasis using temperature, precipitation and altitude as environmental layers.

4. Infectious Disease Aetiology and Disease Spread

Underlying and modulating space–time patterns in infectious diffusion are a variety of environmental and socio-economic factors, including population density and growth [7], and changing transport patterns [29]. For example, changes in the incidence of dengue fever in tropical countries have been related both to urbanization, increased air travel, and climatic factors such as rainfall, temperature, and humidity [30]. Health care access and effectiveness, vaccination uptake, and drug availability, especially in developing countries, also affect infectious disease control [31,32].

As illustrative applications, Zhang et al. [33] analyse the distribution of bacillary dysentery across China in terms of seasonality and meteorological factors, urban–rural disparities, and distribution of Shigella species. They find links to economic development and identify endemically high-risk regions in western China. Cao et al. [34] identify a similar spatial pattern for TB incidence in Chinese provinces and find links to climatic variables. Moise et al. [35] find that impacts on malaria incidence of seasonality and elevation may be modified by high population density and economic activity patterns (such as intensive subsistence farming practice) which affect exposure. Xu et al. [36] develop an ecological niche model for the spatial distribution of H7N9 cases using environmental, climatic and anthropogenic variables (distribution of live poultry processing factories, farms, and human population density), and find the latter as having greatest predictive value. Regarding the impact of health care access, a study of care-seeking for diarrhoea in Southern Malawi [37] show obstacles to obtaining healthcare advice, such as distance and transport costs to health facilities, as well as prolonged waiting times.

In a longer time perspective, environmental factors such as climate change [38], air pollution [39], ecosystem disruption and the loss of biodiversity are also important for understanding and controlling infectious disease. For example, deforestation has been linked to changing patterns of malaria and schistosomiasis. Lal [23] considers impacts of climate change on zoonotic transmission of cryptosporidiosis, as the parasite is easily transmitted through the environment, particularly through water. Historical time-series modelling of cryptosporidiosis incidence with rainfall has reported positive associations in a global meta-analysis of cryptosporidiosis seasonality [40]. Padilla et al. [41] consider impacts on infant mortality (often linked to infection) of socioeconomic factors and air pollution.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Knobler, S.; Mahmoud, A.; Lemon, S.; Pray, L. *The Impact of Globalization on Infectious Disease Emergence and Control*; National Academies Press: Washington, DC, USA, 2006.
2. Schærström, A. Disease Diffusion. In *The Wiley Blackwell Encyclopedia of Health, Illness, Behavior, and Society*; Wiley: Hoboken, NJ, USA, 2014.
3. Sabel, C.; Pringle, D.; Schoerstrom, R. Infectious disease diffusion. In *A Companion to Health and Medical Geography*; Brown, T., McLafferty, S., Moon, G., Eds.; Wiley-Blackwell: Oxford, UK, 2009; pp. 111–132.
4. Keeling, M.; Gilligan, C. Bubonic plague: A metapopulation model of a zoonosis. *Proc. R. Soc. Lond. B Biol. Sci.* **2000**, *267*, 2219–2230. [CrossRef] [PubMed]
5. Kramer, A.; Pulliam, J.; Alexander, L.; Park, A.; Rohani, P.; Drake, J. Spatial spread of the West Africa Ebola epidemic. *R. Soc. Open Sci.* **2016**, *3*, 160294. [CrossRef] [PubMed]
6. Wilesmith, J.; Stevenson, M.; King, C.; Morris, R. Spatio-temporal epidemiology of foot-and-mouth disease in two areas of Great Britain in 2001. *Prev. Vet. Med.* **2003**, *61*, 157–170. [CrossRef] [PubMed]
7. Jones, K.E.; Patel, N.G.; Levy, M.A.; Storeygard, A.; Balk, D.; Gittleman, J.L.; Daszak, P. Global trends in emerging infectious diseases. *Nature* **2008**, *451*, 990–993. [CrossRef] [PubMed]
8. Cromley, E.; McLafferty, S. *GIS and Public Health*, 2nd ed.; Guilford Press: New York, NY, USA, 2012.
9. Cuadros, D.; Abu-Raddad, L. Geographical Patterns of HIV Sero-Discordancy in High HIV Prevalence Countries in Sub-Saharan Africa. *Int. J. Environ. Res. Public Health* **2016**, *13*, 865. [CrossRef] [PubMed]
10. Hitchcock, P.; Chamberlain, A.; Van Wagoner, M.; Inglesby, T.; O'Toole, T. Challenges to global surveillance and response to infectious disease outbreaks of international importance. *Biosecur. Bioterror. Biodefense Strateg. Pract. Sci.* **2007**, *5*, 206–227. [CrossRef] [PubMed]
11. Brownstein, J.; Rosen, H.; Purdy, D.; Miller, J.; Merlino, M.; Mostashari, F.; Fish, D. Spatial Analysis of West Nile Virus: Rapid Risk Assessment of an Introduced Vector-Borne Zoonosis. *Vector-Borne Zoonotic Dis.* **2004**, *2*, 157–164. [CrossRef] [PubMed]
12. Woolhouse, M. How to make predictions about future infectious disease risks. *Philos. Trans. R. Soc. B Biol. Sci.* **2011**, *366*, 2045–2054. [CrossRef] [PubMed]
13. Ramírez-Ramírez, L.; Gel, Y.; Thompson, M.; de Villa, E.; McPherson, M. A new surveillance and spatio-temporal visualization tool SIMID: SIMulation of infectious diseases using random networks and GIS. *Comput. Methods Programs Biomed.* **2013**, *110*, 455–470. [CrossRef] [PubMed]
14. Galvin, S.; Bergin, N.; Hennessy, R.; Hanahoe, B.; Murphy, A.W.; Cormican, M.; Vellinga, A. Exploratory Spatial Mapping of the Occurrence of Antimicrobial Resistance in *E. coli* in the Community. *Antibiotics* **2013**, *2*, 328–338. [CrossRef] [PubMed]
15. De Lima, T.F.; Lana, R.M.; de Senna Carneiro, T.G.; Codeço, C.T.; Machado, G.S.; Ferreira, L.S.; de Castro Medeiros, L.C.; Davis Junior, C.A. DengueME: A Tool for the Modeling and Simulation of Dengue Spatiotemporal Dynamics. *Int. J. Environ. Res. Public Health* **2016**, *13*, 920. [CrossRef] [PubMed]
16. Corley, C.D.; Cook, D.J.; Mikler, A.R.; Singh, K.P. Text and structural data mining of influenza mentions in web and social media. *Int. J. Environ. Res. Public Health* **2010**, *7*, 596–615. [CrossRef] [PubMed]
17. Kleinman, K.; Lazarus, R.; Platt, R. A generalized linear mixed models approach for detecting incident clusters of disease in small areas, with an application to biological terrorism. *Am. J. Epidemiol.* **2004**, *159*, 217–224. [CrossRef] [PubMed]
18. De Moraes, J.C.; Camargo, M.; de Mello, M.; Hersh, B.; Glasser, J. The 1997 Measles Outbreak in Metropolitan São Paulo, Brazil: Strategic Implications of Increasing Urbanization. In *Mathematical and Statistical Modeling for Emerging and Re-emerging Infectious Diseases*; Springer: New York, NY, USA, 2016; pp. 269–289.
19. Lessler, J.; Salje, H.; Grabowski, M.; Cummings, D. Measuring Spatial Dependence for Infectious Disease Epidemiology. *PLoS ONE* **2016**, *11*, e0155249. [CrossRef] [PubMed]
20. Ward, M. Spatio-temporal analysis of infectious disease outbreaks in veterinary medicine: Clusters, hotspots and foci. *Vet. Ital.* **2007**, *43*, 559–570. [PubMed]
21. Longini, I.; Koopman, J.; Monto, A.; Fox, J. Estimating household and community transmission parameters for influenza. *Am. J. Epidemiol.* **1982**, *115*, 736–751. [PubMed]

Int. J. Environ. Res. Public Health **2016**, *13*, 1261

4 of 4

22. Yang, Y.; Sugimoto, J.; Halloran, M.; Basta, N.; Chao, D.; Matrajt, L.; Potter, G.; Kenah, E.; Longini, I. The transmissibility and control of pandemic influenza A (H1N1) virus. *Science* **2009**, *326*, 729–733. [CrossRef] [PubMed]

23. Lal, A. Spatial modelling tools to integrate public health and environmental science, illustrated with infectious cryptosporidiosis. *Int. J. Environ. Res. Public Health* **2016**, *13*, 186. [CrossRef] [PubMed]

24. Dong, W.; Yang, K.; Xu, Q.; Yang, Y. A predictive risk model for A(H7N9) human infections based on spatial-temporal autocorrelation and risk factors: China, 2013–2014. *Int. J. Environ. Res. Public Health* **2015**, *12*, 15204–15221. [CrossRef] [PubMed]

25. Zhou, L.; Xia, J.; Yu, L.; Wang, Y.; Shi, Y.; Cai, S.; Nie, S. Using a hybrid model to forecast the prevalence of schistosomiasis in humans. *Int. J. Environ. Res. Public Health* **2016**, *13*, 355. [CrossRef] [PubMed]

26. Li, L.; Xi, Y.; Ren, F. Spatio-temporal distribution characteristics and trajectory similarity analysis of tuberculosis in Beijing, China. *Int. J. Environ. Res. Public Health* **2016**, *13*, 291. [CrossRef] [PubMed]

27. Adegboye, A.O.; Adegboye, M. Spatially correlated time series and ecological niche analysis of cutaneous leishmaniasis in Afghanistan. *Int. J. Environ. Res. Public Health* **2016**. [CrossRef]

28. Reithinger, R.; Mohsen, M.; Aadil, K.; Sidiqi, M.; Erasmus, P.; Coleman, P.G. Anthroponotic cutaneous Leishmaniasis, Kabul, Afghanistan. *Emerg. Infect. Dis.* **2003**, *9*, 727–729. [CrossRef] [PubMed]

29. Tatem, A.; Rogers, D.; Hay, S. Global transport networks and infectious disease spread. *Adv. Parasitol.* **2006**, *62*, 293–343. [PubMed]

30. Teurlai, M.; Menkès, C.; Cavarero, V.; Degallier, N.; Descloux, E.; Grangeon, J.; Guillaumot, L.; Libourel, T.; Lucio, P.S.; Mathieu-Daudé, F.; et al. Socio-economic and climate factors associated with dengue fever spatial heterogeneity: A worked example in New Caledonia. *PLoS Negl. Trop. Dis.* **2015**, *9*, e0004211. [CrossRef] [PubMed]

31. Radisch, J. More medicines for neglected and emerging infectious diseases. *Bull. World Health Organ.* **2007**, *85*, 572. [CrossRef] [PubMed]

32. Abdallah, S.; Burnham, G. *The Johns Hopkins School of Hygiene and Public Health and the International Federation of Red Cross and Red Crescent Societies*; Public Health Guide for Emergencies: Boston, MA, USA, 2000.

33. Zhang, H.; Si, Y.; Wang, X.; Gong, P. Patterns of bacillary dysentery in China, 2005–2010. *Int. J. Environ. Res. Public Health* **2016**, *13*, 164. [CrossRef] [PubMed]

34. Cao, K.; Yang, K.; Wang, C.; Guo, J.; Tao, L.; Liu, Q.; Gehendra, M.; Zhang, Y.; Guo, X. Spatial-temporal epidemiology of tuberculosis in mainland China. *Int. J. Environ. Res. Public Health* **2016**, *13*, 469. [CrossRef] [PubMed]

35. Moise, I.; Sen Roy, S.; Nkengurutse, D.; Ndikubagenzi, J. Seasonal and geographic variation of pediatric malaria in Burundi: 2011 to 2012. *Int. J. Environ. Res. Public Health* **2016**, *13*, 425. [CrossRef] [PubMed]

36. Xu, M.; Cao, C.; Li, Q.; Jia, P.; Zhao, J. Ecological niche modeling of risk factors for H7N9 human infection in China. *Int. J. Environ. Res. Public Health* **2016**, *13*, 600. [CrossRef] [PubMed]

37. Masangwi, S.; Ferguson, N.; Grimason, A.; Morse, T.; Kazembe, L. Care-seeking for diarrhoea in Southern Malawi: Attitudes, practices and implications for diarrhoea control. *Int. J. Environ. Res. Public Health* **2016**, *13*, 1140. [CrossRef] [PubMed]

38. Morin, C.; Comrie, A.; Ernst, K. Climate and dengue transmission: Evidence and implications. *Environ. Health Perspect.* **2013**, *121*, 1264–1272. [CrossRef] [PubMed]

39. Kumar, R.; Nagar, J.; Kumar, H.; Kushwah, A.; Meena, M.; Kumar, P.; Raj, N.; Singhal, M.; Gaur, S. Association of indoor and outdoor air pollutant level with respiratory problems among children in an industrial area of Delhi, India. *Arch. Environ. Occup. Health* **2007**, *62*, 75–80. [CrossRef] [PubMed]

40. Jagai, J.; Castronovo, D.; Monchak, J.; Naumova, E. Seasonality of cryptosporidiosis: A meta-analysis approach. *Environ. Res.* **2009**, *109*, 465–478. [CrossRef] [PubMed]

41. Padilla, C.; Kihal-Talantikit, W.; Vieira, V.; Deguen, S. City-Specific Spatiotemporal Infant and Neonatal Mortality Clusters: Links with Socioeconomic and Air Pollution Spatial Patterns in France. *Int. J. Environ. Res. Public Health* **2016**, *13*, 62. [CrossRef] [PubMed]