Published in final edited form as:

Transbound Emerg Dis. 2012 October ; 59(5): 464–469. doi:10.1111/j.1865-1682.2011.01301.x.

Epidemic Protection Zones: Centred on Cases or Based on Connectivity?

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Summary

When an exotic infectious disease invades a susceptible environment, protection zones are enforced. Historically, such zones have been shaped as circles of equal radius (ER), centred on the location of infected premises. Because the ER policy seems to assume that epidemic dissemination is driven by a similar number of secondary cases generated per primary case, it does not consider whether local features, such as connectivity, influence epidemic dispersal. Here we explored the efficacy of ER protection zones. By generating a geographically explicit scenario that mimicked an actual epidemic, we created protection zones of different geometry, comparing the cost-benefit estimates of ER protection zones to a set of alternatives, which considered a pre-existing connecting network (CN) – the road network. The hypothesis of similar number of cases per ER circle was not substantiated: the number of units at risk per circle differed up to four times among ER circles. Findings also showed that even a small area (of <115 km²) revealed network properties. Because the CN policy required 20% less area to be protected than the ER policy, and the CN-based protection zone included a 23.8% greater density of units at risk/km² than the ER-based alternative, findings supported the view that protection zones are likely to be less costly and more effective if they consider connecting structures, such as road, railroad and/or river networks. The analysis of local geographical factors (contacts, vectors and connectivity) may optimize the efficacy of control measures against epidemics.

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Supporting Information

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Keywords

health geographics; protection zones; networks; connectivity; roads

Introduction

Circular protection zones of equal radius (ER) have classically been applied to control epidemics (Thrusfield et al., 2005; Jewell et al., 2009; Lu et al., 2010; Knight-Jones et al., 2011; Thulke et al., 2011). They are geographical zones where some control measures against disease dispersal are applied. The validity of ER circular protection zones has not yet been explored (Cook et al., 2006). Because ER protection zones assume all infected individuals possess a similar ability to spread disease, such constructs do not consider the bio-geographical structure of the infected area (Filipe and Maule, 2004; Aparicio and Pascual, 2007; Dangerfield et al., 2009).

An alternative view has proposed that disease spread may be explained by network properties (those of points or nodes, connected by lines, Watts and Strogatz, 1998; Barthélemy, 2011). While most network-based studies have measured contacts (e.g. people, animals), only a few reports have assessed connectivity, for example, that associated with road networks (Rivas et al., 2003, 2010; Martinez-Lopez et al., 2009; Ahmed et al., 2011). Network properties may express Pareto's '20: 80' pattern, that is, approximately 20% of all infected sites may include approximately 80% of the cases (Andriani and McKelvey, 2009). When such a pattern is observed, control measures based on the homogeneous dissemination hypothesis may not be optimal (Chowell et al., 2008). However, less costly/more beneficial control measures can be generated when the local geography is considered (Rivas et al., 2004, 2008).

While the ER policy assumes that all cases are epidemiologically similar in their ability to disseminate disease – regardless of connecting networks – the connecting network (CN) model assumes that, to disseminate, the invading microbe needs a pre-existing connecting structure, in addition to a susceptible population. To assess both views, we created a bio-geographical scenario, which summarized some features associated with an actual epidemic. The structure analysed was not hypothetical: it was based on geo-referenced data collected from past epidemics (Supporting Information). This study did not consider the infective agent, host species or time; instead, it focused on relationships among boundaries of the protection zone and the connecting structure. While the dataset under study should not be construed as representative of all epidemics (on the contrary, unless shown otherwise, every epidemic may be suspected to be unique), epidemic scenarios similar to the data analysed have been reported in numerous epidemics where different species and pathogens have been involved (Rivas et al., 2003, 2010; Ahmed et al., 2011). Connectivity was assessed in terms of proximity, continuity and length, as suggested by Xie and Levinson (2007). The total road length included in the protection zone was measured, as well as its degree of fragmentation (continuity). Proximity expressed the distance from farms to highways and/or highway intersections. For simplicity, we only measured major highways.

Here we empirically explored whether an epidemic control policy, based on ER protection circles, was empirically justified. For comparison, we assessed a CN control policy. Two questions were asked: (i) whether ER circles revealed a similar number of 'sites at risk', and (ii) whether the cost/benefit estimates associated with ER circles were similar to those of the CN control policy. To answer these questions, we determined the number of farms at risk/km² and the road structure associated with the ER model and evaluated the CN model in three versions: (i) based on the smallest circle that included both roads or road intersections and the highest density of farms at risk, (ii) based on the smallest polygon that included most farms at risk, which were partially connected through roads; and (iii) based on the smallest polygon that included all farms at risk, which were totally connected through a continuous road structure. We also asked whether CN properties could be documented, based on geo-referenced data, within the area under study.

Methods

Creation of a geographically explicit epidemic scenario

The image of a geographically specific region, where a specific epidemic took place at a specific point in time ('epidemic report', described in Supporting Information), was exported into a JPG file format. Using ArcGIS 10.1 (ESRI, Redlands, CA, USA), the epidemic report (JPG file) was geo-referenced to the WGS 1984 Web Mercator Auxiliary Sphere projection, taking four road intersections shown on the JPG file to correspond with the same intersections reported on a BING map layer accessed from ArcGIS Online (<http://www.arcgis.com/home/>). To facilitate area and distance calculations, the geo-referenced image was projected into the ETRS 1989 UTM (Zone 30, North) projection. The radius of individual 'farm at risk' site areas was empirically derived from the protection zone of the epidemic report, that is, circles of various radii were created until their perimeters matched the boundaries of the protection zone shown in the epidemic report. After such procedure identified nine circles of equal radius, their corresponding centroids (sites where 9 'farms at risk' were located) were identified. The road network associated with the protection zone was digitized, including road segments located outside such zone. *Buffers* were created (a polygon was generated), centred on the road layer. Such polygon included all farms at risk. An additional site location (centroid and circle #10) was digitized, which corresponded to a road intersection located near to but outside the south-east border of the protection zone. A second set of buffers (a second polygon) was created by joining the additional site location (circle #10) with a polygon that included both all farms at risk and road segments in a way such that a continuous (non-fragmented) road network was generated. The original road layer, which included road segments outside the epidemic report's protection zone, was clipped to include the larger polygon described above (which included the 10th circle, that is, the road intersection located outside the protection zone). Areas (km²) and distances (km) were calculated for each data layer using the 'calculate geometry' field tool provided by ArcGIS 10.1.

Statistical analysis

The Wilcoxon signed rank test was used to determine whether the number of 'farms at risk' per circle was similar among ER circles (as expected under the assumption of homogeneous

epidemic dispersal). The Mann–Whitney *U*-test for the median was applied to determine whether the distance from farms to roads (or intersections) or the inter-farm (Euclidean) distance differed. A Chi-square goodness-of-fit test explored the contribution of each ER circle to the global Chi-square value. Statistical tests were conducted using Minitab 15® (Minitab Inc., State College, PA, USA).

Results and Discussion

The protection zone under study (Supporting Information) was the result of nine partially overlapping circles of ER (Figs 1a-f). The centroids of such circles were assumed to be ‘farms at risk’ (Fig. 1b). The true health status of each farm (infected or non-infected) was not determined. The number of farms at risk per circle differed up to four times (Figs 1b and e). The median number of farms at risk per ER circle was 2.5 (Supporting Information). The circles that revealed the highest number of farms at risk included a highway intersection (Fig. 1f).

The overall risk density in the ER protection zone was 0.063 farms/km² (9 farms/142.5 km²). Because the length of roads in that zone was 32.34 km, road density was 0.22 km/km² (32.34 km of roads/142.5 km², Fig. 2a).

A higher density of farms at risk was found in the CN model, when circular protection zones were created and they were centred on the only highway intersection found within the area under study. By creating circles of various radii, three farm risk densities were calculated, which ranged between 0.056 and 0.144 farms at risk/km² [6/106.37 farms at risk/km², in the largest (5.7-km radius) circle; and 4/27.75 farms at risk/km², in the smallest (2.9-km radius) circle; Fig. 2b].

The road density associated with the smallest circle was 0.429 km/km² (11.91 km/27.75 km², Fig. 2b). Therefore, road density was almost two times greater in the smallest circle centred on a highway intersection than in the overall ER zone (0.429 versus 0.22 km/km²). The median distance from each farm to the nearest road intersection (proximity) was twice as short for the four farms located within the smallest circle than for the remaining farms (2.297 versus 4.721 km, $P = 0.02$, Mann-Whitney *U*-test, Fig. 2c and Supporting Information). The smallest circle included 44.4% (4/9) of all farms at risk, which were located within 19.5% of the total area (27.75/142.5 km²). If the percentage of farms at risk was considered to represent ‘benefit’, and the area to be covered was regarded to be a ‘cost’, the benefit-cost ratio of a policy based on the 2.9-km-radius circle, centred on a road intersection, would be 2.3 (44.4/19.5), that is, 2.3 times more beneficial than the ER policy.

However, the CN policy described above would only cover less than half of all farms at risk. To address such a limitation, an alternative protection zone was created, which was built as the smallest polygon that, through a non-fragmented area, included all farms at risk. Such policy reported a density of 0.132 farms at risk/km² (7/52.86, Fig. 2d). That would represent a twofold better policy, if compared to the farm density of the ER zone (0.063 farms/km²). However, the CN policy based on the smallest polygon that included all farms at risk did not

possess a continuous CN: two farms at risk lacked connectivity – they could only be connected if a road segment, located outside the protection zone, was considered (Fig. 2d).

To address the limitation indicated above, a third CN policy was explored, where the protection area was expanded to include the highway intersection located outside the south-east border of the original protection zone (Fig. 2e). If the polygon so created was wide enough to include both all farms at risk and the added area, the total area of the expanded protection zone that totally connected all farms through a non-fragmented CN would be 114.42 km² (Fig. 2f). In this CN policy, farm density (0.078 or 9 farms/114.42 km²) was 23.8% greater than that of the ER zone (0.063 farms/km² or 9 farms/142.5 km²). The total area to be protected, in the totally connected polygon, was 19.8% smaller than that of the ER zone (114.42 versus 142.5 km²). The road density of the totally connected, polygon-based protection zone was 0.473 km of roads/km² (54.17 km/114.42 km²), a road density twice as great as that of the ER protection zone (0.47 versus 0.22 km of roads/km²). Because benefits (farm density) were 123.8% greater and costs (area to be intervened) were 80.2% (19.8% smaller), the benefit-cost ratio of the totally connected policy was 1.54 (123.8/80.2) compared to that of the ER policy (Fig. 2f).

Spatial correlation analysis (Moran's I test) indicated that farms at risk were clustered (a network property), where approximately 37% of the variance in at-risk farm location was accounted for by distance from farm to the nearest road or road intersection (Supporting Information). An additional finding also rejected the hypothesis that farms at risk were homogeneously disseminated: farms at risk were, on average, 9.3 times closer to a road than to one another (Supporting Information). Therefore, findings indicated that disease clusters are not necessarily circular: 'along-road' clusters can also be found. A second network property (a Pareto-like distribution) was also suggested by the data (Supporting Information).

Hence, a small (115 km²) epidemic area revealed network properties. Road network-associated epidemic dispersal has been reported before (Rivas et al., 2003; Ahmed et al., 2011).

While ER circular protection zones may be a starting point when control policies are planned, it is suggested that protection zones can be more effective if connectivity is taken into account. That proposition is based on the fact that, to disseminate, an exotic or emerging microbe needs not only a susceptible host, but also a pre-existing CN – the microbe cannot build such network. Protection zones could be built based on a region-specific analysis, which may consider variables such as the number of sites at risk/km², total area to be protected, proximity, continuity and/or network length.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

Authors thank the permission given by the British Department for Environment, Food and Rural Affairs (DEFRA) to utilize their data.

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Fig. 1. Features of the equal radius (ER) protection zone. (a) Protection and highway structure. (b) Individual ER circles, centred on farms at risk. (c–e) number of cases per circle, at selected circles. (f) Farms at risk and highway intersections.

Fig. 2.

Cost-benefit estimates of the equal radius (ER) and connecting network (CN) protection zones. (a) In the ER protection zone, case density was 0.063 cases/km² (9/142.5 km²) and road density was 0.22 km/km² (32.34 km/142.5 km²). (b) When connectivity was considered (protection zones were centred on a highway intersection) and circular protection zones were created, the case density ranged between 0.144 cases/km² (4/27.75, smallest circle), 0.102 (5/48.79, intermediate circle) and 0.056 (6/106.37 cases/km², largest circle). The road density was 0.429 km/km² within the smallest circle (11.91 km of roads/27.75 km²). (c) The median distance from farms to the nearest intersection was less than half for the four farms included in the smallest circle than for farms located outside such circle (2.297 versus 4.721 km, respectively). (d) Because the previous CN policy did not include all farms at risk, a second CN version was considered, based on the smallest polygon that included all farms at risk. The case density in the smallest polygon was 0.132 cases/km² (7/52.86). However, this polygon only partially connected farms through roads: 2 of the 9 farms at risk could only be connected if a road segment, located outside the polygon, was considered. (e) To address that limitation, the protection zone was expanded to include a highway intersection located outside the ER protection zone. (f) A third CN alternative

considered both a polygon and a continuous road structure. The polygon was wide enough to include the additional area described in c. In this solution, case density was 0.078 (nine cases/114.42 km²), which was 23.8% greater than that of the ER zone (0.063); the total area to be protected represented 80.2% of the ER area (114.42/142.5 km²); and road density (0.473 km/km² or 54.17 km/114.42 km²) was 2.15 times greater than that of the ER protection zone (0.22 km/km²).