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Spread of Ebola virus disease based on the density of roads in West Africa

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Abstract

On March 23rd 2014 the World Health Organization announced that a new Ebola outbreak had appeared in West Africa involving three countries. The objective of this study was to show how a road density index (RDI) could be constructed and a study of its association with Ebola cases during the outbreak. The study was carried out at the district level across the affected countries. RDI was calculated by km^2 of territory as a proxy for the mobility of the population. To calculate this index, the number of km of road constructed in each district was estimated and subsequently divided by the area of each district expressed in km^2. The accumulated incidence of Ebola was calculated per district. A generalised linear model with a Poisson distribution was used. The RDI varied from 0.12 to 0.84 between the districts. An RDI increase of 0.01 indicates a 3% increase in Ebola infection risk (RR is 1.03; CI 1.03-1.04). The density of the road network can influence the increased incidence of Ebola cases in the affected zone. An exhaustive mapping of the area could help the relevant organisations to manage another outbreak in the future and it could help the distribution of resources in an emergency situation.

Introduction

Disease caused by the Ebola virus was first reported in 1976 (Bowen *et al*., 1977), virtually simultaneously in Sudan and what is now the Democratic Republic of Congo. The outbreaks that have occurred since have mostly appeared in remote rural areas of central Africa, resulting in around 2,400 cases according the Centers for Disease Control (CDC), Atlanta, GA, USA (CDC, 2016a, 2016b). On March 23rd 2014, the World Health Organization (WHO) announced that a new Ebola outbreak had occurred in the Republic of Guinea and four days afterwards it was announced that cases had been reported in the capital, Conakry, making it the first large city with Ebola transmission. On 30th March, Liberia announced its first cases and on 25th May Sierra Leone did the same. This was the origin of an unprecedented Ebola epidemic as regards both geographic scope and number of cases (WHO Ebola Response Team, 2014).

Ebola virus disease (EVD), formerly known as Ebola haemorrhagic fever, is a zoonotic infection with a reservoir in bats that can transmit the virus to other animals including humans. The transmission cycle is animal-to-animal, animal to human (spillover event) and human-to-human. Transmission of the virus from one human to another can occur through contact with blood and body fluids of infected people or from the bodies of those having died of Ebola (CDC, 2016a, 2016b). The current outbreak occurred in West Africa, a region characterised by high population densities and elevated population movement levels as much within as across national borders (WHO, 2015a, 2015b). The epidemic spread across almost the whole territory of the three affected countries, including rural and urban areas and also the capital cities (WHO, 2016).

The objectives of this study were to show how a road density index (RDI) could be constructed and used as a proxy of population movements in the region, and which could also be replicated in other regions or countries if the need arises. This Index was based on information about the national road networks and we studied its association with occurrences of cases during the recent EVD outbreak in the Republic of Guinea, Sierra Leone and Liberia.

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Materials and Methods

Study area

The study was carried out at the district level across the three affected countries: the Republic of Guinea, Liberia and Sierra Leone. The maps for each country were obtained from the global administrative areas (GADM, 2015) website (http://www.gadm.org/), which is a spatial database of the location of the world's administrative areas (or administrative boundaries) for use with geographical information systems (GIS) and similar software. The administrative areas in this database are countries and lower level subdivisions, in this case specific districts of the three countries. The administrative areas of Guinea include 33 prefectures and the capital, Conakry. Liberia is divided into 15 regions, while Sierra Leone is divided into 12 districts in addition to the capital, Freetown, itself divided into two zones: the urban west and the rural part. The distribution of administrative areas in the region of study can be found in Figure 1.

Road network and road density index calculation

The spatial information regarding the road network of the three countries was downloaded from Socioeconomic Data and Applications Center (SEDAC, 2013a, 2013b), where road information on a global level may be obtained through an open-source system. This road network includes primary, secondary, tertiary and local roads, as well as urban thoroughfares and tracks. From this information, the RDI was calculated by km^2 of territory as a proxy for the mobility of the people resident in the three affected countries. To calculate this index the number of km of road in each district was first estimated and then divided by the area of each district expressed in km^2.

Population data Ebola virus disease case information

Population data for 2010 was obtained from the Gridded Population of the World, V.3, from Socioeconomic Data and Applications Center (SEDAC, 2013a, 2013b). This information is available in raster format with a resolution of 0.00833 degrees (30 arc seconds); *i.e.* this information allowed the extraction of the number of inhabitants for every 0.5 km^2 of territory studied. In order to calculate the population in each district, the population of each cell in a district was added up using a geographical calculator.

The EVD cases used for this study were those reported during the outbreak in western Africa, from the start of the outbreak in the first week of 2014 through week 21 (18-24 May) of 2015 (73 weeks in total) in the three affected countries. The case details were obtained from the patient database of WHO's Global Health Observatory (GHO) (http://www.who.int/gho/en/). The data were available on this web page with weekly updates throughout the outbreak. The data published on 27 May 2015 was used for this study (WHO, 2015a, 2015b) with confirmed and probable cases analysed jointly. The weekly EVD incidence by district and the accumulated incidence were calculated per district during the period of study using the population references. A video with the spatio-temporal evolution of Ebola rates during the outbreak was done.

Statistics

A spatio-temporal mixed zero inflated negative binomial model was used in order to estimate the association between Ebola risk and RDI. We used this model because the dependent variable, number of Ebola cases, had many zero values. The offset was population and the fixed parameter RDI. The random effects were the district and the weekly number of the cases.

$$logt_{ijk}=\beta_0 + \beta_1 RDI_{11ijk} + \beta_2 week_{jk} + \beta_3 district_k$$

Where t_{ijk}=number of Ebola cases in the week j and the district k; RDI_{ijk}=RDI in the week j and the district k; $Week_{jk}$=week j in the district k; $District_k$=district k. We used a ArcGIS 10.1 (ESRI, Redlands, CA, USA) software to perform the spatial information and R and INLA packages for statistical analysis.

Results

A total of 20,667 cases were studied (16,723 confirmed and 3,944 probable). By country, the distribution was 3,627 in Guinea, 5,553 in Liberia and 11,487 in Sierra Leone. The video of the Ebola rates (Appendix 1) shows the evolution of rates in time and space during 73 weeks (week 1/2014 to week 21/2015). The rates start to go up in week 28/2014 and started to come down in week 1/2015.

Figure 2 shows the global incidence rates for each district. The highest incidence rates were in Sierra Leone's Western Urban dis-

Figure 1. Administrative areas of the study region and road system.

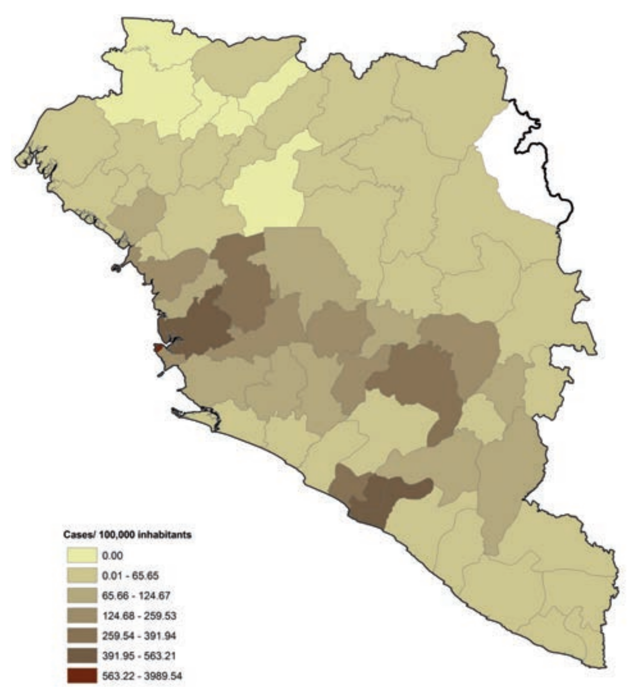

Figure 2. Global Ebola virus incidence rates during the outbreak.

trict (3,989.59 cases/100,000 inhabitants), followed by Monserado in Liberia (563.21 cases/100,000 inhabitants), Port Loko in Sierra Leone (551.25 cases/100,000 inhabitants). After that came the Liberian districts of Margibi (504.47 cases/100,000), Lofa (391.93 cases/100,000), and Bomi (320.04 cases/100,000). In the Republic of Guinea, the highest incidence rate was in the capital Conakry with a rate of 259.52 cases per 100,000 inhabitants.

Figure 3 shows the population distribution in the study area. The population tends to be concentrated in large urban areas with much lower densities in the remaining territory. Table 1 shows the RDI for the districts in each of the three countries studied. The highest RDI was found in Labé with 0.84, a district of the Republic of Guinea. The district with the lowest RDI was Sinoe in Liberia with 0.12. The RDI mean was 0.44 and the median 0.4. Table 1 also shows the number of accumulated cases, population and area for each district. The district with the highest number of accumulated cases was Western Urban in Sierra Leone followed by Monserrado in Liberia.

The results of the spatio-temporal model showed an association between RDI and the rates of Ebola infection. An increase of 0.01 in the density of the road network per km^2 resulted in a 3% increase in Ebola infection risk (RR is 1.04; CI 1.01-1.06). Table 2 shows the result of the model, while Figure 4 shows the effect by week of RR of EVD cases adjusted by RDI. The risk increased in the middle of the outbreak when the transmission was higher.

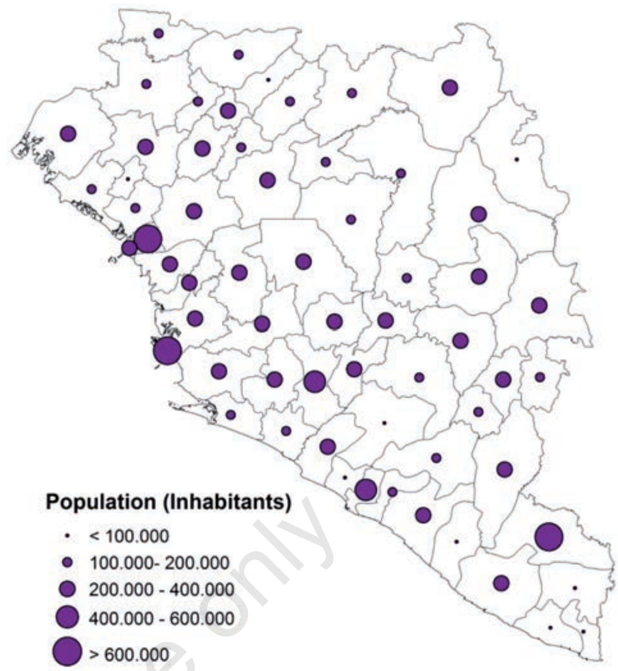

Figure 3. Distribution of the population in the studied region.

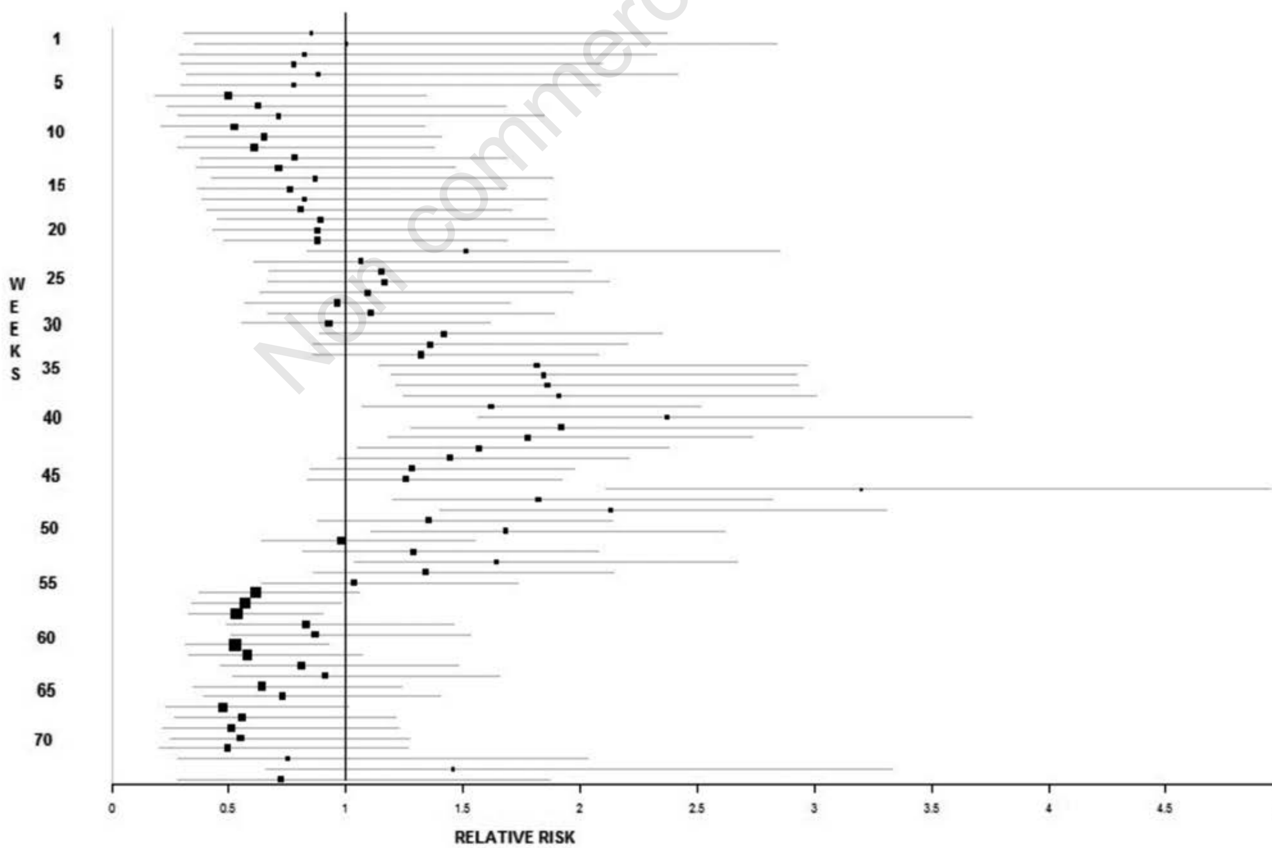

Figure 4. Weekly relative risk evolution.

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Table 1. Road density index, km of roads, populations, cases and area by district in the study region.

Country	District names	Density roads index (km/km²)	Km roads	Infected cases (n)	Population (n)	Area surface (km²)
Liberia	Bomi	0.51	1093.68	197	61553	2145.85
	Bong	0.36	3020.01	180	177886	8491.07
	Gbapolu	0.15	1442.96	23	73440	9388.39
	Grand Cape Mount	0.28	1398.54	141	214762	5039.07
	GrandBassa	0.33	2531.41	118	248602	7580.91
	GrandGedeh	0.13	1364.97	4	603750	10330.03
	GrandKru	0.17	633.68	22	90666	3717.26
	Lofa	0.27	2758.65	472	120427	10393.15
	Margibi	0.48	1358.50	832	164923	2851.71
	Maryland	0.48	1060.07	6	50512	2205.75
	Montserrado	0.68	1247.57	2685	476731	1839.52
	Nimba	0.30	3609.01	243	277011	12008.77
	River Cess	0.25	1312.16	36	68538	5346.59
	River Gee	0.17	1030.53	12	88356	6236
	Sinoe	0.12	1114.06	36	324498	9457.34
Republic of Guinea	Boffa	0.62	3330.11	52	190280	5403.38
	Boké	0.33	3666.40	7	353886	11243.15
	Fria	0.70	1138.21	9	62957	1634.6
	Gaoual	0.24	2810.28	0	164602	11497.44
	Koundara	0.28	1519.42	0	101851	5392.83
	Conarky	0.39	169.57	572	220400	433.94
	Dabola	0.45	2418.09	14	106156	5328.41
	Dinguiraye	0.40	4665.31	1	145548	11668.89
	Faranah	0.40	5230.60	71	169553	13084.78
	Kissidougou	0.58	3618.54	43	182057	6283.78
	Kankan	0.36	6378.30	34	299502	17490.81
	Kérouané	0.48	4520.65	163	274921	9480.91
	Kouroussa	0.34	5461.39	20	177038	16028.3
	Mandiana	0.32	3739.48	0	10	11677.27
	Siguiri	0.35	6242.07	33	310690	17878.05
	Coyah	0.39	520.60	236	847217	1329.46
	Dubréka	0.52	2030.75	145	184279	3921.91
	Forécariah	0.38	1667.69	422	231005	4348.32
	Kindia	0.49	4450.56	115	355263	9051.52
	Télimélé	0.48	3708.75	43	243365	7778.86
	Koubia	0.48	1751.16	0	95928	3623.54
	Labé	0.84	1814.43	0	250915	2159.36
	Lélouma	0.46	1274.49	0	172500	2795.62
	Mali	0.27	2288.24	5	176675	8563.8
	Tougué	0.32	1991.65	2	171709	6129.4
	Dalaba	0.64	2019.82	9	137402	3178.26
	Mamou	0.35	3606.30	0	334786	10441.84
	Pita	0.55	2536.04	8	282633	4630.33
	Beyla	0.49	6165.30	46	213168	12562.89
	Guéckédou	0.58	2479.27	379	368837	4301.38
	Lola	0.38	1711.66	110	197385	4511.67
	Macenta	0.40	3239.01	743	317012	8147.29
	Nzérékoré	0.39	1615.24	255	317439	4092.44
	Yamou	0.27	878.26	12	130993	3259.45
Sierra Leone	Kailahun	0.44	1847.68	737	291416	4222.36
	Kenema	0.40	2529.75	535	429137	6339.38
	Kono	0.45	2463.35	545	324811	5475.36
	Bombali	0.35	2966.81	1066	360760	8418.39
	Kambia	0.41	1302.42	248	243651	3169.5
	Koinadugu	0.44	5532.24	162	216104	12649.59
	Port Loko	0.45	2782.60	2144	388932	6116.69
	Tonkolili	0.42	2750.74	610	298065	6510.5
	Bo	0.55	3118.48	423	397460	5707.32
	Bonthe	0.42	1586.81	2	135711	3789.6
	Moyamba	0.45	3191.62	313	253921	7142.72
	Pujehun	0.46	1846.25	35	181658	3979.5
	Western rural	0.44	284.98	1568	646580	654
	Western urban	0.60	50.82	2928	73392	85.29

Discussion

In this study we have investigated the effects of RDI as a proxy for movement between districts and related that to the spread and occurrence of Ebola cases. The results support the hypothesis that the magnitude and area affected by the outbreak is due to a combination of factors, one of which being the magnitude of the number of people living and moving around the affected area. Ebola risk appears to increase 3.7% with each increase of the RDI of 0.01 km/km^2.

The region of Africa studied is characterised by high population density, which has increased across the three countries by 200% in the last 50 years with a strong focus on the cities (Alexander *et al*., 2015). Another distinctive feature of the region is the high mobility levels of the population (Maconachie *et al*., 2007), which some studies estimate to be seven times higher than any other region globally (Wesolowski *et al*. 2015). This is potentially linked to the search for improved socio-economic conditions and flight from the armed conflicts that have afflicted the region for a number of decades. Furthermore, our study concerns a region which is highly interconnected with relatively easy movement between villages and cities, including the capitals, and which has substantial cross-border traffic in an area where borders barely exist and where people identify more with the region rather than particular nation states (Médecins Sans Frontières,, 2015). For this reason, this study has considered the three countries jointly as a common area.

In addition to the normally high levels of population movement in the region, the epidemic provided additional reasons for people to move across the region. Patients have moved in search of medical assistance or in order to follow the ancient custom of returning to their birth villages to die and be interred alongside their ancestors. People also moved to care for or visit sick friends or family and to assist with their funerals when needed. On occasion, entire villages have been abandoned by people fleeing the epidemic. Studies carried out during previous Ebola outbreaks showed that less than 1/5 of those who lived with a confirmed or probable case developed the disease, and that secondary cases only occurred when there was close contact with the patient (Mylne *et al*., 2014). This requirement means that secondary transmission is primarily limited to three scenarios: in hospitals with insufficient protection measures, during traditional funeral ceremonies and in communities where close relatives care for the sick. What distinguishes this outbreak from previous strains of the Ebola virus is that the levels of transmission in the community remained high, while the measures taken to control transmission in hospitals and at funerals limited the transmission of the disease (Faye *et al*., 2015).

In Africa, the most plentiful source of data about population movements are national censuses (Tatem and Smith, 2010; Garcia *et al*., 2014) which quantify patterns of movement according to changes of residence over the course of a year and over large spatial areas. Another method of gathering more up-to-date data is the use of mobile phone call data (González *et al*., 2008; Wesolowski *et al*., 2014). However, when interpreting the data, it is necessary to take into account the particularities of the region, such as socio-economic heterogeneity and the effects of gender on ownership and use (Wesolowski *et al*., 2012). This evidently makes the use of such data a difficult task for the area under study.

The highest infection rates, more than 500 cases for every 100,000 inhabitants, were found in the Western Urban Area of Sierra Leone, where the capital Freetown is located; in Montserrado County, Liberia, which includes the city of Monrovia; and in the Margibi district of Liberia. In the Republic of Guinea, however, the incidence of the disease in the Conakry District – which has the highest population density and includes the capital of the same name – was broadly similar to the rest of the country, but still the highest in the country.

A number of studies attempting to predict the geographical spread of the Ebola virus in West Africa based on the movement of the population have been conducted. One of these was developed by the Spatial Ecology and Epidemiology Group of Oxford University, who constructed a model to identify which areas were at risk of importing Ebola cases and published their results in the form of maps on the Web (http://seeg-oxford.github.io/ebola-spread/) (SEEG-Oxford, 2015). Weslowski *et al.* (2014) have produced spatial model of movement patterns in 15 countries in West Africa by analysing data obtained from national micro-censuses, telephone calls and spatial data about the population. These models estimate the most important travel routes between different settlements in the region and the relative volume of traffic. This study, however, used historical data without taking into account the changes in behaviour induced by the epidemic.

Valdez *et al.* (2015) developed a stochastic compartmental model using the movement patterns from Weslowski *et al.* (2014) with the aim of understanding how the movement of the population affected the propagation of the Ebola virus across the different regions (counties) of Liberia. They concluded that although a reduction in movements slows the propagation of the disease it does not contain it. In previous Ebola outbreaks, control was based on following and monitoring contacts with rapid isolation of suspected cases. This task is potentially much more difficult when the cases occur in multiple locations, especially in densely populated ones. High levels of population movement produce significant problems for controlling the disease: on the one hand, the teams tracking cases are frequently detained at the borders (Médecins Sans Frontières, 2015), while on the other, the improvement of the situation in a given country attracts patients from neighbouring countries looking for treatment centres and thus restarts the chain of transmission.

One of the limitations of this study is that, although information about the road network is fairly complete, there could still be unmapped neighbourhood byways that could be used for movements in between villages. Another limitation is derived from the data itself, which only provide disaggregation at the district level with the consequence that the data can only be studied in aggregate form. To remedy this, complete information about road networks is needed, which is not always available in the rural areas. New technologies, *e.g.*, satellite-generated remote sensing images or application of the global positioning system (GPS) offer, however, a new opportunity to study the roads and the movements of people in close to real time. This approach can contribute to better public health decisions during future Ebola outbreaks.

Table 2. Spatio-temporal zero inflated multilevel results.

	RR	CI low	CI upper
RDI	1.037	1.010	1.066
Random effects variance			
District	0.162		
Week	1.14		

RR, relative risk; CI, confidence interval; RDI, road density index.

Conclusions

The density of the road network influences the incidence of Ebola cases in the affected zone. This information should be considered for risk evaluation in a way that would aid the distribution of resources in emergency situations. Finally, an exhaustive mapping of the area could help the relevant organisations to better manage another outbreak in the future.

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