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Spatio-temporal patterns of foot-and-mouth disease transmission in cattle between 2007 and 2015 and quantitative assessment of the economic impact of the disease in Niger

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Summary

Foot-and-mouth disease (FMD) is endemic in Niger, with outbreaks occurring every year. Recently, there was an increasing interest from veterinary authorities to implement preventive and control measures against FMD. However, for an efficient control, improving the current knowledge on the disease dynamics and factors related to FMD occurrence is a prerequisite. The objective of this study was therefore to obtain insights into the incidence and the spatio-temporal patterns of transmission of FMD outbreaks in Niger based on the retrospective analysis of 9-year outbreak data. A regression tree analysis model was used to identify statistically significant predictors associated with FMD incidence, including the period (year and month), the location (region), the animal-contact density and the animal-contact frequency. This study provided also a first report on economic losses associated with FMD. From 2007 to 2015, 791 clinical FMD outbreaks were reported from the eight regions of Niger, with the number of outbreaks per region ranging from 5 to 309. The statistical analysis revealed that three regions (Dosso, Tillabery and Zinder), the months (September, corresponding to the end of rainy season, to December and January, i.e., during the dry and cold season), the years (2007 and 2015) and the density of contact were the main predictors of FMD occurrence. The quantitative assessment of the economic impacts showed that the average total cost of FMD at outbreak level was 499 euros, while the average price for FMD vaccination of one outbreak was estimated to be more than 314 euros. Despite some limitations of the clinical data used, this study will guide further research into the epidemiology of FMD in Niger and will promote a better understanding of the disease as well as an efficient control and prevention of FMD.

KEYWORDS
clinical signs, economic impacts, foot-and-mouth disease, Niger, outbreak, retrospective study

1 | INTRODUCTION

Foot-and-mouth disease (FMD) is a highly contagious transboundary disease that affects all cloven-hoofed animals. The causative agent is a member of the *Picornaviridae* family, belonging to the genus *Aphthovirus* (Belsham & Sonenberg, 1996). There are seven FMD virus (FMDV) serotypes, namely O, A, C, South African Territories (SAT1, SAT2 and SAT3) and Asia1, with limited cross-protection between them (Paton, Ferris et al., 2009; Paton, Sumption, & Charleston, 2009). FMDV serotype C was last detected in Kenya (Sangula et al., 2011; WRLFMD, 2016). Serotypes O and A and the SAT FMDVs are endemic in Africa; serotype O is the most widely distributed in eastern and western Africa, whereas SAT FMDVs are mostly found in sub-Saharan Africa (SSA) (Brito, Rodriguez, Hammond, Pinto, & Perez, 2015; Tekleghiorghis, Moormann, Weerdmeester, & Dekker, 2016).

In Niger, FMD is endemic and causes several outbreaks every year due to continuous infection of FMDV in the absence of prevention and control measures. Referring to the data recorded monthly in the frame of the official passive (clinical) surveillance, FMD is the second most widely distributed disease in Niger after pasteurellosis. Recently in 2014, the country confirmed outbreaks of FMDV serotype O (WRLFMD, 2016). In contrast, to the best of our knowledge, there are no FMD control measures in Niger such as vaccination because the circulating antigenic types of FMDV are not well known. Factors associated with FMD outbreaks are not clearly understood, and the spatio-temporal distribution of FMDV has not been studied obviously. On the other hand, the economic impact of FMD in Niger, particularly the reduction in milk production and the depreciation in value of meat, has been overlooked or is not well understood by livestock owners. These factors, combined with the low mortality rate in adult animals, may explain the relative lack of attention to FMD infections in livestock. However, in recent years the situation has changed with the increasing interest from veterinary authorities to implement FMD prevention and control. However, to effectively prevent or control the threats posed by FMD or by other diseases, there is a need to understand clearly the epidemiology of the animal disease in question (Grubman & Baxt, 2004; Knight-Jones & Rushton, 2013). Nevertheless, in general, few studies were performed on FMD in West African countries, fact that makes that those countries represent a potential risk for other regions such as North Africa through the trade of live animal from the Sahel (e.g., Niger and Mali) to North African countries such as Libya and Algeria (Di Nardo, Knowles, & Paton, 2011; Rweyemamu et al., 2008). More specifically, no recorded studies in Niger have been carried out to determine the prevalence of FMD as well as to investigate the disease distribution, the risk factors and the economic costs. For a developing country with such a large area as Niger, a deep understanding of FMD epidemiology is strongly recommended to gain knowledge on when and where resources should be optimally directed to prevent or to reduce the incidence of the disease directly related to the dynamic of FMD. In addition, to determine epidemiological evidence for the need to invest resources to control FMD in such a country, it would be appropriate to better understand the economic impact of the disease. The objective of this study was therefore to obtain insights into the incidence and related economic costs of the disease as well as to determine the spatio-temporal patterns of transmission and the predictors of FMD outbreaks in Niger based on a retrospective analysis of 9-year (from 2007 to 2015) outbreak data.

2 | MATERIALS AND METHODS

2.1 | Study area

The Republic of Niger covers 1,267,000 km^2 (490,000 miles^2). It is a landlocked country bordered by seven other countries, namely Algeria and Libya to the north, Chad to the east, Nigeria and Benin to the south, Burkina Faso to the south-west and Mali to the west (Figure 1). Niger is in the heart of the Sahel, the transitional zone between the tropical West African coast and the Sahara Desert. Since 2002 and until 2012, Niger is administratively divided into eight regions, 37 (until 2012) up to 63 (since 2012) departments and 265 municipalities. A group of municipalities forms a given department, while a set of departments forms a region. In this study, the regions are considered as the epidemiological units of interest because available data were more complete at this level. Niger has an arid subtropical climate characterized by a short rainy season (RS) from May–June to September, and a long dry season lasting from 8 to 9 months. The dry season is composed of two periods, namely the dry and cold season (DCS) from October to January and the dry and hot season (DHS) from February to May.

Crop and livestock production are greatly important to the national economy, contributing around 40% to its gross domestic product (GDP). Agricultural and pastoral activities are carried out in four distinct major agro-ecological zones, namely (i) the semi-desert area in the north, with a rainfall of 0–50 mm per year; (ii) the sub-Saharan pastoral zone in the longitudinal East–West centre core of the country with a yearly rainfall of 50–200 mm; (iii) the Sahelian agro-pastoral zone extending in the central to southern part of the country with 200–500 mm of yearly rainfall; and (iv) the Sudano-Sahelian zone covering the southern part of the country, receiving 600–800 mm of rain per year, and being the most suitable for agriculture. The well-known informal cross-border movement of animals or animal products and feed is a traditional practice among the countries in the Sahel region including Niger. In addition, livestock production is highly limited by multiple constraints including disease occurrence (e.g., FMD). FMD is in general clinically and economically more important in cattle and pigs (Grubman & Baxt, 2004; Kitching, 2002). However, in Niger the pig population was estimated in 2013 to be only 42,500 heads,

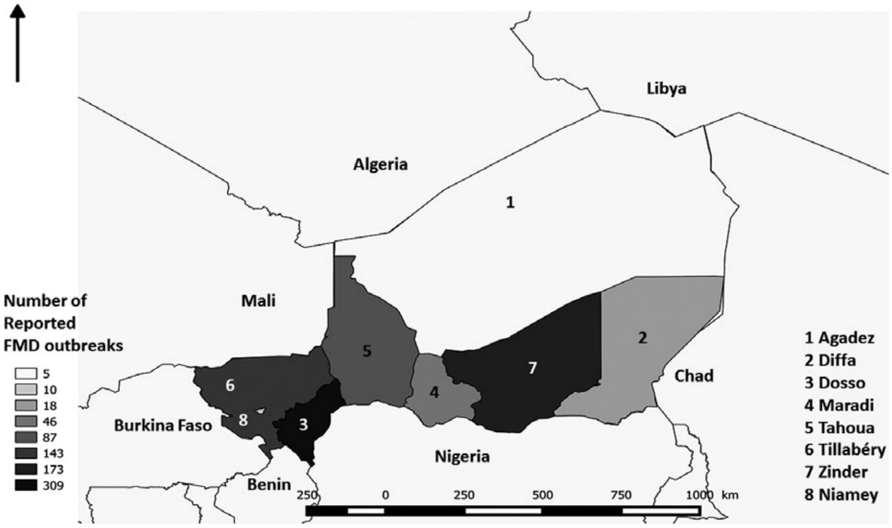

FIGURE 1 Map of Niger showing the regions where FMD outbreaks were notified from 2007 to 2015. 1, Agadez; 2, Diffa; 3, Dosso; 4, Maradi; 5, Tahoua; 6, Tillabery; 7, Zinder; 8, Niamey

while the cattle population was larger with 10,733,314 of heads (World Data Atlas, 2017). Accordingly, cattle, which constitutes the main livestock sector in Niger, will be the only species considered in this study.

2.2 | Nature and source of data

A database with the total number of cattle FMD outbreaks in Niger from 1 January 2007 to 31 December 2015 was provided by the Statistical Unit of the Ministry of Agriculture and Livestock. For this study, a FMD outbreak was defined as the occurrence of one or more cases of the disease in a department as clinically diagnosed by the veterinary officer. A continuous sequence of cases within a department was considered as one outbreak unless successive cases were separated by a time gap of at least one month. Usually, animals seen by the veterinary officer are sick animals presented by farmers. The signs and/or lesions are typically sufficient for veterinary officers to make a provisional diagnosis of the endemic diseases such as FMD in Niger. The livestock services of each department send monthly passive surveillance reports to the regional level office, which in turn send them to the Statistical Unit of the Ministry of Agriculture and Livestock. The collected data include the number of cattle with FMD signs (morbidity data), the number of dead cattle (mortality data) and the cattle, sheep and goat population for each region which varies upon time (year). In addition, data related to water points, livestock markets and pastoral enclaves were also included in the statistical analyses. The pastoral enclaves are defined as “areas traditionally reserved for pastures in agricultural zones.” Animal population and contact place (water points, livestock markets and pastoral enclaves) data were standardized using its density by area of surveillance.

2.3 | Descriptive analysis

The recorded data were first transferred to a spreadsheet program (Excel 2016; Microsoft). The database was cleaned and merged to the list of all regions in Niger obtained from the Pastoral Unit of the Ministry of Agriculture and Livestock. All geographical data were projected to UTM Zone 31N coordinate system (datum WGS84 EPSG:32631) and represented using QGIS 2.12.0. A descriptive statistical analysis was conducted to determine the reported outbreaks per year and per month and per region.

2.4 | Statistical analyses

2.4.1 | Regression tree analysis

One of the main research questions addressed in this article is whether the distribution of the occurrence of FMD outbreaks (count data) is influenced by the recorded temporal data such as the year and months, and the spatial data including the region, the annual animal density (cattle, sheep and goats), the water crossing points, the livestock markets and the pastoral enclaves. The latter three were merged as they are related to the animal-contact frequency. The merging variable is the sum of the numbers of the water crossing points, the livestock markets and the pastoral enclaves, divided by the area of the region of interest expressed in km^2.

All of the variables were entered into a regression tree model with FMD occurrence at time–region level as response variable. The regression tree model was used to identify predictors and their interactions which influence FMD occurrence at region level (Speybroeck, 2012).

A classification and regression tree (CART) analysis is a nonlinear and nonparametric model that is fitted by binary recursive partitioning of multidimensional covariate space (Breiman, Friedman, Olsen, & Stone, 1984; Crichton, Hinde, & Marchini, 1997). It can be used to analyse either categorical (classification) or continuous data (regression). In our case, the target variable is continuous. Using Salford Predictive Modeler software (Salford Systems, San Diego, CA, USA), the analysis successively splits the data set into increasingly homogeneous subsets until it is stratified to meet specified criteria. The Gini index was used as the splitting criteria, and 10-fold cross-validation was used to test the predictive ability of the obtained trees. CART performs cross-validation by growing maximal trees on subsets of data and then calculating error rates based on unused portions of the data set. To accomplish this, CART divides the data set into 10 randomly selected and roughly equal parts, with each “part” containing a similar distribution of data from the populations of interest (i.e., FMD outbreaks). CART then uses the first nine parts of the data, constructs the largest possible tree, and uses the remaining 1/10 of the data to obtain initial estimates of the error rate of the selected subtree. The process is repeated using different combinations of the remaining nine subsets of data and a different 1/10 data subset to test the resulting tree. This process is repeated until each 1/10 subset of the data has been used as to test a tree that was grown using a 9/10 data subset. The results of the 10 minitests are then combined to calculate error rates for trees of each possible size; these error rates are applied to prune the tree grown using the entire data set. The consequence of this process is a set of fairly reliable estimates of the independent predictive accuracy of the tree, even when some of the data for independent variables are incomplete and/or comparatively small. For each node in a CART generated tree, the “primary splitter” is the variable that best splits the node, maximizing the purity of the resulting nodes. Further details about CART are presented in previously published articles (e.g., Chaber & Saegerman, 2016; Saegerman, Alba-Casals, Garcia-Bocanegra, Dal Pozzo, & van Galen, 2016; Saegerman, Porter, & Humblet, 2011; Saegerman, Speybroeck, Dal, & Czaplicki, 2015).

2.4.2 | Stochastic model for the estimation of clinical and economic FMD impacts

A framework of economic impact of animal disease including FMD has been outlined by Rushton (2009) (Figure 2). The direct visible losses include milk production loss, draft power loss, weight loss and death loss. The direct invisible losses include fertility problems that lead to a change in herd structure and a delay in sale of animals and/or livestock products. On the other hand, there are indirect losses including the additional costs related to control, diagnostic and surveillance, while the revenue forgone is essentially related to denied access of market and the use of less productive but disease-resistant breeds (Rushton, 2016). However, in this study, two components of the visible losses, namely the milk production losses and losses due to animal deaths (specifically of young animals), were considered for the direct impact. The indirect impact considered in the study is related to the costs associated with FMD vaccination.

Model input variables used to estimate the economic impacts of FMD are in Table 1. Data used to create input variables are based on the following information: the structure of the cattle population in a FMD outbreak, the clinical impact of FMD at outbreak level and the costs of FMD (morbidity, mortality and costs of FMD vaccination). To better capture variability and uncertainty of input variable, a stochastic model was used for the estimation of clinical and economical FMD impacts.

Structure of the cattle population

The structure of the cattle population in an outbreak of FMD (number of cattle per outbreak, proportions of cows, heifers, bulls and young bulls in the outbreak) was extracted from a study on FMD outbreaks which occurred in 2014 in south-western of Niger (Souley Kouato et al., 2017). These FMD-infected herds were composed of 23, 55 and 250 cattle, representing respectively the minimum, the mode and the maximum number of cattle. The proportions of cows, heifers, bulls and young bulls in the FMD outbreak were respectively 0.25, 0.34, 0.17 and 0.24 (Table 1).

Estimation of clinical impacts

The number of sick animals and the number of dead animals recorded during each FMD outbreak were those included in the data provided by the Ministry of Agriculture and Livestock. However, to get an idea of the percentage of clinically affected cattle (morbidity) and dead animals (mortality), the cattle population structure of the infected herds investigated during FMD outbreaks that occurred in 2014 (Souley Kouato et al., 2017) has been considered. The average number of cattle per herd was estimated at 74.43. Hence, in this study, the morbidity was determined as the number of animals clinically affected during a FMD outbreak divided by the average number of cattle per herd (considered to be at risk). Similarly, the mortality was determined as the number of animals dying of FMD during the outbreak divided by the average number of cattle per herd. On the other hand, as a stochastic model was used for the estimation of clinical and economical FMD impacts, a PERT distribution was therefore used in the model development. Hence, based on the FMD-infected herds’ structure, the number of clinically sick animals (morbidity) was estimated at 4, 15 and 250, representing respectively the minimum, the mode and the maximum number of sick animal. Similarly, the number of animal supposed to die from FMD (mortality) was estimated at 1, 1.001 and 11, representing respectively the minimum, the mode and the maximum number of died cattle (Table 1).

Estimation of production losses

In this study, the costs of production losses due to FMD include the cost due to the morbidity (herein only loss of milk production) and the cost due to the mortality of young animals. In this analysis, heifers and young bulls were considered as young cattle susceptible to die from acute FMD. The prices of heifers and young bulls considered for these estimates are those provided by the Food and Agriculture Organization (CountrySTAT Niger, 2017). The price per litre of milk and the average daily milk production per cow were extracted from studies carried out in Niger respectively by Boukary, Chaibou, Marichatou, and Vias (2007) and Vias, Bonfoh, Diarra, Naferi, and Faye (2003). The average milk production per cow varies according to the season. For example, cows raised in the peri-urban area of Niamey produce an average of 2.44 L in the rainy season, 2 and 1.44 L respectively in the dry and cold season and in the dry and hot season

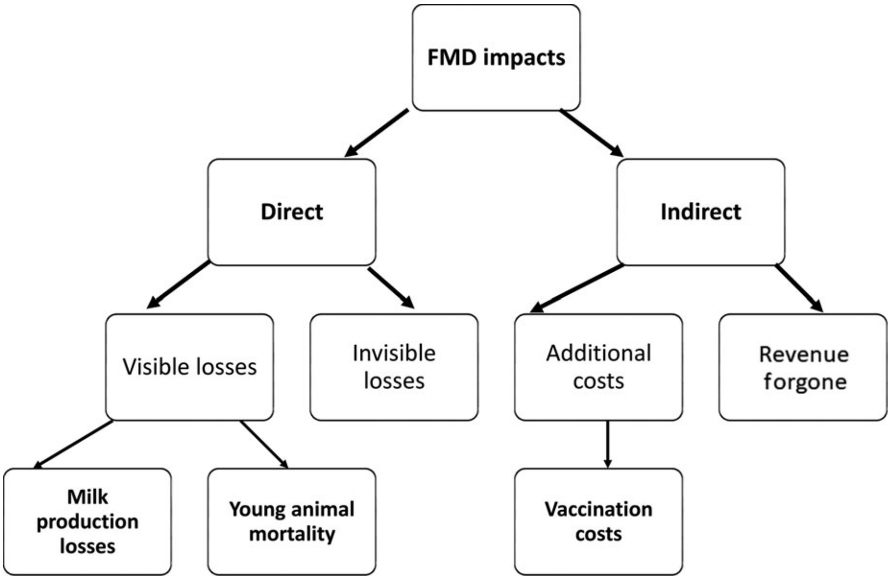

FIGURE 2 Framework of economic impacts of FMD (adapted from Rushton, 2009)

(Vias et al., 2003). Indeed, a uniform distribution to characterize the daily milk production was used in this study with a range of values between 2 and 2.44 L because most of the FMD outbreaks occur in the end of the rainy season and during the dry and cold season.

Raw milk prices also vary according to the season. Thus, the price per litre of raw milk was 0.34, 0.36 and 0.38 euros in the dry and cold season, the rainy season and the dry and hot season, respectively (Boukary et al., 2007). Similarly for the daily milk production, a uniform distribution to characterize the price of milk per litre was used in this study with a range of values between 0.34 and 0.36 euros because most of the FMD outbreaks occur in the end of the rainy season and during the dry and cold season.

The duration of acute FMD illness was considered to be between 7 and 14 days (OIE, 2012) using a uniform distribution.

Estimation of FMD control (vaccination) costs

In Niger, vaccination against contagious bovine pleuropneumonia (CBPP) is annual and mandatory for all cattle over 6 months of age. Other vaccinations of cattle as against pasteurellosis, anthrax and blackleg disease are optional. FMD vaccination strategy considered as preventive mass vaccination strategy (PMVS) would be similar to that of CBPP with some differences. For the FMD PMVS, it is assumed that all cattle above 4 months of age are vaccinated. An initial double vaccination with a 4- to 6-week interval is considered, followed by an annual vaccination until the incidence of the disease becomes <5% after which the strategy would be re-adopted to maintain the incidence at this level. A trivalent vaccine (with serotypes A, O and SAT2) supposed to match with the circulating field strains was assumed to be used in the country. The data of the cost of the vaccine were provided by the Botswana Vaccine Institute laboratory which manufactures and distributes this vaccine to some West African countries neighbouring Niger. The vaccine cost is 159.60 euros per 100 doses, so 1.596 euros per dose.

The vaccine delivery costs per animal, and the distribution and cold storage costs based on the experience of the CBPP vaccination campaign, were also included in the assessment of the total costs of vaccination. At the time of this study, there was no official FMD vaccination programme in Niger. FMD-infected cattle are either treated with antibiotics or by traditional means or not treated at all. Data on the costs of vaccination against CBPP were provided by the Ministry of Agriculture and Livestock.

Table 2 reports the estimated costs of vaccination campaign implementation in each region of Niger based on the CBPP vaccination experience. Indeed, according to the Ministry of Agriculture and Livestock for the 2016–2017 vaccination campaign, Niger imported CBPP vaccines from Ethiopia. To determine the part of the cost of the vaccine per animal in the total budget allocated for each region, estimates were made taking into account the respective cattle population. The cattle population for each region in 2016 was estimated based on the results of the last general census of agriculture and livestock in 2007. Hence, an annual growth rate of 1.06 has been applied for each year since 2007. For CBPP vaccination, an objective of 80% of the cattle population was considered to be vaccinated. Considering the possible losses of vaccine in the field during the vaccination process, the total required number of vaccine doses was estimated as the sum of 80% of the cattle population and 5% of this latter number giving the proportion of 1.05 of the number of cattle to be vaccinated. Therefore, the cost of implementation of vaccination per animal varies according to the region. The values of the PERT distribution mentioned in Table 1 (0.07, 0.12 and 1.42) represent respectively the minimum, the median and the maximum values. To estimate the cost of vaccination at FMD outbreak level (C_{VACC}), one scenario was

TABLE 1 Model inputs to estimate the economic impacts of FMD in cattle and the costs of the vaccination

Inputs data	Distribution and value or calculation	Unit	Description and/or source
Number of cattle per outbreak (1)	PERT[a] (23;55;250)	Heads	Inputs (1) to (5) derived from FMD outbreak investigation study (Souley Kouato et al., 2017)
Proportion of cows in the outbreak (2)	Fixed = 0.25	Heads	
Proportion of heifers in the outbreak (3)	Fixed = 0.34	Heads	
Proportion of bulls in the outbreak (4)	Fixed = 0.17	Heads	
Proportion of young bulls in the outbreak (5)	Fixed = 0.24	Heads	
Morbidity per outbreak (6)	PERT (4;15;250)	Heads	This study
Mortality per outbreak (7)	PERT (1;1.001;11)	Heads	This study
Number of cows (8)	=(1) * (2)	Heads	Calculation
Daily milk yield per lactating cow (9)	Uniform[b] (2;2.44)	Litre	Vias et al. (2003)
Duration of illness (10)	Uniform (7;14)	Days	OIE (2012)
Price per litre (11)	Uniform (0.34;0.36)	Euros	Boukary et al. (2007)
Cost of milk losses (12)	Output (12) + (8) * (9) * (10) * (11)	Euros	Calculation
Number of young bulls affected (13)	=[(7) * (5)]	Heads	Calculation
Number of heifers affected (14)	=[(7) * (3)]	Heads	Calculation
Price per young bulls (15)	PERT (152;210;250)	Euros	CountrySTAT (FAO) Niger, 2017
Price per heifer (16)	PERT (152;152;225)	Euros	CountrySTAT (FAO) Niger, 2017
Costs of young bulls mortality (17)	Output (17) + (13) * (15)	Euros	Calculation
Costs of heifers mortality (18)	Output (18) + (14) * (16)	Euros	Calculation
Total costs of FMD at herd level (C_{FMD})	Output (C_{FMD}) + (12) + (17) + (18)	Euros	Calculation
Price per doses of FMD vaccine (19)	Fixed = 1.60	Euros	BVI
Cost of vaccine delivery, distribution and cold storage (based on experience for CBPP vaccination) (20)	PERT (0.07;0.12;1.42)	Euros	M/L of Niger
Costs for the FMD vaccination of one outbreak (two doses/animal) (C_{VACC})	Output (C_{VACC}) + [(1) * 2 * (19)] + [(1) * 2*(20)]	Euros	Calculation
Ratio costs of FMD/costs of vaccination at outbreak level (R)	Output (R) + (C_{FMD})/(C_{VACC})		Calculation

BVI, Botswana Vaccine Institute; M/L, Ministry of Agriculture and Livestock.

[a] PERT distribution includes minimum, most likely and maximum parameters. Values around the most likely are more likely to occur. It can generally be considered as superior to the triangular distribution when the parameters result in a skewed distribution.

[b] Uniform distribution in which all values have an equal chance of occurring; it includes the minimum and maximum parameters.

[#] Two doses per animal (inactivated vaccine) have been considered for vaccination cost estimation.

considered. It consists in vaccinating each animal with two doses of vaccine (one primary dose and a second one after a 4- to 6-week interval). Moreover, in this simulation, it was assumed that FMD vaccination has been carried out during a campaign devoted exclusively to vaccination against FMD rather than being part of a vaccination programme against other livestock diseases such as CBPP.

Model development

A stochastic model was developed to include both the variability and the uncertainty concerning the input parameters. The relations between input parameters and outputs were described using the formula that appears in Table 1. The spreadsheet with economic model was constructed in Microsoft Excel (Microsoft® Office 2016, Redmond, WA). The model was run for 10,000 iterations (Monte Carlo sampling) in @Risk version 7.5 (© Palisade Corporation, Ithaca, NY). This allowed the convergence of all the output probability distributions using a 1.5% convergence tolerance with 95% confidence level.

Sensitivity analysis

To identify those inputs which were more influential on the final outputs, a sensitivity analysis was carried out using the rank order correlation method, which is based on the Spearman rank correlation coefficient calculations. With this analysis, the rank correlation coefficient is calculated between the selected output variable and the sampled values from each of the input distributions. The sensitivity analysis was performed by means of the sensitivity analysis tool in @Risk version 7.5. Hence, probability density and tornado graphs were produced using the same software.

3 | RESULTS

3.1 | Descriptive analysis

From 2007 to 2015, 791 FMD outbreaks were reported from the eight regions of Niger, with the number of outbreaks per region ranging from 5 to 309 (Figure 1). The regions where outbreaks were less recorded were the regions of Agadez in the north and Diffa in the far south of the country. The most affected regions are those of Dosso, Zinder and Tillabery. Although the geographical distribution of outbreaks varies according to the year in these three regions, FMD-affected departments were mainly located at the borders of neighbouring countries, especially departments in the south-west bordering with Benin and in the south centre of the country bordering with Nigeria (data not shown). The geographical distribution of outbreaks according to the year is provided in Appendix 1.

Although each year there were more than 50 FMD outbreaks, the number of reported outbreaks varied over the study period. During 2007 and 2015, the number of outbreaks was high (126 and 161, respectively) compared to the rest of the years (Figure 3). The number of reported FMD outbreaks decreased from 2007 to 2009, after which it remained relatively stable up to 2013 with a small peak in 2011. The incidence of reported outbreaks then increased steeply from 2013 to 2015.

There is an important monthly variation in the occurrence of FMD outbreaks. Indeed, a high number of outbreaks were recorded in January and February. The number of FMD episodes was low from March to August with a modest peak in May. From September to December, the number of outbreaks increased (Figure 4). This monthly trend was confirmed by the regression tree model, which revealed that the months at risk were January and September to December. In Niger, this period corresponds with the end of the rainy season (September) and with the cold dry season (October to January or February).

3.2 | Statistical analyses

3.2.1 | Regression tree analysis

The regression tree analysis revealed that three regions (Dosso, Tillabery and Zinder), the months (September to December and January), the years (2007 and 2015) and, in addition, the density of animal contacts were the main predictors of FMD occurrence in Niger (Figure 5 and Table 3).

3.2.2 | Stochastic model for the estimation of clinical and economic FMD impacts

Clinical impact estimates

In the frame of the 791 FMD outbreaks recorded during the study period, 8,804 cattle were clinically affected, and among these, 247 animals died from the disease. Figure 6 shows the yearly variation in the number of sick animals with peaks in 2008, 2012, 2013 and especially in 2015. The mortality appeared to be stable during the study period, although the number of dead animals was relatively high in 2007 (n = 36) and in 2015 (n = 51). However, at outbreak level, the mean stochastic estimates were respectively 52.33 cattle affected by the disease and 2.67 cattle assumed to die from FMD (Table 1). The cattle population of the infected herds investigated during FMD outbreaks that occurred in 2014 were composed, on average, of 74.43 cattle per herd. Therefore, the percentage of clinically affected cattle (morbidity) and dead animals (mortality) were respectively estimated at 70.30% and 3.59%.

Production losses due to FMD

Table 4 summarizes the results of the Monte Carlo simulations estimating the economic impacts of FMD at outbreak level. The average total costs of FMD at herd level (C_{FMD}) were estimated at 499.34 euros (*SD* 196 euros). The cost of milk losses accounted for

TABLE 2 Estimation of vaccination campaign implementation costs (based on current CBPP vaccination programme 2016–2017)

Region	Cattle population (a) (head)	Number of cattle to be vaccinated (b) (head)	Vaccine doses required (c)	Vaccine cost (d) (FCFA)	Overall budget (e) (FCFA)	Part of the vaccine cost in the overall budget (f) (%)	Cost of vaccine distribution, delivery and cold storage (g) (euros)	Vaccination cost by animal (euros) (h)
Agadez	99,383	79,506	83,481	4,257,531	78,051,005	5.45	112,497	1.42
Diffa	1,425,179	1,140,144	1,197,151	61,054,701	149,559,400	40.82	134,925	0.12
Dosso	1,336,658	1,069,327	1,122,793	57,262,443	153,015,302	37.42	145,974	0.14
Maradi	1,914,002	1,531,202	1,607,762	81,995,862	152,141,425	53.89	106,936	0.07
Tahoua	2,428,403	1,942,722	2,039,858	104,032,758	224,130,512	46.42	183,088	0.09
Tillabery	2,618,909	2,095,127	2,199,883	112,194,033	312,213,249	35.94	304,927	0.15
Zinder	2,741,712	2,193,369	2,303,037	117,454,887	212,795,965	55.20	145,347	0.07
Niamey	58,297	46,637	48,969	2,497,419	16,202,000	15.41	20,892	0.45
National	12,622,543	10,098,035	10,602,937	540,749,787	1,298,108,858	41.66	1,154,586	0.11

(b) = 80% * (a); (c) = (b * 1.05); (d) = (45 + 6) * (c). The vaccine was purchased at 45 FCFA per dose plus 6 FCFA for the dilution solution; (f) = (d) * 100/(e); (g) = ((e) − (d))/655.957); 1 euro corresponds to 655.957 FCFA (XOF – CFA franc, the currency used in Niger); (h) = (g)/(b).

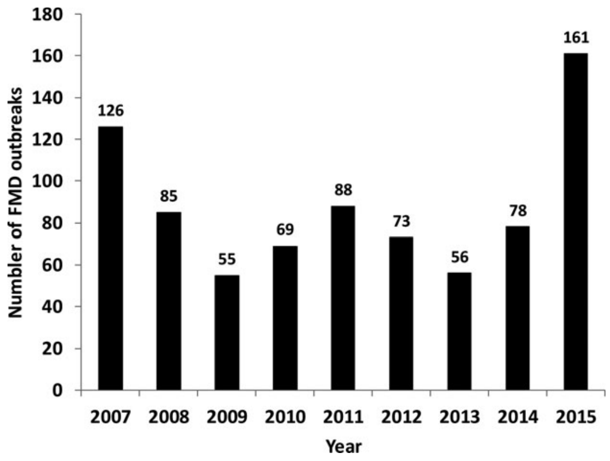

FIGURE 3 Annual distribution of reported FMD outbreaks in Niger during the period 2007–2015

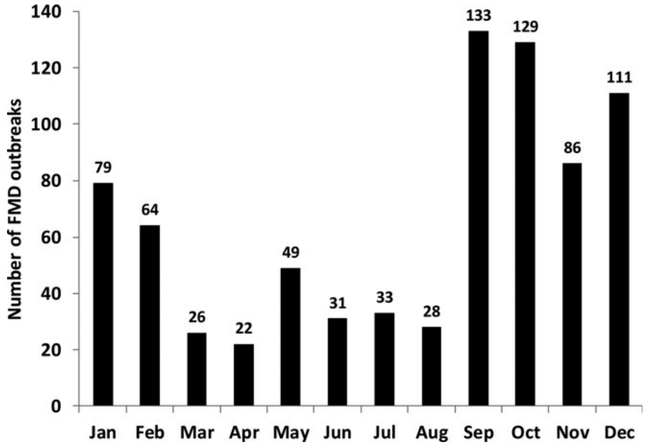

FIGURE 4 Monthly trend of FMD outbreaks for all years combined

33.21% of the total costs (average: 165.82 euros), while costs related to mortality of young bulls and heifer mortality were respectively 37.27% (average: 186.09 euros) and 29.52% (average: 147.42 euros) of the total costs of FMD at outbreak level.

FMD vaccination costs

The average cost of implementing vaccination in the field was estimated at 0.11 euros per vaccinated animal (with 0.07, 0.12 and 1.42 representing the minimum, the median and the maximum values, respectively). Although an important variation of this cost was observed from one region to another, the highest costs were observed for the regions of Agadez (in the north of the country) and Niamey (capital city) with 1.42 and 0.45 euros per vaccinated cattle, respectively (Table 2).

The cost of vaccination at FMD outbreak level (C_{VACC}) was estimated at 313.97 euros on average at herd level. Consequently, the average ratio total costs of FMD/costs of vaccination at outbreak level (R) (C_{FMD}/C_{VACC}) was estimated at 1.87 (Table 4).

Sensitivity analysis

Figure 7a-c shows tornado graphs with the inputs that accounted for the greatest variation in the outputs of the model. The most influential input parameter (i.e., with the highest rank order correlation coefficients) on the total costs of FMD (C_{FMD}) at herd level was the mortality per outbreak, which had a correlation coefficient >0.86. The number of affected cattle per outbreak also showed a relatively high correlation with C_{FMD} and the stage of FMD infection in relation to the duration of illness (Figure 7a). Likewise, the mortality per outbreak and the number of affected cattle per outbreak were the two input variables to which the C_{FMD}/C_{VACC} ratio was most sensitive, based upon the Spearman rank correlation coefficients. Indeed, the number of affected cattle per outbreak significantly influenced the cost of vaccination per FMD outbreak (C_{VACC}) with a correlation coefficient of 0.68 (Figure 7b); accordingly with increase in the number of affected cattle, the ratio would change significantly (Figure 7c).

4 | DISCUSSION

This study was performed with an overall objective of generating epidemiological information and economic estimates of FMD in Niger to support decision-making in a future control plan. Initially, a spatio-temporal analysis of reported clinical FMD was conducted. Several FMD outbreaks were recorded in Niger for about a decade. This study obviously illustrated that the occurrence of FMD is frequent and widespread in the country. Indeed, only the semi-desert areas including Agadez and Diffa were less affected by FMD, although the farmers and the veterinary officers must consider this cautiously because of the fact that in Niger, the notification of the disease is not always performed. However, based on regression tree analysis results, several areas of Niger were more prone to FMD outbreaks. It was demonstrated that regions with a high risk of occurrence of FMD were the regions of Dosso, Tillabery and Zinder. These three regions account for more than half (53%) of the country's livestock population when considering the projections made for the livestock population in 2015. It was therefore expected that the animal density would be an important predictor variable of outbreaks occurrence as it is indicated by the regression tree analysis. In accordance with the transboundary nature of the disease (Balinda et al., 2010; Knowles et al., 2016; Ludi et al., 2016), FMD has been mostly recorded in departments bordering with neighbouring countries, in particular with Benin and Burkina Faso in the south-west; Mali in the west; and Nigeria in the south of the country (Figure 1). This would be related to one of the livestock systems prevailing in Niger, characterized by the practice of both internal and cross-border transhumance consisting in long-distance animal movements in search of better feeding conditions in neighbouring countries. This study is in some respect in agreement with that of Couacy-Hymann et al. (2006), which identified among others the regions of Niger bordering with Nigeria, Chad and Mali and the park W area (which is

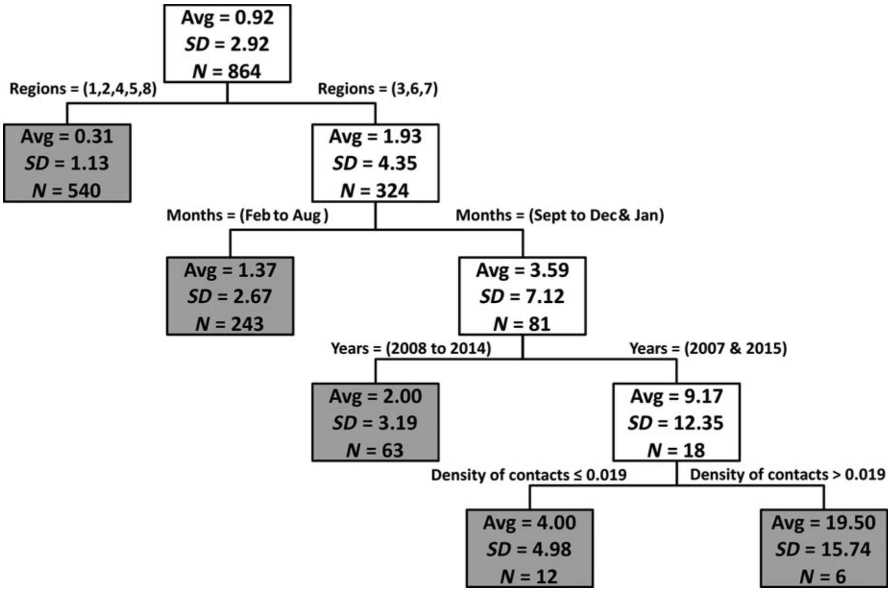

FIGURE 5 Regression tree analysis results showing the main important variables (and their interactions) that characterize the occurrence of FMD outbreaks. Avg: average of FMD cases. *SD*, standard deviation; *N*, number of observations; Region 1, Agadez; Region 2, Diffa; Region 3, Dosso; Region 4, Maradi; Region 5, Tahoua; Region 6, Tillabery; Region 7, Zinder; Region 8, Niamey; Month: Jan, Feb, Aug, Sept and Dec for January, February, August, September and December, respectively

TABLE 3 Relative importance of the different FMD predictors obtained after regression tree analysis (maximum relative importance = 100)

Predictor	Variable importance
Region	100
Density of contacts	75.86
Density of sheep	65.12
Density of goats	55.24
Year	48.15
Density of cattle	28.33
Month	20.01

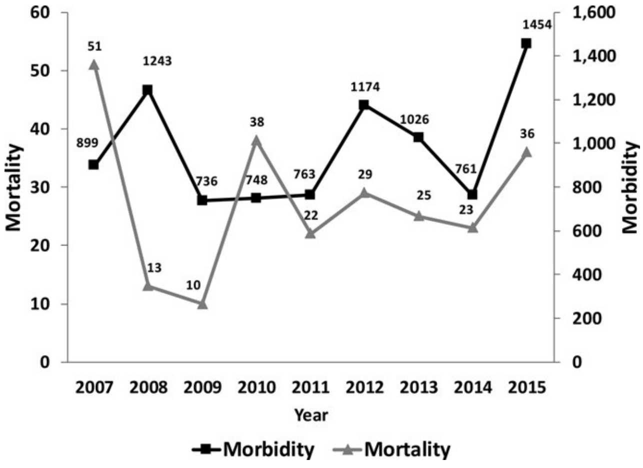

FIGURE 6 Trends of FMD morbidity and mortality between 2007 and 2015

TABLE 4 Results of Monte Carlo simulations estimating the economic impacts of FMD at outbreak level (expressed in euros)

Outputs	Minimum	Maximum	Mean	*SD*	Median
Costs for milk losses	32.63	562.81	165.82	87.74	149.20
Costs for young bulls mortality	56.10	768.03	186.09	99.69	159.52
Costs for heifers mortality	56.10	621.00	147.42	78.01	127.21
Total costs of FMD at herd level (C_{FMD})	157.88	1520.55	499.34	196.00	459.75
Costs of FMD vaccination of one outbreak (two doses/animal)/value (C_{VACC})	81.39	976.33	313.97	149.12	289.13
Ratio costs of FMD/costs of vaccination at outbreak level	0.45	9.14	1.87	1.04	1.57

at the junction between Benin, Burkina Faso and Niger) as primary sources of infection of FMD in West Africa.

This retrospective study showed also that in Niger, FMD occurs almost everywhere but also at any time period of the year indicating that the disease is endemic all over the country. However, according to regression tree analysis results, most FMD outbreaks occurred during the cold and dry season (from October to January) and started at the end of the rainy season (September). The seasonality

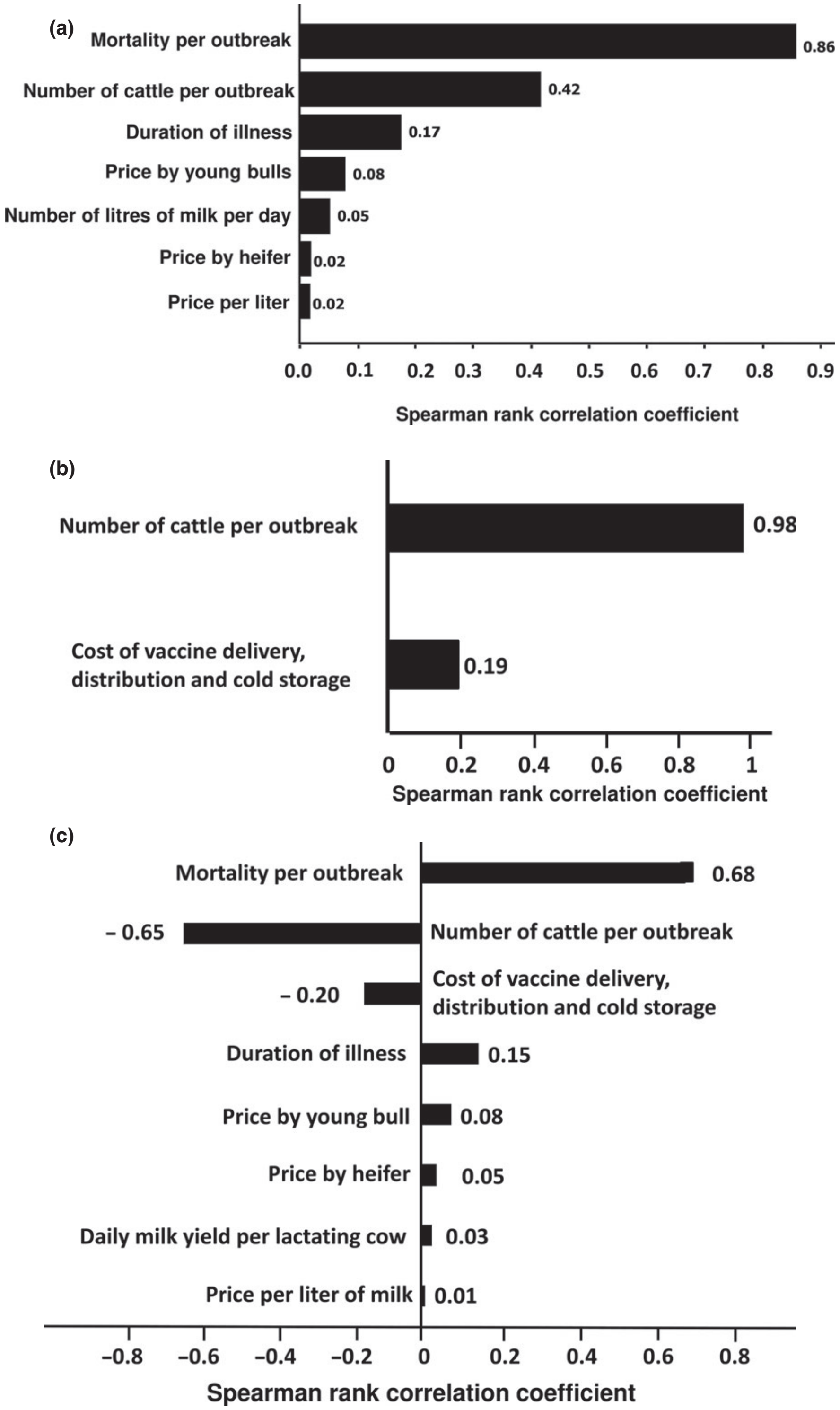

FIGURE 7 Tornado graph showing correlation coefficients between model input variables and the total costs of FMD [a], costs of FMD vaccination of one outbreak [b] and ratio costs of FMD/costs of vaccination at outbreak level [c]

of FMD in Africa and elsewhere has been reported by several studies (Bayissa, Ayelet, Kyule, Jibril, & Gelaye, 2011; Bronsvoort et al., 2003; Dukpa, Robertson, Edwards, & Ellis, 2011; Genchwere & Kasanga, 2014; Molla & Delil, 2015; Rufael, Catley, Bogale, Sahle, & Shiferaw, 2008) even though the eco-climatic conditions differ from one region to another. However, in the case of Niger this is undeniably related to the livestock system. Indeed, transhumance in the Sahel region in general is practised based on a classical pattern rarely modified and consistent with seasonal cycles. Overall, from October to June (corresponding to the dry season until the beginning of rainy season) herdsmen keep their animals locally to exploit the available pastures. From June to October (with the period between June and September corresponding to the rainy season and October consistent with the beginning of cold and dry season), transhumant herdsmen move first with their animals towards the north of the country (pastoral zone) or the neighbouring countries. Consequently, during the cold and dry season (October, November, December, January and even February) there is a high concentration of animals in the south of the country where pastures are more abundant and where the animal can often benefit from agricultural products. Moreover, this high animal density could explain the large number of FMD outbreaks in this period (Allepuz et al., 2015; Shiilegdamba, Carpenter, Perez, & Thurmond, 2008; Sumption, Rweyemamu, & Wint, 2008). On the other hand, in Niger, the vaccination campaign against CBPP is usually performed in the dry and cold season, from October to the end of January. During such event, there is a high animal density with animals from several villages in a specific vaccination point, and this could alternatively explain the fact that the animal density was one of the predictors of FMD occurrence.

One of the main purposes of this study was to assess the economic impact of FMD. The epidemiological information presented in this study is essential to such assessment. However, based on Rushton's (2009) economic impact framework for FMD, most of the required data to achieve these economic analyses are currently lacking for Niger, and consequently, only some aspects of the production losses (milk production losses and animal mortality) and the vaccination costs were considered in this analysis. Furthermore, in the context of Niger in particular, the influence of these input variables related to livestock production and access to international markets could not be attributed solely to FMD. However, with the available data mostly based on already performed studies, economic assessment was possible using a stochastic modelling approach which allowed generating a range of model outputs that give insights into the impacts of FMD in the country.

This study reveals a high herd-level morbidity of about 50 cattle per outbreak affected by FMD and resulting in a mortality of about three animals per outbreak. The direct consequence of these clinical impacts is the drastic economic losses with an average total cost of 499 euros per outbreak. Although the estimated FMD costs could be considered as a minimum because some variables were not considered (e.g., the draft power losses), this study reveals that FMD infection resulted in important economic losses for a poor country such as Niger.

The mean cost of milk losses was estimated at 166 euros per outbreak in Niger. Lyons et al. (2015) and Barasa et al. (2008) showed also that milk yield decreased due to FMD. In Niger, livestock breeding and particularly milk production play a major role in poverty alleviation and economic growth (Boukary et al., 2007). Indeed, in peri-urban dairy farms, the daily milk production consists of two parts, namely a sold fraction of 62% of the daily milk production and 38% for self-consumption (Vias et al., 2003). Hence, these estimates highlighted the considerable impacts of FMD on rural communities due to the reduced income of households from dairy sale as well as the negative effects on human nutrition.

Despite these adverse consequences of FMD in Niger, there is no control and prevention plan yet for FMD. Although FMD eradication seems not to be realistic at short time, especially in the context of Sahel countries including Niger, it will be economically beneficial to protect livestock by vaccination (James & Rushton, 2002; Orsel & Bouma, 2009). Results of the economic assessment from this study revealed that the mean price for FMD vaccination of one outbreak was more than 314 euros, although only the animals of the assumed FMD-infected herds were considered for these estimates. Nevertheless, it would be beneficial to vaccinate because the costs related to the losses due to the disease (499 euros) are greater than the costs of the vaccine and vaccination. However, even when the total cost of FMD inclined to be lower than the cost of control, vaccination should be continued until the burden of clinical outbreaks of FMD is substantially reduced for a sufficient time period as stated by OIE and FAO about one of the objectives of FMD vaccination, especially in endemic countries. Furthermore, the costs of vaccination were variable from region to region, probably influenced by different factors. For instance, the estimated vaccine costs per animal (Table 2) were much higher for the region of Agadez (in semi-desert area) and for Niamey. The region of Niamey, likely because of its position as capital of the country, has a relatively smaller cattle population than the other regions, and consequently, the allocated budget for the vaccination is lower than that of the rest of the regions. On the other hand, for the region of Agadez, the overall relatively more expensive vaccination costs could be explained by the existence of longer distances between two vaccination centres within the region. However, the overall vaccine cost per animal (0.11 euros) estimated in this study was in some respect in accordance with that of Jemberu, Mourits, Rushton, and Hogeveen (2016) in Ethiopia (0.08 euros). Although for Niger the estimated cost of the vaccine was provided by the Botswana Vaccine Institute, the same laboratory where Ethiopia purchased their FMD vaccine, in contrast to the cost calculation of Jemberu et al. (2016) the estimations from our study were based on empirical data rather than on expert opinion. Moreover, the empirical data in this study at regional level and the use of a stochastic modelling approach most likely considered the uncertainty and variability of the input parameters in the analysis (Briggs et al., 2012).

On the other hand, it should also be noted that the costs of the vaccine are probably high because it is a multivalent vaccine composed of three serotypes (A, O and SAT2). Likely, this vaccination cost could possibly be lower for a monovalent vaccine which has a single serotype prevalent in the field as it was the case during the last FMD outbreak in the south-western part of Niger where only FMD serotype O was isolated (Souley Kouato et al., 2017). Furthermore, in the case that FMD vaccination would be integrated in the present national vaccination framework, this study demonstrated that this option would allow positive economic returns on the costs of FMD vaccination. Indeed, with this strategy of FMD vaccination simultaneously applied with that against other transboundary disease such as CBPP, the cost–benefit ratio would be improved and therefore economically more profitable. As these estimates were carried out only for cattle, it would be interesting to vaccinate as well other sensitive species, such as small ruminants and pigs.

This study has some limitations that are worth mentioning. One of the shortcomings is that no records on laboratory confirmation of FMD outbreaks could be found in the statistics of the Ministry of Agriculture and Livestock. The only laboratory findings confirming FMD outbreaks are those of the World Reference Laboratory for FMD (WRLFMD) and those of one study recently performed in Niger (Souley Kouato et al., 2017). However, Morgan et al. (2014) stressed that in Cameroon (another FMD endemic country), estimates reported by herdsmen (clinical surveillance) were comparable to those obtained from serologic testing indicating the high level of awareness about FMD among herdsmen. On the other hand, the constraints to this study are perceived to be related to the disease reporting system. In fact, over the 9-year period of this study, the levels and the reliability of reporting of FMD outbreaks varied from one region to another. For some reports, the only information available was that outbreaks occurred in a specific department. No indication was given regarding the exact location and the number of exposed animals (GPS coordinates). Furthermore, in addition to missed diagnosis, there was underreporting of animal disease in general and especially of FMD. It is therefore likely that some FMD outbreaks could have been missed and were never recorded or reported. This could result in inaccurate estimations of the disease impact. The above-mentioned discrepancies resulted in values of predictors that are not always necessarily reflecting actual spatio-temporal patterns of FMD outbreaks. Therefore, the effect of these shortcomings is that the estimates of the associations between the predictors and the outcome may be biased. In addition, in Niger, major issues to account for the continuing occurrence of transboundary animal diseases such as FMD include inadequate monitoring, surveillance and disease reporting, lack of herdsmen awareness and lack of any controls over animal movements. Moreover, this study was restricted to cattle, although in Niger, as in many African countries, the traditional animal husbandry practice involves rearing cattle, sheep and goats in close proximity. Similarly, communal grazing is practised in most of the areas, and both small and large ruminants share the same pasture land and water sources. Accordingly, the silent and discrete feature of FMD infection of small ruminants could pose a potential risk of virus dissemination to cattle and other susceptible animals (Barnett & Cox, 1999; Elnekave, Zamir, Hamd, Even, & Klement, 2015; Paton, Ferris et al., 2009; Paton, Sumption et al., 2009). Furthermore, according to one of the studies performed in Niger, herd composition (cattle and small ruminants together) was significantly associated with FMD outbreaks in Niger (Souley Kouato et al., 2017). Hence, FMD surveillance activities as well as epidemiological researches associated with economic impact estimation should be addressed to small ruminants alongside cattle population. Regarding the estimation of the economic impact of FMD, one limitation to this study is the lack of accurate data on animal prices as, for example, the age of animals influences the market prices. Indeed, the data on prices of heifers and young bulls provided by the FAO database are those of market prices but irrespective of the exact age of the animals.

However, despite some limitations, this study explored useful epidemiological information to support national decision-making related to FMD control. For the first time, the location and season of all the recorded FMD outbreaks in the country were documented. Additionally, the clinical incidence was statistically estimated at herd level through FMD mortality and morbidity. This study is also the first estimation of the economic impact of FMD and evaluation of the economic benefits of vaccinating against FMD in Niger. Indeed, the quantitative assessment of this study provides an overview of the significant economic impacts of the disease when considering the total losses due to animal mortality and reduced milk production. On the other hand, this study reported the temporal and spatial distribution of FMD outbreaks in Niger and highlighted which areas are more susceptible to experience an outbreak. Moreover, higher animal densities were mostly apparent in the dry season and thus increasing the probability of FMD outbreaks. Accordingly, intensive FMD control should be more focused in these high-risk areas, specifically in departments bordering neighbouring countries. Future vaccination programmes must also consider the transhumance schedules, and the transhumant animals should be vaccinated before and after transhumance. Additionally, the high-risk period, which is the dry and cold season, coincides in Niger with the vaccination of cattle against CBPP. It would therefore be technically appropriate and as mentioned above economically profitable to associate this annual vaccination campaign with that against FMD.

However, given the limitations of the study as discussed above, the suggested approaches may not be conclusive enough and further studies are needed to evaluate the effectiveness of these options. Moreover, for an effective FMD control using vaccination, a thorough understanding of the specific frequency, distribution of FMDV serotypes and subtypes causing the outbreaks is required, highlighting the need for more extensive molecular epidemiology studies. In conclusion, this study will certainly guide further research into the epidemiology of FMD in Niger and will promote a better understanding of the disease. This will accordingly help to set up FMD risk-based surveillance as well as better preparedness for the disease prevention and control. Additionally, for FMD to be efficiently controlled especially in West Africa, it is strongly recommended to implement a regional strategy which considers the true epidemiological situation as well as the existing livestock system including transhumance, nomadism and live-animal trade.

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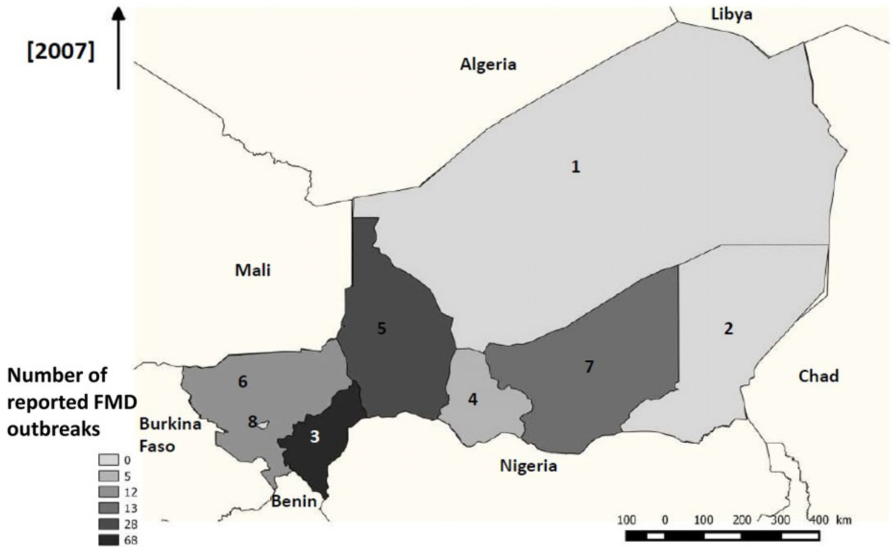
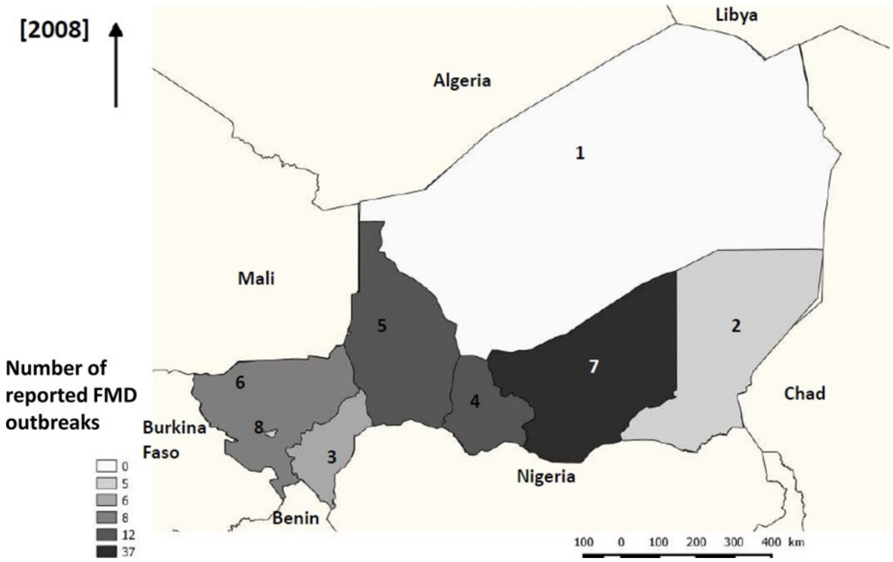
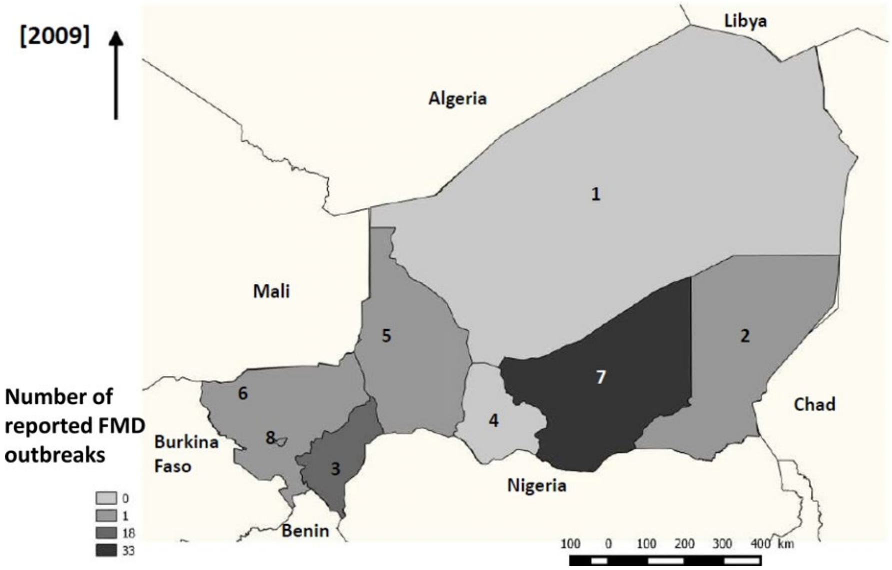
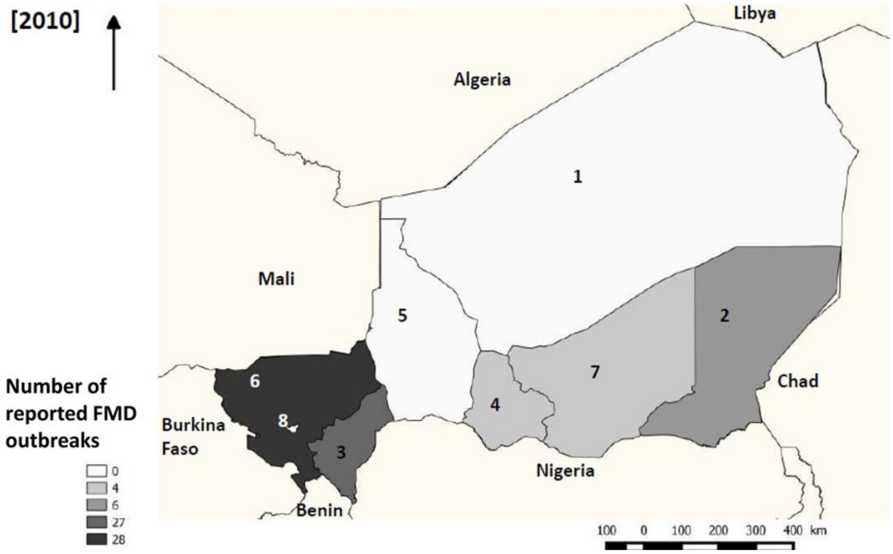
APPENDIX 1

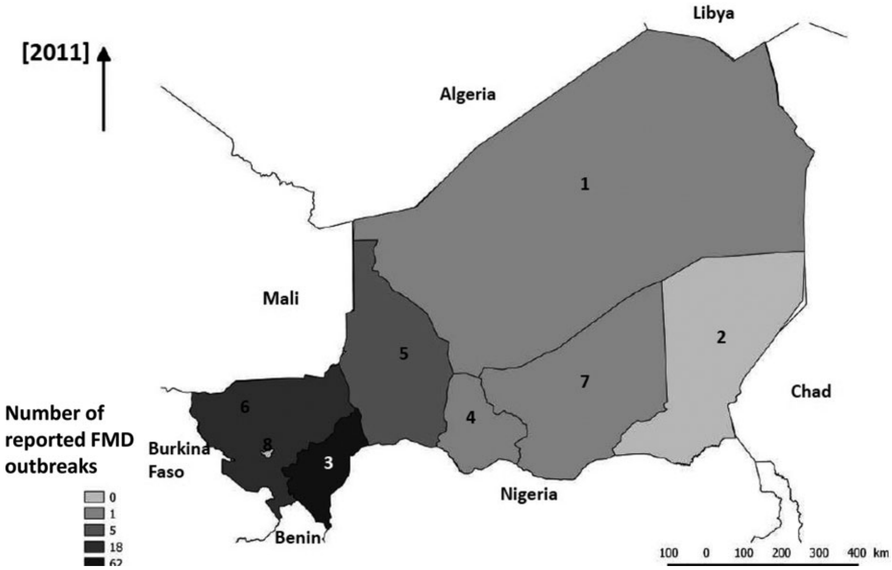
ANNUAL SPATIAL DISTRIBUTION OF SUSPECTED OUTBREAKS OF FMD IN NIGER FROM 2007 UNTIL 2015

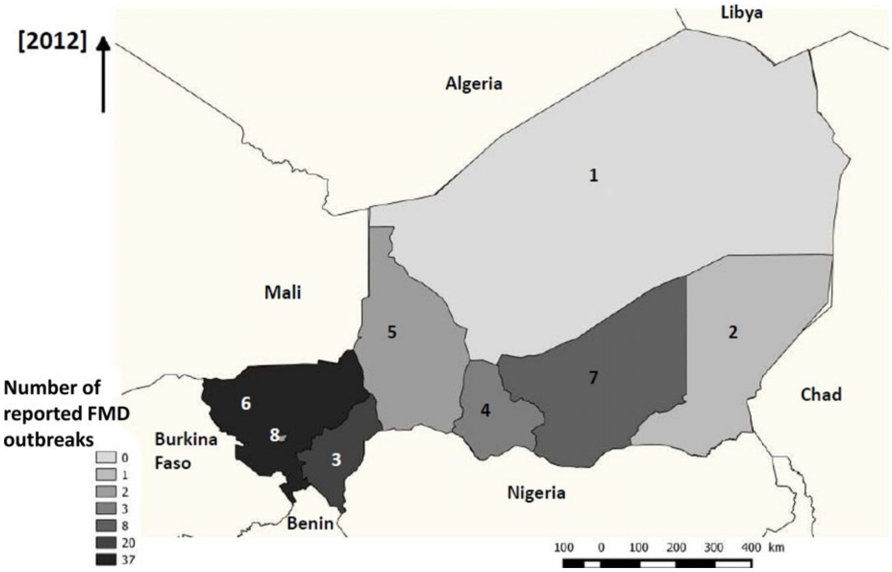


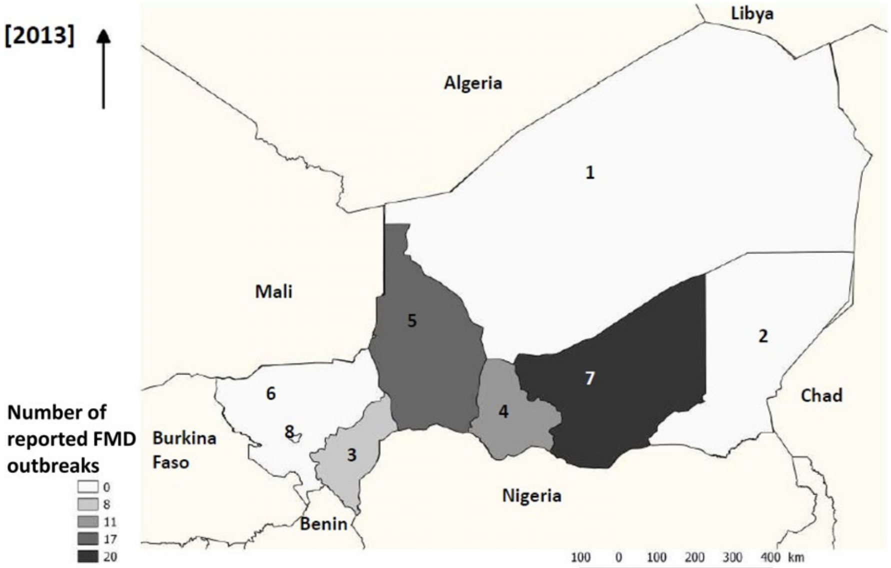


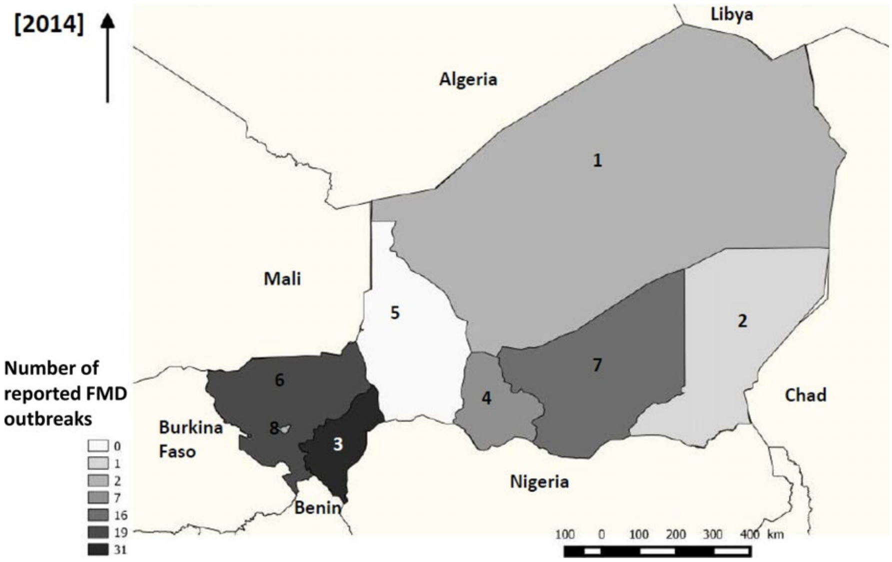

[2009]
Libya
Algeria
Mali
Chad
Nigeria
Burkina Faso
Benin
1
2
3
4
5
6
7
8
Number of reported FMD outbreaks
0
1
18
33
100 0 100 200 300 400 km

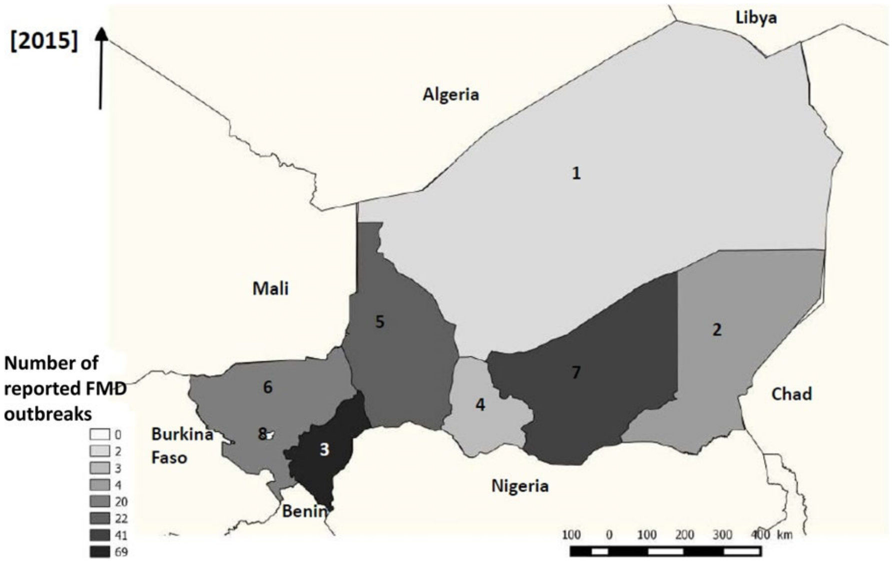

[2010]
Libya
Algeria
Mali
Chad
Nigeria
Burkina Faso
Benin
1
2
3
4
5
6
7
8
Number of reported FMD outbreaks
0
4
6
27
28
100 0 100 200 300 400 km


[2011]
Libya
Algeria
Mali
Chad
Nigeria
Burkina Faso
Benin
1
2
3
4
5
6
7
8
Number of reported FMD outbreaks
0
1
5
18
62
100 0 100 200 300 400 km


[2012]
Libya
Algeria
Mali
Chad
Burkina Faso
Benin
Nigeria
1
2
3
4
5
6
7
8
Number of reported FMD outbreaks
0
1
2
3
8
20
37
100 0 100 200 300 400 km


[2013]
Libya
Algeria
Mali
Chad
Burkina Faso
Benin
Nigeria
1
2
3
4
5
6
7
8
Number of reported FMD outbreaks
0
8
11
17
20
100 0 100 200 300 400 km


[2014]
Libya
Algeria
Mali
Chad
Burkina Faso
Benin
Nigeria
1
2
3
4
5
6
7
8
Number of reported FMD outbreaks
0
1
2
7
16
19
31
100 0 100 200 300 400 km


[2015]
Libya
Algeria
Mali
Chad
Burkina Faso
Benin
Nigeria
1
2
3
4
5
6
7
8
Number of reported FMD outbreaks
0
2
3
4
20
22
41
69
100 0 100 200 300 400 km