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Article type : Review

Using a participatory qualitative risk assessment to estimate the risk of introduction and spread of transboundary animal diseases in scarce-data environments.

A Spatial Qualitative Risk Analysis applied to foot and mouth disease in Tunisia 2014-2019

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This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1111/TBED.13920

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Abstract

This article presents a participative and iterative qualitative risk assessment framework that can be used to evaluate the spatial variation of the risk of infectious animal disease introduction and spread on a national scale. The framework was developed though regional training-action workshops and field activities. The active involvement of national animal health services enabled the identification, collection and hierarchization of risk factors. Quantitative data were collected in the field and expert knowledge was integrated to adjust the available data at regional level. Experts categorized and combined the risk factors into ordinal levels of risk per epidemiological unit to ease implementation of risk-based surveillance in the field.

The framework was used to perform a qualitative assessment of the risk of introduction and spread of foot-and-mouth disease (FMD) in Tunisia as part of a series of workshops held between 2015 and 2018. The experts in attendance combined risk factors such as epidemiological status, transboundary movements, proximity to the borders and accessibility to assess the risk of FMD outbreaks in Tunisia. Out of the 2,075 Tunisian imadas, 23 were at a very high risk of FMD introduction, mainly at the borders; and 59 were at a very high risk of FMD spread. To validate the model, the results were compared to the FMD outbreaks notified by Tunisia during the 2014 FMD epizootic. Using a spatial Poisson model, a significant alignment between the very high and high-risk categories of spread and the occurrence of FMD outbreaks was shown. The relative risk of FMD occurrence was thus 3.2 higher for imadas in the very high and high spread-risk categories than for imadas in the low and negligible spread-risk categories.

Our results show that the qualitative risk assessment framework can be a useful decision-support tool for risk-based disease surveillance and control, in particular in scarce-data environments.

Keywords: risk assessment, animal movements, risk mapping, transboundary animal diseases.

1 Introduction

Over the last few decades, different methods for risk assessment and risk mapping have been widely used to support targeted and cost-effective animal disease surveillance (Peeler et al., 2015). Qualitative risk assessment and disease mapping have been in particular useful in data-scarce environments, often encountered in developing countries, with little available quantitative data on potential risk factors, such as animal movements, livestock and farm distribution, etc. (Wieland et al., 2011; Bridges et al., 2007; Wieland et al., 2015). One of the most widely used frameworks for qualitative risk assessment is the one proposed by Murray et al. (Murray, 2002) to assess the risk of disease introduction through the introduction of live animals. This methodology has been adopted by the World Organization for Animal Health (OIE) (Murray, 2010) and adapted to different country case studies (Chazya et al., 2014; Dejyong et al., 2018; Oliveira et al., 2019). To estimate the risk of disease occurrence, Murray et al. (2002) propose a scenario tree model with three steps: release, exposure and consequence assessment. For each step, a detailed risk pathway outlining the risk factors leading to the animal disease occurrence is developed. In data-scarce environments, the scenario tree model can be built using qualitative descriptors of the risk supported by expert opinion (Dufour et al., 2011; Wieland et al., 2011). For example, to qualitatively estimate the risk of foot-and-mouth disease (FMD) occurrence in Mongolia, local experts collected existing data from regional and national statistics and completed questionnaires based on knowledge of FMD risk factors and risk practices (Wieland et al., 2015). Despite being subjective and with a tendency to overestimate the risk (Cox, 2008), the qualitative risk assessment approach has proven to be transparent and efficient to estimate the likelihood of animal disease occurrence when limited data are available.

In this study, we present a qualitative framework to overcome the limited availability of the data required to assess the risk of infectious animal disease (further referred to as animal disease) introduction and spread at a national scale. The framework relies on an iterative participatory approach combining expert opinions and consensus to identify, collect, categorize and combine spatial risk factors (multi-criteria evaluation method), including data on transboundary and national animal movements to assess the risk of animal disease occurrence.

The study had two primary aims. The first was to conduct national semi-quantitative risk assessment using quantitative and qualitative data on disease risk factors, including data on animal movements to produce risk maps. The second was to assist countries to adapt their surveillance and control activities according to national and regional spatial variation of risk and to the animal disease (transboundary, zoonotic, vector-borne diseases, etc.). The general framework presented was described and validated using FMD in Tunisia as a case study. It was later applied to other diseases and countries, attesting to its potential as an efficient decision support tool for risk-based animal disease surveillance and control.

2 Material and methods

2.1 General process

The qualitative risk assessment framework consists of two consecutive pathways: i) assessment of the risk of introduction of an animal disease not known to be present in the country, and ii) assessment of the risk of spread of an animal disease known to be present in the country. The framework adopts a participatory and semi-quantitative approach to estimate the risk of introduction and spread based on collected data and the elicitation of national and regional experts, and to identify and rank the relevant risk factors for disease emergence, including data on animal movements and other national data collected by national animal health services. The analysis can be updated when new data (e.g., data on animal movements or epidemiological events) becomes available.

Expert elicitation is a crucial to identify the relevant risk factors for each risk pathway (introduction and spread) in the framework. The pool of experts that are mobilized for the assessment represent different domains, such as veterinary services (central and local level), technicians of the value chain, experts of the specific disease, animal mobility experts, epidemiologists, etc. During participatory and regional sessions chaired by a moderator, these experts identify the relevant spatial information available for the risk assessment related to identified risk factors, as well as additional data for the risk mapping and assessment necessitating the implementation of field surveys.

For example, to assess the risk of introduction, experts would evaluate the risk of release of a given pathogen from a source country given the available epidemiological information. The source country would be scored based on several criteria including the efficiency of the management of animal health of the given disease (explanations below). Experts also would consider the existing data on transboundary animal movements (formal and/or informal), such as data from literature or data from field surveys to complete the evaluation **(**Figure 1A).

To assess the risk of spread, experts would collect data on the distribution of susceptible animal population using national registers or data from the literature. Similarly, they would collect information on national animal movements and animal-gathering areas (water points, markets, pastures, quarantine stations, etc.). The pathogen and animal disease epidemiology would be considered (e.g., persistence of the pathogen and transmission routes) in order to list the potential risk factors of importance to the spread (Figure 1B).

For each pathway (risk of introduction or spread), experts set Boolean combinations for the chosen risk factors. To facilitate the combination, quantitative risk factors such as animal density or accessibility to cities, are transformed into four qualitative categories of risk according to their distribution. For example, in case of normal distribution, the limits of the categories are defined according to quartiles, with data from the fourth quartile representing a very high class and data lower than the first quartile a negligible class. For presence/absence risk factors such as presence of live animal markets, only two classes are defined. All risk factor categories are mapped per epidemiological unit.

The final risk is also calculated per epidemiological unit and by combining the risk factor categories. It is also represented using four risk levels: negligible (occurrence of an event is only possible in exceptional circumstances), low (occurrence of an event is possible in some cases), high (occurrence of an event is possible), and very high (occurrence of an event is probable).

2.1.1 Factors to estimate the risk of animal disease introduction

This pathway aims to discriminate epidemiological units at higher or lower risk for disease occurrence through the introduction of live animals (hereafter referred to as "animals") from a source country, using at least three main spatial layers of information. The first layer considers the epidemiological status and most updated knowledge on the animal disease surveillance and control activities in the source country. The second layer uses the in-degree centrality measure from the transboundary animal mobility network analysis. The third layer considers the accessibility to cities or/and the density of the road network to complement the data on the transboundary animal movements in case this data is incomplete.

i) Epidemiological status and mitigation measures in source countries

Each source country that has registered animal movements with the destination country is a potential source of disease. To assess the health status of a specific country, ten criteria grouped into four categories are used: i) type of animal movements, ii) disease status, iii) disease surveillance programs and iv) disease control programs (Supplementary table 1: Source countries and associated risk of emission of a disease through the introduction of live animals).

Experts assign a score to each of the ten criteria to estimate the final risk of disease emission from each source country. Each of the ten criteria, depending on its importance, is weighted by scores varying from 0.5 to 3. The sum of these scores gives a final score on a scale of 12, giving the risk of emission from a source country. The final score for each source country is categorised into one of the four qualitative risk levels of emission: negligible (final score from 1 to 3), low (final score from 4 to 6), high (final score from 7 to 9) and very high (final score from 10 to 12). National and regional experts discuss together to adjust theses scores in a participatory and qualitative approach, according to their knowledge of precise national activities implemented.

ii) Transboundary animal movements

Transboundary animal movements, such as informal trade and transhumance are major factors for the introduction of animal diseases. For vector-borne diseases, the process of risk assessment can be more complicated. However, even in the latter case, livestock trade is a major driver (Dean et al., 2013; Di Nardo et al., 2011; Domenech et al., 2006; Lancelot et al., 2017; Rossiter and Al Hammadi, 2009). A good knowledge of transboundary animal movements is necessary to build the risk assessment for the introduction of animal diseases (Guinat et al., 2016). The framework therefore includes the in-degree measure of transboundary animal movements, which is the number of animal movements (and the volume of animals when available) directed to a given epidemiological unit (node), derived from Social Network Analysis (SNA) of cross-border mobility data registers or collected by national experts via animal mobility surveys.

iii) Accessibility

An understanding of how areas are connected, the strength of these connections, and how this translates into disease introduction is valuable for animal disease surveillance and control (Guinat et al., 2016). While analyses have been undertaken to identify and map connectivity in global air, shipping and migration networks for public health (Huang and Tatem, 2013; Pindolia et al., 2012; Strano et al., 2018), The framework takes into account the road networks and/or traveling time to cities (accessibility). Accessible areas are more likely to be at risk of introduction and spread of a pathogen. Roads can act as major routes for trade and movement of animals, thus a high road network might be associated to a higher risk of disease introduction and spread. Similarly, if an area is close to a border, it might also have multiple informal crossing points, and thus be at a very-high risk for disease introduction (Allepuz et al., 2015).

2.1.2 Factors to estimate the risk of animal disease spread

This pathway aims to discriminate areas at higher or lower risk of disease spread through at least three main layers of spatial information. The first layer considers the distribution of susceptible animal and/or vector population if necessary. Next, the experts use the degree and betweenness centrality measures of the SNA analysis of the national animal movements such as trade and transhumance. The degree is the number of outgoing and incoming links (movements) of a node (i.e., epidemiological unit), and taking in addition, where available, the volume of the animals traded. The betweenness centrality measure shows, for one node, the number of shortest paths using this node to link a pair of other nodes in the network, and considering the volume of animals, when available. The betweenness centrality measure shows, for one node, the number of shortest paths using this node to link a pair of other nodes in the network. The third layer of information is the presence and distribution of animal gathering areas, which are considered as national hotspots for increased contacts among animals.

i) Susceptible animal and vector population

Animal density is one of the most significant determinants of disease occurrence. The presence of animals and their density favour the emergence of an epidemic as the spread of a pathogen is facilitated by a high number of animal contacts (Allepuz et al., 2015; Mosomtai et al., 2016; Munsey et al., 2019). For vector-borne diseases, the presence and density of a vector might complement the data on animal population for a more solid risk assessment (Attaway et al., 2014). Additionally, some agro-ecological factors might determine the presence of vectors and suitability of areas for disease exposure. For example, for assessing the risk of spread of Rift valley fever virus, experts can adjust the model by including risk factors such as land cover, rainfall, temperature, etc.

ii) National animal movements

Animal disease transmission dynamics partly depend on animal movements and the connectivity of the origin and the destination of the animals. In general, areas that are highly connected (high degree) and that fall on the shortest path between any two other areas of a network (high betweenness) play a greater role in disease spread (Ogola et al., 2018; Rautureau et al., 2012). Dynamic simulation models have shown that removing the high betweenness links from a network decreases pathogen transmission (Kiss et al., 2006). The framework focuses on detecting the highest degree and betweenness of national animal movements to maximise the number of high-risk connections between different epidemiological units and increase the sensitivity of the evaluation of the risk of spread.

iii) Animal gathering areas

Animal gathering areas (communal grazing and water points, live animal markets, quarantine centres, etc.) are well known hotspots for disease spread within value chains and wildlife-animal interactions. Thus, besides the presence and distribution of animal gathering areas, the panel of experts take into account several other considerations, such as the concentration of animals, the diversity of animal origins (national, regional) and presence of multi-species at the sites (Dean et al., 2013; Meunier et al., 2017; Motta et al., 2017).

2.2 Case study: foot-and-mouth disease in ruminant populations of Tunisia

Foot-and-mouth disease (FMD) is one of the most important viral diseases of terrestrial livestock due to the associated production and economic losses (domestic ruminants, pigs). Tunisia is vulnerable to FMD epizootics, mainly due to the frequent movement of sheep across the borders shared with Algeria and Libya. Recent estimates suggest that over 12 million small ruminants (mainly sheep) are traded through markets in Tunisia to be slaughtered during the Eid El Kebir religious festival (Bouguedour and Ripani, 2016).

From 1975 to 1999, Tunisia was affected by five FMD episodes. In the 1999 epizootic, phylogenetic analyses revealed that the serotype O (O/TUN/1/99 and O/TUN/5/99) had a 99% similarity with the FMD virus that emerged in Algeria and Morocco that same year (Bouguedour and Ripani, 2016). This serotype belonged to the West Africa topotype, thus suggesting a possible introduction of the virus through movements of ruminants from West to North Africa (Kardjadj, 2017).

Between 1999 and 2014, Tunisia was considered as free from FMD with vaccination (serotypes O, A, SAT-2 in cattle and serotypes O and A in small ruminants). In 2013, the OIE validated the official FMD control program in Tunisia (Bouguedour and Ripani, 2016). However, in 2014, FMD was reintroduced in Tunisia, with the first outbreak declared in the Nabeul governorate in the northeast of the country. The FMD virus then spread across twenty governorates (Sana et al., 2018). The sequencing of the isolated strain identified topotype O/MESA/Ind 2001d, which was 99% related to the FMD virus circulating in Libya (LIB/2/2013) and Saudi Arabia (SAU/3/2013). Again, the fragility of the animal-movement control system in the region was considered as the main source of FMD introduction in Tunisia (Bouguedour and Ripani, 2016; Kardjadj, 2017).

Following the FMD re-occurrence in 2014, Tunisia suspended the validation of the official FMD control program. The main objective of the country case study was to assess the risk of FMD introduction and spread in Tunisia through ruminant (cattle, sheep and goats) movements and relevant risk factors, and restore the official FMD control program validated by the OIE.

2.2.1 Expert elicitation

A panel of national and regional experts was constituted in 2015, including several authors of this paper (SK, JC, AD, ML, YL, and KR) and competent animal health authorities from Algeria, Morocco and Tunisia with experience in FMD surveillance and control. In 2015 and 2016, the experts attended two regional workshops each year. During the first workshops, the experts listed and, when missing, organised the protocols for field data collection in Tunisia (and in Algeria and Morocco as well, data and results not shown). During the following workshops (with West African experts I. Seck, B.O. Elmamy, B. Yahya, authors), they analysed the data, weighted the risk factors, updated the risk maps and drafted a risk-based surveillance plan. All risk factors, data needs, data sources and hypotheses used to estimate the risk of FMD introduction and spread in rumination population of Tunisia are available in Supplementary Table 2. To facilitate implementation of the resulting risk assessment, all data were aggregated by the smallest epidemiological units (*n*=2,075 imadas).

2.2.2 Risk factors for FMD introduction

To estimate the risk of FMD introduction, the experts used the three main risk factors proposed in the framework:

i) Exporting countries and associated risk of virus emission. During the study period, the only countries exporting ruminants into Tunisia were Libya and Algeria. Data on the FMD status, surveillance and control activities in Libya and Algeria were collected from the OIE's World Animal Health Information System (WAHIS) (OIE, 2016), and the Food and Agriculture Organization of the United Nations (FAO) Empress-i database (FAO, 2016), and opinion experts. The Supplementary file 3: Source countries and associated risk of emission of foot-and-mouth disease virus through the introduction of bovine, ovine and caprine animals in Tunisia shows the risk of FMD emission score attributed to Libya and Algeria for the movement of ruminants into Tunisia and their management of animal health in the field.

ii) Indegree of transboundary ruminant movements. The origin, destination and headcount of transboundary ruminant movements (cattle, sheep and goats) were collected using a field survey in 2016 (before and after Eid El Kebir) at all border governorates with Libya and Algeria by the Tunisia's National Animal Health Surveillance Centre (CNVZ). Once collected, the in-degree was calculated for the transboundary animal flows per imada and discretized (quantiles) into four classes of in-degrees.

iii) Accessibility. Accessibility data were downloaded from Weiss et al. (2018). The authors define accessibility as the inverse of mean travel time in minutes (1/travel time) according to road and railway infrastructure. The average travel time in minutes was calculated per imada and discretized (quantile) into four classes of accessibility.

Table 1 shows the Boolean combination of risk factors for the assessment of the risk of disease introduction for each imada in Tunisia.

2.2.3 Risk factors for FMD spread

To estimate the risk of FMD spread through ruminant populations, the experts used the following risk factors based on the three main layers proposed in the framework.

i) Density of ruminant population. Studies in Chad, Niger and Uganda have shown that increased density of cattle and small ruminants is a risk factor of FMD spread (Munsey et al., 2019; Ouagal et al., 2018; Souley Kouato et al., 2018). The average density of small ruminants and cattle per imada was retrieved from the Gridded Livestock of the World animal density dataset (Robinson et al., 2014). The resulting values were discretized (quantiles) into four categories respectively per imada.

ii) Degree and betweenness of national trade ruminant movements. Studies in the Maghreb region have shown the importance of animal movements to the spread of the FMD virus in the past epizootics (Bouguedour and Ripani, 2016; Kardjadj, 2017). Similarly, a study in Ethiopia suggested that livestock movements contributed to the occurrence of FMD (Ayelet et al., 2012). To obtain data on national ruminant trade movements, CNVZ conducted a cross-section survey in June 2015 at all livestock markets in Tunisia (*n*=106). All movements in and out of each livestock market were registered during the survey. Once collected, the calculated degree and betweenness of the national animal flows per imada were discretized (quantiles) into four classes respectively.

iii) Road density. Assessment of FMD epidemics, have suggested a spread pattern that follows the distribution of the road networks, especially in early stages of infection spread (Abbas et al., 2018; Rivas et al., 2003). The Ministry of Agriculture of Tunisia provided data on road networks. Firstly, the total length of road (km) in each imada was calculated and then divided by the area (km^2) of each imada. Road densities were discretized (quantiles) into four classes.

iv) Presence of primary and secondary livestock markets. In Tunisia, livestock markets are considered as major hotspots for disease transmission. The close contact between traded animals from different parts of the country, may contribute to the FMD spread (Abbas et al., 2018). Livestock markets per imada were mapped using the data from a national field survey conducted by CNVZ in 2015.

v) Presence of fattening centres. The epidemiologic aspects of the FMD epidemics in Ethiopia and Ecuador have shown the importance of the farming production systems in the spread of FMD (Gezahegn et al., 2014). Data on the distribution of fattening farms were collected using a national field survey by official veterinarians from the Tunisian Ministry of Agriculture in 2015.

vi) Presence of animal watering points. Distribution of animal watering points were collected from a national survey in 2015 conducted by CNVZ.

Table 2 shows the Boolean combination of risk factors for the assessment of the risk of disease spread for each imada in Tunisia.

While wind is recognized as having a significant influence on the spread of the FMD virus, this modality of transmission is considered to be mainly related to the existence of intensive pig farms, linked to the modalities of virus transmission by pigs, farm size and the overall density recorded in these intensive farms. Pigs excrete the highest amount of airborne virus compared to other ruminants, and large pig farms pose a greater risk of inducing local spread than cattle farms (Hayama et al., 2015, 2012). Pigs is not a significant value chain in the Maghreb region and in Tunisia, thus the distribution of pig population was excluded from analysis.

In addition, FMD can be transmitted over a long distance in an airborne manner (Donaldson et al., 2001). Conditions that prompt the long-distance transmission of FMD include a high relative humidity, usually 55 % or higher (Sajid et al., 2019). These are not the climatic conditions generally encountered in Tunisia. In addition, in FMD transmission models, reproduction rate is related to species (cattle versus sheep) and farm size (Chis Ster et al., 2012.). In Tunisia, farms are relatively small and small ruminants are predominantly represented, thus this risk factor (wind) was not identified and selected by the experts.

2.2.4 Validation

Geographical information was collected for the 142 FMD outbreaks notified by the Tunisian Veterinary Services to the OIE from the FAO EMPRES-i database during the 2014 FMD epizootic. The relationship between FMD outbreak locations and the corresponding risk levels of FMD spread was assessed (Figure 3).

3 Results

3.1 Risk areas for FMD introduction and spread in Tunisia

The experts estimated a very high risk of FMD emission from Libya, and a high risk from Algeria (Supplementary file 3). The limited information on the FMD status, surveillance and control activities in Libya was considered as a marker for a very high risk of FMD introduction in Tunisian imadas. Out of the 2,075 imadas in Tunisia, 23 (1.1%) were at a very high risk of FMD introduction, 480 (23.1%) at a high risk, 1,081 (52.1%) at a low risk and 491 (23.7%) at a negligible risk of introduction, respectively (Figure 2A). Additionally, 59 (2.8%) imadas were at a very high risk of FMD spread, 1,010 (48.7%) at a high risk, 755 (36.4%) at a low risk and 251 (12.1%) at a negligible risk, respectively (Figure 2B).

3.2 Validation of the risk assessment framework

3.2.1 Risk of FMD introduction

Given the validation of the risk of introduction, the challenge for most - if not all - African countries with porous borders and limited resources is the control of transboundary animal movements. In addition, the introduction of a few infectious animals might cause an epizootic, making the assessment of the introduction risk very difficult, namely in the frame of this participatory qualitative risk assessment approach. The formal validation of the risk of introduction therefore appeared difficult and perhaps pointless, given the many past examples of non-elucidated disease introduction, even in countries with more advanced capacities in quantitative risk analysis (e.g., bluetongue in The Netherlands, 2006 (Mintiens et al., 2008), or more recently African swine fever in Belgium, 2018 (Gilliaux et al., 2019; Linden et al., 2019).

3.2.2 Risk of FMD spread

At first glance, two large clusters of FMD outbreaks could be identified during the 2014 FMD epizootic in Figure 3: (i) around Tunis and Nabeul in northern Tunisia, (ii) and around Sidi Bouzid in the central part of the country. The latter area is well known for its key role in the trade and fattening of sheep, notably for the celebration of Eid El Kebir.

As mentioned previously, the epidemiological unit was the imada, which is the smallest administrative unit in the country (*n*= 2,075). Therefore, the outcome in the model validation was the number of FMD outbreaks in each imada. As the surface areas of these imadas vary widely (range: 1 - 13870 km²), this area item was used to standardize the outcome. If the risk of FMD emergence was constant over the territory, independent of the level of risk of spread, then the proportion of cases in each risk level would match the proportion of surface area. Yet, the proportion of cases was much smaller than the proportion of surface area at negligible risk, confirming that the risk in those imadas was smaller than expected (Figure 4). On the other hand, it was very similar at low spread-risk but much larger at high risk. Finally, it was also larger at very high-risk levels, even when the proportion of surface was very small. This illustrated empirically a good alignment between the evaluation of spread-risk and the field situation.

Figure 4 also shows the proportion of imadas in each risk of spread category. Comparing these proportions with the proportions in areas allowed an understanding of the relative average size of the imadas in each category, with respect to the global average size. For instance, in the level 1 (negligible) category, the proportion of imadas was smaller than their relative aggregated surface, meaning that they were relatively larger on average. The frequencies of spread-risk levels were strongly unbalanced in the FMD-infected imadas. The lower-two and upper-two categories were merged before modelling, thus forming a binary variable taking the value 0 for low or very low risk of spread, and 1 elsewhere. A Besag-York-Mollié spatial Poisson model was later chosen to analyse these data, which accounted for the intense spatial clustering and provided unbiased and accurate estimates of the effect of exposition on the probability of FMD occurrence (Besag et al., 1991). Supplementary file 4 shows the details of the model (Supplementary file 4: Validation model for the FMD risk assessment framework in Tunisia).

Figure 5 displays the posterior distribution of the exposition effect in the observations' scale (thus, a multiplicative effect). The relative risk of emergence was increased by a factor between 2 and 5 if the imada was exposed (high and very-high risk category) with respect to not exposed (low and negligible category). More precisely, the relative risk of FMD occurrence was thus 3.2 times higher (95% credible interval: [1.9; 6.0]) for imadas in the high and very-high spread risk categories than for imadas in the low and negligible risk categories.

4 Discussion and conclusions

This paper describes an iterative and participatory qualitative risk assessment framework that can be implemented at a regional scale, and which is suitable for data-scarce environments such as developing countries where data are missing or are of poor quality. The original feature of this approach lies in the combination of spatial data, animal mobility analysis and domain-expert opinions within the same framework. It includes methodologies such as geographic information systems (GIS) and social network analysis (SNA), which are routinely used in epidemiology. Consequently, it is flexible in the use of datasets varying from one disease to another as well as one country to another. Additionally, it can consider a large diversity of risk factors depending on the disease, the availability of data and the socio-economic and agro-ecological context.

The process was implemented via training-action sessions on a regional scale and national surveys linked to risk factors identified. The transfer of knowledge was progressive, starting from training on the collection, analysis and mapping of livestock flows and the design of field surveys at markets, farms and veterinary posts. In a second step, national experts were trained in geographic information systems (GIS), statistical analysis, weighing of risk factors, risk mapping, qualitative risk assessment, and risk-based surveillance.

Our method revealed possible uncertainty introduced by the subjectivity of experts or the quality of data. To reduce the subjectivity of the experts, regional workshops were conducted with a group of national and international domain experts to reach a consensus for the risk factors. Animal movement data collection then was optimized by involving the main country stakeholders and veterinary services in the collection of realistic and new data (such as informal animal movements) to counterbalance the subjectivity of the method and obtain quantitative and realistic data. Several sources of information were used to account for data-scarcity and national quantitative data (gathering points, ruminant density, animal markets, etc.). The group effect was used to validate the data collected and weighted at different levels on a regular basis throughout the process. Different information relating to the same risk then was combined to reduce uncertainty or gaps in data. For example, if no list of farms was available, this information was replaced by combining density of animals and secondary markets.

Risk estimates are invariably subject to a certain degree of uncertainty due to imperfect data, and it is a common practice in risk assessments to make this explicit by providing an estimate of the degree of uncertainty. In the context of a developing country, the availability and quality of data for risk assessments are even more of a problem than in developed countries. In many cases, either no data are available, or they only represent short time spans, cover a limited geographical area, or focus on subpopulations. In such situations, using the standard approach for estimating uncertainty based on the quality of data, most risk estimated would be categorised as having a high uncertainty, leaving little room for differentiation between risk estimates.

This process followed in this study resulted in a stepwise reinforcement of skills of national experts in risk assessment and risk mapping via face-to-face regional workshops, thus permitting weighing of risk factors and consensus, then remote companionship follow-up using innovative technologies for data collection and pedagogical toolkit online on the methodology. In return, national experts provided input on risk factors for disease emergence and knowledge about entry points of animals, as they were best informed regarding the local and regional disease situation and practices linked to the value chain. The process became iterative and adaptive each time relevant data become available, for example through the direct implication of national experts in the organisation and implementation of field surveys (e.g., collect data on livestock market distribution, surveys on animal movements between livestock markets, surveys on illegal movements between countries, etc.). The process also allowed an expert consensus to be built on the relevant risk factors, weighing, and combination for risk estimation, thus lowering uncertainty and increasing the transparency of the results (Tran et al., 2016). Finally, the entire process was moderated by international experts in disease surveillance and animal mobility, thus the national and regional experts were well guided in the approach (Wieland et al., 2015). Our integrated approach with validation and integration in the process of expertise from national and regional experts (and not only from a literature review) allows us to deploy an iterative and integrative process, complementing the semi quantitative analysis (Paul et al., 2016; Tran et al., 2016).

The framework considered a few basic inputs, among which were data on animal movements. As there is a general lack of national animal identification systems and movement monitoring in data-scarce environments, in the future we intend to test proxies on animal movements to tailor the qualitative risk assessment. For example, it may be possible to add weight to animal gathering points (livestock markets, slaughterhouses, proximity to water points) or to use road networks as proxies of animal mobility (Rivas et al., 2003; Traulsen, 2008).

Following the emergence of FMD in Libya, Tunisia, Algeria and Morocco in 2014, the need to consolidate national animal health capacities in risk-based surveillance has become more than evident, as has the use of epidemiological tools to anticipate the risks associated with livestock trade.

In 2014 and 2015, two regional training-action workshop sessions were conducted for the Maghreb. An integral part of the risk assessment was to assess the flows of animal trade and transhumance, along with informal exchanges, notably on the borders, by planning field surveys on animal mobility. However, during this period, only Tunisia implemented animal mobility surveys, and thus only Tunisia was considered as a case study. For the FMD case study in Tunisia, in addition to the collection of data and analysis of animal mobility, other layers of spatial information, such as livestock markets and accessibility per imada, were assessed and integrated. The risk assessment included the most detailed information and experts' inputs by weighing and combining the risk factors to obtain the best prediction of FMD occurrence. The areas identified by the framework as being at risk for FMD spread in ruminant populations in Tunisia corresponded to the areas with the highest number of FMD outbreaks in 2014-2019. This suggests that the framework was able to identify the epidemiological units associated with an increased risk of FMD spread related to existing national and regional risk factors.

However, in the case of Tunisia, it was not possible to validate the results for the areas at risk of FMD introduction. In the absence of regional information system on animal movements, the assumptions on the introduction processes and routes rely more on the results of molecular epidemiology than on the analysis of animal movement data, thus emphasizing the importance of sampling and genotyping pathogen agents, and sharing the results (Bachanek-Bankowska et al., 2018; Kardjadj, 2017; Pezzoni et al., 2019). Also, new opportunities to improve semi-quantitative risk analysis models might be provided by the development of event-based surveillance, and more broadly, epidemic intelligence systems (Arsevska et al., 2018, 2016). Far from being fully automated tools, these systems also needed a participative implementation to provide meaningful insights. Nevertheless, the semi-quantitative analysis of the risk of disease introduction proposed in this paper was still useful because it required the compilation of existing information and the mobilization of collective epidemiological thinking which might not have otherwise occurred (Dufour et al., 2011).

Following the case study, the Tunisian veterinary services have adapted their surveillance protocols using the maps that were produced through the exercise. They have implemented serological surveys in the imadas with a high and very high risk of spread, and they also have reinforced surveillance activities along the Libyan border. Finally, the Algerian borders have been targeted by two vaccination campaigns.

During the regional workshops, there were many discussions on the FMD status of neighbouring countries due to uncertainties regarding the disease situation in these countries and the control measures along the borders. This highlights the importance of choosing a range of national experts, from virologists, epidemiologists, to central and local disease surveillance officials. It also highlights the importance of strengthening regional disease information exchanges and of ensuring the dissemination of information from the central to provincial and district levels. Their expertise and knowledge were are inescapable in the deployed method in order to make solid the qualitative analysis that we carry out with bibliographical data, field data but also with the weighting of risk factors by the experts (Paul et al., 2016). This complements the methods already developed elsewhere (Tran et al., 2016), like on GIS-based MCE method to build risk maps that could be used for early warning detection and implementation of control measures.

Using free open-source software and data, the proposed framework could be easily used by veterinary services working in data-scarce settings and with low resources. These analyses on a regional scale could also become essential for implementing risk-based surveillance on both side of borders. An important perspective would be to include risk mitigation factors (rate of immunization, specific control activities, etc) to apply on the risk maps and develop new risk-based control strategies.

This generic framework is suitable for the assessment of risk related to any animal infectious disease, for a large range of available data sets, and in a diversity of contexts (national and regional). In particular, the framework could be useful for priority diseases set by domain experts (field veterinarians, veterinary services, and academics) through training action programs considering a regional approach to optimize surveillance systems based on risk.

Contribution

Methodology: CSD, EA, CC, BD, RL, PH, FM, IS. Expert panel: JC, AD, ML, YL, KR, SK, IS, BOE, BY, CSD, EA, RL. Data curation: JC, SK. Model validation: FM, RL. Writing – original draft: CSD, CC, EA, SK. Writing – Review & Editing: CSD, EA, BD, PH, SK, EC, RL, FM. All authors have approved the final article. The data that support the findings of this study are available from the vet services of Tunisia and CNVZ upon reasonable request.

Acknowledgments

"Posthumous tribute - This article is dedicated to the memory of our colleagues and friends, Ms Caroline Coste and Mr Jamel Cherni, who left us far too early."

The data that support the findings of this study were provided upon reasonable request by the veterinary services of Tunisia and the Tunisia's National Animal Health Surveillance Centre (CNVZ, accredited as OIE Collaborating Centre).

The authors would also like to thank Assia Daoudi and Mohamed Karim Laoufi from the Ministry of Agriculture and Rural Development, Alger, Algeria, and Yassir Lezaar and Kechna Rachid from Office National de Sécurité Sanitaire des Produits Alimentaires, Rabat, Morocco, Bezeid Ould Elmamy and Barry Yahya from LNERV, Mauritania, for contributing to the expert panel and Raphaelle Metras, INSERM, Paris.

Funding

This research was partially funded by France Vétérinaire International, the French Ministry of Agriculture, the EU- FMD programme and Cirad, research unit ASTRE.

Conflict of interest statement

The authors declare no conflict of interest.

Ethics Statement

The authors confirm that the ethical policies of the journal, as noted on the journal's author guidelines page, have been adhered to. No ethical approval was required as this is a review article with no original research data.

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6 Tables

Table 1: *Combination table of risk factors to estimate the risk of FMD introduction in Tunisian imadas*

Risk category for FMD introduction	**Boolean combination of risk factors**
Very high (level 4)	release >1 AND accessibility >=146 OR in-degree transboundary>=47
High (level 3)	release >1 AND 86<=accessibility <146 OR 23<=in-degree transboundary<47
Low (level 2)	release >1 AND 86>accessibility >=33 OR 7<=in-degree transboundary<23
Negligible (level 1)	all the remaining imadas

Table 2: *Combination table of risk factors to estimate the risk of FMD spread in Tunisian imadas*

Risk category for FMD spread	**Boolean combination of risk factors**
Very high (level 4)	[road density >3 OR degree national>68 OR betweenness national >50915] OR (ruminant density >106 AND secondary markets) OR (primary markets =1 OR fattening units =1) OR watering gathering points=1
High (level 3)	[2< road density <=3 OR 46< degree national <=68 OR 33944< betweenness national <=50915] OR [(secondary markets OR fattening units =1) AND (50<

	ruminant density <=106)] OR ruminant density > 106
Low (level 2)	[1< road density <=2 OR 23<degree national <=46 OR 16972< betweenness national <=33944] OR [5< ruminant density <50) AND secondary markets OR 50< ruminant density <=106]
Negligible (level 1)	all the remaining imadas

7 *Figures*

Figure 1. Outline of the qualitative risk assessment framework to estimate the risk of A) disease introduction and B) disease spread to a susceptible animal population in a given country

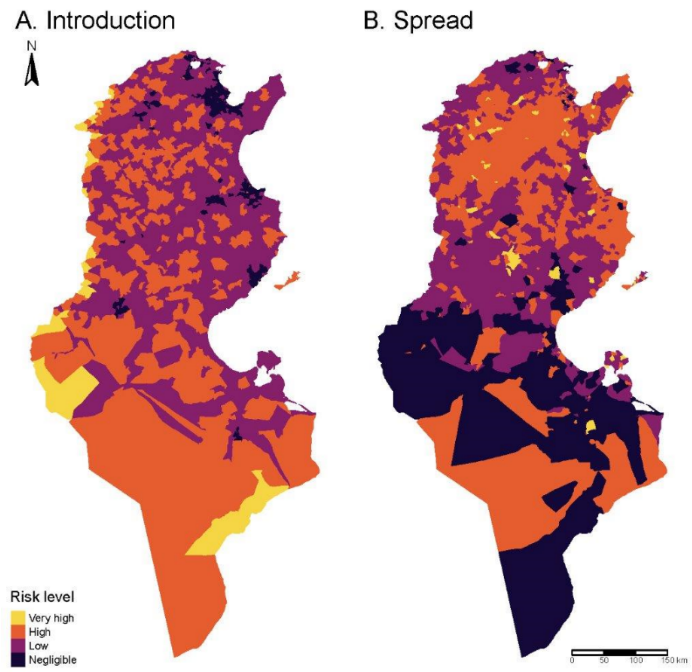

Figure 2. *Risk levels of FMD A) introduction and B) spread in Tunisian imadas*

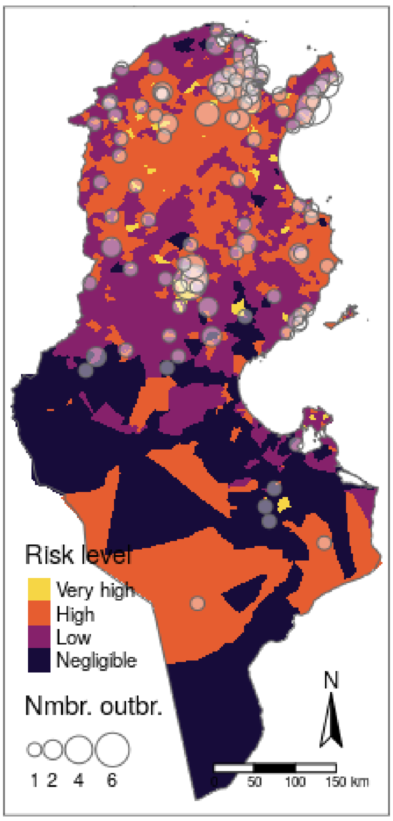

Figure 3. *Spatial distribution of the FMD outbreaks per level of FMD risk of spread in Tunisian imadas.*

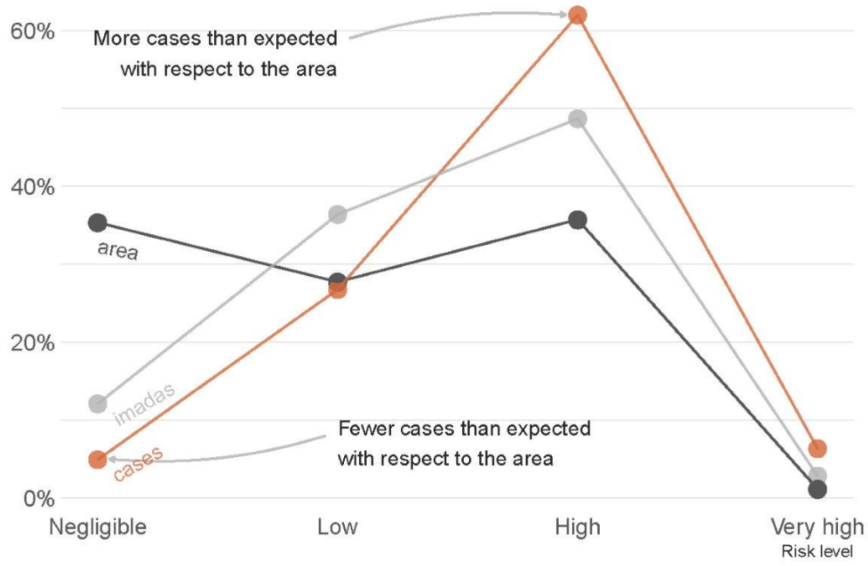

Figure 4. *Proportion of area, FMD outbreaks and imadas in each level of exposition*

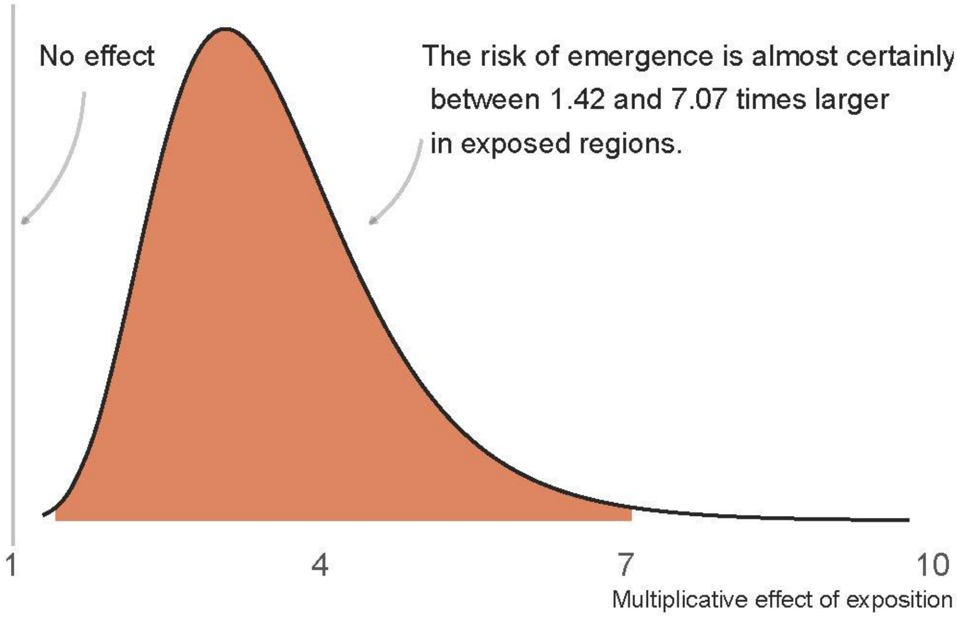

Figure 5*. Posterior distribution and 99% HPD (Highest Posterior Density) interval of the multiplicative effect of the FMD spread.*