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Ovine Network in Morocco: Epizootics Spread Prevention and Identification of the At-Risk Areas for "Peste des Petits Ruminants" and "Foot and Mouth Disease"

Yassir Lezaar, DVM, MSc[1*]; Mehdi Boumalik, DVM[2]; Youssef Lhor, DVM, PhD[1]; Moha El-Ayachi, PhD[2]; Abelilah Araba, PhD[2]; Mohammed Bouslikhane, DVM, PhD[2]

[1]*National Office of Food Safety (ONSSA), Rabat, Morocco*
[2]*Institut Agronomique et Vétérinaire Hassan II (IAV Hassan II), Rabat, Morocco*

[*]***Corresponding author***
Yassir Lezaar, DVM, MSc
Veterinarian, Department of the Epidemiology, National Office of Food Safety (ONSSA), Rabat, Morocco; E-mail: Lezaaryassir@hotmail.com

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ABSTRACT

Objectives: Because contagious diseases spread among domestic ruminants are closely linked to livestock movements, the present study aims to analyze the sheep movements network in Morocco during its two periods of regular movements and more intense movements in the festive period, to map it and identify central points and movement structures that influence its functioning, but also to highlight the articulation points at which actions should be taken to prevent or control the epizootics spread. The aim of this study is also to produce risk maps for introduction and exposure to Peste des Petits Ruminants (PPR) and Foot-and-Mouth Disease (FMD), to guide the epidemiological surveillance efforts.

Methodology: This is a descriptive study, and which results placed it within the framework of epidemiological surveillance on a national scale. A two-stage random sampling was carried out in 52 provinces belonging to regions with very high sheep populations and whose municipalities have been subject to previous outbreaks of diseases, notably PPR and FMD. A sampling proportion of 25% of municipalities was adopted for each province. Within each commune, sheep farms and markets, if existed, were drawn randomly. In the absence of a breeder database, the sample relating to farms was carried out by representativeness of the sheep population for each municipality. The sample relating to markets was carried out as representative of the trading volume of the markets. An "Origin-destination" survey concerning the origin and destination of sheep routes made by breeders or traders was deployed in the field. The results of this survey were entered into a database and then mapped by the Geographic Information System (GIS) to distinguish regular movements from periodic ones. After data reorganization into two movement periods, the database was processed by the network analysis method to highlight the main central points and the main structures that condition the movement. All these analyses were conducted using the "R" software. The risk analysis of introduction and exposure to PPR and FMD was also carried out. The results obtained were compared with the epidemiological data of these diseases.

Results: The sheep movement network in Morocco is much more sensitive to the epizootics spread during intense movement periods corresponding to preparation for the festivities, namely Aid al Adha than during regular periods. The centrality of certain municipalities exposes them to the risk of diseases during periods of intense movement, while others appear exposed during both periods. This study has traced back the different regions by cohesive structures of movement which condition the circulation of disease pathogens across the country and which strongly contribute to their diffusion across regions which are sometimes very distant geographically. However, the movement articulation municipalities "cutpoints", that allow to neutralize flows between these structures have been identified. The introduction and exposure risk analysis provided satisfactory results for the PPR and FMD about their validation by health epidemiological data related to outbreaks. Thus, 82.88% and 67.39% of outbreaks were included in the high to very high risk strata respectively for PPR and FMD.

Conclusion: This study's results allowed a better understanding of sheep movements extent and articulation at the national level during periods of regular movements and periods of more intense movements and consequently a better knowledge of the pathogen's dissemination paths. Highlighting "cutpoint" municipalities in addition to the at-risk municipalities for introduction and exposure to diseases represents valuable guidance for targeted actions that would contribute to remobilizing and optimizing available surveillance resources more efficiently.

Keywords: Morocco; Ovine; Mobility; Contagious diseases; Mapping; Network analysis; Risk analysis.

INTRODUCTION

Due to the intensification of livestock movements in the world and Africa, Morocco has experienced over the last two decades, as in several other African countries, the introduction of contagious animal diseases. These diseases were responsible for epizootics occurrence, particularly Peste des Petits Ruminants (PPR) in 2008 and Foot and Mouth Disease (FMD) in 2015 and 2019. The PPR epizootic of 2008, with its low morbidity (11.93%) and mortality (5.53%) rates observed in small ruminants, has nevertheless generated 257 outbreaks which spread into 131 municipalities in the northern half of the country.[1] The FMD epizootic of 2015 has generated only 6 outbreaks located in six municipalities,[2] while the epizootic of the same disease in 2019 concerned 46 outbreaks spread across 39 municipalities.[3] However, although these diseases were introduced across the eastern borders of the Kingdom, given the phylogenic evidence of viruses, the first outbreaks tended to occur only in the central areas of the country. Therefore, mobility surveys were deployed in the field to understand the movement structure and its organization.

The model intended to analyze separately the two profiles of livestock movements that alternate during the year. One is distinguished by regular movements and the other is characterized by the establishment of periodic movements which intensify the movements network. Indeed, over around six months, preceding the sheep sacrifice festivity Aid al Adha, the annual commercial movements are added to the other regular components of the network which corresponds to the preparation for this religious event, notably by implementing fattening feedlots.[4] This period is also characterized by transhumance movements,[5] which come essentially from the south to join the other movements in the network when this fits with the availability of pastures in the northern half of the country.

In Morocco, apart from the areas of almost goat vocation, confined to the high altitudes of the north (Rif mountains) and the center of the country (High Atlas mountains), small ruminants evolve in mixed herds of sheeps and goats (when the latter exists) throughout the rest of the Kingdom. At the national level, the sheep population which is about 20,036,518 heads is four times higher than the goat population with 5,091,320 heads.[6] Consequently, considering that sheep mobility is predominantly higher than goats,[7] it was decided to focus on sheep species movements only.

For countries that don't have sheep identification and traceability systems, animal mobility surveys are an important epidemiological tool for studying livestock movements and determining the main crossroads exchange and movement structures to guide surveillance efforts.

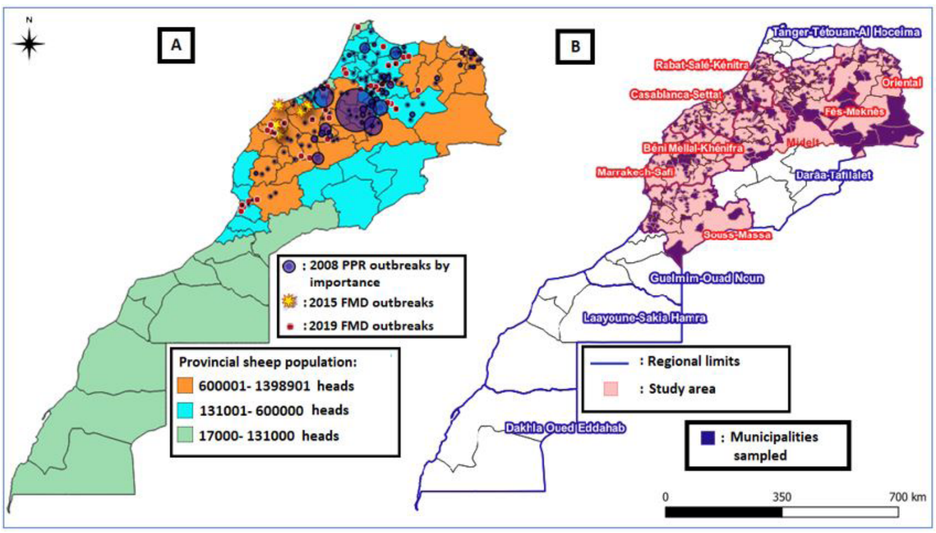
Surveillance can be significantly improved through qualitative risk analysis as recommended by the World Organization for Animal Health (WOAH), particularly in cases of animal cross-border movements.[8] In this context, a risk analysis method which was developed by our contribution with the International Cooperation Center in Agronomic Research for Development (CIRAD)[9] was used, while however involving deep changes in the risk factors choice, which have proven to be the most adapted to the Moroccan context.

MATERIALS AND METHODS

Choice of Study Area

To identify sheep concentration areas, the provinces were classified according to their livestock size into three classes (Figure 1A). Almost all provinces with the highest numbers correspond to the four administrative regions of Casablanca-Settat, Oriental, Beni-Mellal-

Figure 1. *Determination of the Study Area*



***A:** Representation of the study area according to diseases outbreaks and sheep size. **B:** Delimitation of the study area and its sampled municipalities.*

Khenifra and Marrakech-Safi, whose they are an integral part (Figure 1B), while three remaining provinces with very high livestock size are part of other regions with an average provincial livestock size: Rabat-Salé-Kenitra (Khemisset province), Fès-Meknes (Taza province), Sous-Massa (Taroudant province). Therefore, the previous seven regions in addition to Midelt province were selected in the study for the following reasons:

1. Their significant sheep potential[10] suggesting an importance in movements,
2. The concentration of PPR (in 2008) and FMD (in 2015 and 2019) outbreaks at their level.[1-3]
3. The presence of 80% strategic cattle markets in these regions.[11]
4. The province of Midelt was part of the Region of Beni-Mellal-Khenifra (province of Khenifra) during the PPR epizootic of 2008.

Type of Study and Period

This is an epidemiological descriptive study, aiming to study the ovine movements network in Morocco to identify its actors, its structure, and its fragility points regarding the transmission of epizootics, in the perspective to guide the epidemiological surveillance efforts. This is the first study carried out at the national level with such an extensive study area, combining three different analysis methods, namely mapping, network analysis, and risk analysis.

Regional surveys were carried out in the field at various periods:

1. In 2015: Casa-Settat, Beni-Mellal-Khenifra, Marrakech-Safi and Oriental regions.
2. In 2018: Fes-Meknes and Sous-Massa regions,
3. Between 2022 and 2023: Region of Rabat-Salé-Kénitra.

SAMPLING

A two-stage random sampling was applied. The provinces belonging to the administrative regions surveyed were retained in their entirety. Within these provinces, the municipalities were sampled with a 25% sampling rate. Within the municipalities, two types of establishments corresponding to farms including breeders and fatteners on the one hand and to livestock markets (souks) on the other hand were sampled. Concerning the municipalities, several 50 farms per municipality have been set. In the absence of the availability of a breeder database, this number was multiplied by the number of municipalities retained for each province and summed for all the provinces of each region, to then be redistributed by the weighting of sheep numbers at the municipal level, to obtain representativeness of the farms according to the size of the herd. Concerning the markets, markets of large, medium, and small trading volumes were sampled according to their presence in the municipalities or abundance in the provinces. Several 110 breeders, traders or intermediaries to be investigated were set for large markets. It was reduced to 90 for smaller markets, 60 for medium, 30 for small ones, and 15 for the smallest ones if existing.

A total of 52 provinces (study area) out of 75 (national total) were investigated, 275 municipalities were sampled for livestock breeding and 191 livestock markets were surveyed. Sampling was carried out using "Statistical Package for the Social Sciences (SPSS)" software.

SAMPLE SIZE

In total, no less than 22,952 breeders, fatteners, traders, intermediaries, and transhumants were surveyed at the level of breeding farms and livestock markets.

DATA COLLECTION AND GATHERING

Questionnaire used: For this survey, a specific anonymous questionnaire of a light nature not exceeding one line per owner was used. It includes questions on the municipalities of origin and destination of the movements that took place, on the type of origin and destination (fatteners, breeders, transhumants, or livestock markets).

Testing the questionnaire: The questionnaire, which showed its reliability and easy use, was tested before each field survey campaign in 2014.

Field investigations: The defined epidemiological unit is the herd unit and the investigation was carried out in the form of a face-to-face interview with the owner (breeder, trader). In each farm and market, the surveys were carried out by interviewers who were previously trained on the questionnaire.

Data Entry and Processing

The data was entered into an "Excel" database with a municipality of origin and a municipality of destination to be transformed into routes using a single line after the elimination of duplicates.

The mapping analysis was carried out on the Quantum GIS (Qgis) 3.22 software. The map coordinates of the municipalities are centered on the center of their polygon. They were calculated and obtained by QGIS software version 3.22. The reference coordinate system (SCR) used is EPSG: 4326, WGS 84.

The network analysis was carried out by the "R" and "Rstudio" software using specific scripts corresponding to the "sna", "igraph" and "ggplot2" packages to calculate the different parameters and indicators according to their mathematical formulas.

The exclusive animal species concerned by the investigation is the ovine species, The routes recorded and represented concern commercial movements and transhumance movements.

Data relating to the 2008 PPR outbreaks and the 2015 and 2019 FMD outbreaks were downloaded from the WOAH website (2023) and were also provided by the Moroccan National Office of Food Safety.

Choice of Analysis Methods

Movement analysis and risk mapping: The geographic information system "GIS" was used for movement mapping, risk mapping, and geographical representation of structures and indicators resulting from network analysis.

Network analysis method: The network analysis (NA) method has proven to be the most appropriate for studying the relationships between the actors in the movement network. Based on graph theory in mathematics, it starts from the hypothesis that the contact network has a greater influence than personal behavior on the spread of the disease.[12] The method has shown importance in the epidemiology of diseases which makes the link between central individuals (who maintain the disease) and individuals on the periphery (with a lower prevalence), it allows an evaluation of the influence of connections between actors in the transmission of a disease.[13] Historically, its first example of use in epidemiology dates back to sexually transmitted diseases (STD). Thus in 1985, Klovdahl used this method to describe an outbreak and thus provided arguments in favor of the theory of an infectious agent causing acquired immunodeficiency syndrome (AIDS).[14] Since the 2000s, and following the FMD epizootic which affected Great Britain, the method has been widely used in veterinary epidemiology, particularly in livestock movements.[15] Indeed, in Great Britain, Webb used it in 2006 to determine the role of agricultural competition in the transmission of sheep diseases.[16] Kao and al studied livestock movements in the United Kingdom to estimate the risk of a large outbreak of FMD and were able to provide advice for targeted surveillance and control, which would be effective in reducing this risk.[17]

A network is a representation of a complex system, simplified by two elements: nodes and links. Nodes corresponding to a set of actors (individuals or interest groups), and links representing a certain type of relationship between 2 actors.[18] In this study, the nodes correspond to municipalities with livestock farms and/or markets and a link indicates the existence of a movement between the two.

This method makes it possible to calculate a large number of indicators and parameters, which will make it possible to qualify the network and classify the nodes according to their importance.[19] Many measures have been proposed to quantitatively describe the structure of networks, but we will only cite those used in the context of this work. These measures characterize networks from both global and local scales.[20,21]

First category: It brings together global measures that consider the entire network through statistical properties calculated over its entire structure and provide information on the cohesion parameters at the network scale. They apply to all nodes and links, and provide, for example, an idea of how the structure of the network influences the spread of the disease.[12,22-24]

Second category: It brings together local measurement parameters that are only interested in the properties of nodes and links. This type of measurement aims to provide information on the neighborhood of a node or to highlight certain structural properties.[17,25-31]

They include:

• **Centrality parameters:** These indicators indicate whether a node occupies an important, central place in the network. These are parameters widely used in epidemiology to detect individuals, nodes, or key players.

• **Cohesion parameters:** Whose indicators make it possible to identify subgroups of individuals whose relationships are strong and cohesive.

A definition of these different indicators and their implication in epidemiology, based on in-depth documentation[20-31] is presented in Table 1.

Network analysis allows also us to detect the existence of communities within the structure. A community is defined in a current graph as a group of nodes that are particularly linked to each other and weakly linked to the rest of the network. To highlight the communities in the context of this work, two methods (algorithms) based on modularity[32] were applied. The latter, which is a measure of the quality of partitioning, makes it possible to highlight the significant existence of homogeneous community structures with similar behavior when its value is high (>0.3)[33]:

The "Edge betweenness" algorithm: Often referred to as the Girvan and Newman[32] algorithm, this is a division algorithm that operates according to the hypothesis that the links connecting nodes of distinct communities will have centrality scores of high betweenness.

The "Fast Greedy Cluster" algorithm: The Fast Greedy Cluster algorithm is an agglomerative hierarchical clustering method that optimizes modularity by merging the pair of communities at each step to produce the greatest increase in modularity.[34] At the beginning, it considers each node as a community and it proceeds by analyzing the modularity of each pair of communities, to choose those with the highest modularity and unite them. It repeats this passage until all the nodes are part of a single community and finally, it chooses the partition with the maximum modularity.[35]

Risk analysis: Risk analysis was also carried out to assess the risks of the introduction and dissemination of PPR and FMD at the municipality (communal) level.

Calculation of the Introduction Risk

Considering that when sheep imports are carried out by Morocco, they are done from reliable partner countries, complying with rigorous health measures and specific controls, the risk of pathogens introduction therefore only involves the risk of illegal emission from the neighboring countries sharing land borders with Morocco, namely Algeria and Mauritania as well as the risk of external diffusion from these same countries.

Emission risk: Calculated based on data relating to the epidemiological status of the country at the origin of the movement such as the existence of either commercial or illegal movements, the evaluation of actions carried out on the ground in surveillance and control of the diseases concerned. This information was analyzed according to experts and noted with weighting coefficients specific

Table 1. *Defining Network Analysis Indicators and their Implications for Epidemiology*

Measurement Type	Concept	Indicator	Definition and Implications for Epidemiology
Global	Cohesion across the network	Density	Its value, between 0 and 1, provides information on the overall connectivity within the network in relation to the percentage of links established between nodes, and gives an indication of the speed at which an epidemic would spread.
		Mean distance	For a graph with "n" nodes, it provides information on the proximity of nodes in the network and their ease of communication and exchange.
		Diamètre	The diameter of a graph is the greatest distance between two nodes on the graph. This diameter, like the average distance, provides information on the ease with which network nodes can communicate.
		Réciprocity	Reciprocity corresponds to strong connectivity in graph theory. A graph is strongly connected if, for any pair of distinct vertices, there is a path from one vertex to the other, in both directions. Sheds light on the importance of reciprocal contamination between nodes for the spread of disease.
		Transitivity	Transitivity is the overall probability of the network having adjacent interconnected nodes, revealing the existence of closely connected communities at which pathogens can circulate in a loop and maintain themselves. It is calculated as the ratio between the observed number of closed triplets and the maximum possible number of closed triplets in a graph.
Local	Inbound activity centrality	Indegree	Informs about incoming movements and expresses the node's power to self-infect.
	Outbound activity centrality	Outdegree	Indicates outgoing movements and expresses infectivity towards other nodes in contact with this node.
	Intermediarity centrality	Betweenness	This is the number of times a node in the network connects pairs of other actors who would otherwise not be able to join. In other words, it represents the node's ability to force flows to pass through it before reaching other nodes, and provides information about the node's essential role as a mobility hub.
Detection of cohesive subgroups	Cohesion	Component	A component is the largest set of connected nodes. It is weak when there is no path for each node to reach the rest of the nodes in that component. This translates into epizootics that do not affect the entire component.
		Strong Components	Strong components are commonly studied as predictors of final epizootic sizes. These are subsets of connected nodes with very strong relationships, with a path for each node to reach the rest of the nodes in its component. They therefore provide information on strongly connected establish-ments that can favor the spread of a disease.
Articulation points	Cohesion and fragmentation	Cutpoints	These are critical points, when removed from the network, increases the number of components and the fragmentation degree. At articulation points with high centrality, the graph is highly vulnerable in terms of communication. These points are used to stop the spread of epidemics within the network.

to each activity about their importance in the spread of diseases, the calculation was based on the "Arsevska" method.[36] The sum of the calculations results in the calculation of the introduction probability for each municipality. This probability will be reclassified into four risk levels following the approach proposed in 2011 by Dufour et al[37] to facilitate mapping representation.

External diffusion risk: To refine the introduction risk at the borders, an accessibility factor, differentiating the most accessible borders municipalities from those which are less accessible, was adopted. The risk of introduction obtained concerns both the introduction of PPR and FMD from the eastern borders.

Risks characterization

- **"Very high" risk (4)**: Municipality with positive emission risk, whose accessibility is very high.

- **"High" risk (3)**: Municipality with positive emission risk whose accessibility is high.

- **"Low" risk (2)**: Municipality with positive emission risk whose accessibility is low.

- **"Negligible" risk (1)**: Municipality with positive emission risk whose accessibility is negligible.

Calculation of the Exposition Risk

The calculation of the exposition risk or diffusion risk in the destination country is based on different risk factors, including the movement network, which is translated by the network analysis

Table 2. *List of Risk Factors Used to Calculate Exposition Risk*

Risk factor by Municipality (by commune)	Source
National administrative division	National Office of Food Safety[38]
Animal density (Bovines, Ovines, Goats)	Gridded Livestock of the World, GLW4[39]
Roads density (accessibility)	Calculated by « GIS », inspired by Nelson[40]
Movement structure: Communties	Network analysis of the national sheep mobility database
Cohesion structure: «Strong component»	Network analysis of the national sheep mobility database
Centrality indicators: incoming links or «Indegree»	Network analysis of the national sheep mobility database

method into centrality indicators and cohesion structures that give meaning to all these movements. After testing the different indicators and structures calculated by the network analysis method, the risk of diffusion in the Moroccan context appears best explained by the combination of three of them, especially, the communities, the strong component, and the inbound links. The calculation of this risk is also based on data from administrative subdivisions (municipal level), animal density, in particular those of sheep, goats, and cattle, but also on road density or accessibility data (Table 2). The quantitative data of risk factors were divided into equal quantile classes, corresponding to four risk levels.

Risks Characterization

For Peste de Petits Ruminants

"Very high" risk (4): Municipality belonging to one of the communities and part of the strong component, or municipality belonging to one of the communities and with very high accessibility, or municipality belonging to one of the communities, with very high accessibility and whose density of small ruminants is very high, or commune belonging to one of the communities and whose density of goats is very high, or commune belonging to one of the communities and whose the number of incoming links is very high.

"High" risk (3): Municipality belonging to one of the communities and whose accessibility is high, or municipality belonging to one of the communities and whose density of small ruminants is high, or municipality belonging to one community and with a high number of inbound links.

"Low" risk (2): Municipality belonging to one of the communities and whose accessibility is low, or municipality belonging to one of the communities and whose density of small ruminants is low, or municipality belonging to one of the communities and whose number of incoming links is low.

"Negligible" risk (1): Municipality belonging to one of the communities and whose accessibility is negligible, or municipality belonging to one of the communities and whose density of small ruminants is negligible, or municipality belonging to one community and whose number of incoming links is negligible.

Foot and Mouth Diseases

"Very high" risk (4): Municipality belonging to one of the communities and part of the strong component, or municipality belonging to one of the communities and having very high accessibility, or municipality whose accessibility is very high, or commune belonging to one of the communities and whose total density of ruminants is very high, or commune belonging to one of the communities and whose bovine density is very high, or commune belonging to one of the communities and whose number of incoming links is very high.

"High" risk (3): Municipality belonging to one of the communities and whose accessibility is high, or municipality belonging to one of the communities and whose total density of ruminants is high, or municipality belonging to one community and whose bovine density is high, or common belonging to one of the communities and whose number of incoming links is very high.

"Low" risk (2): Municipality belonging to one of the communities and whose accessibility is low, or municipality belonging to one of the communities and whose total density of ruminants is low, or municipality belonging to one community and whose bovine density is low, or municipality belonging to one community and whose number of incoming links is low.

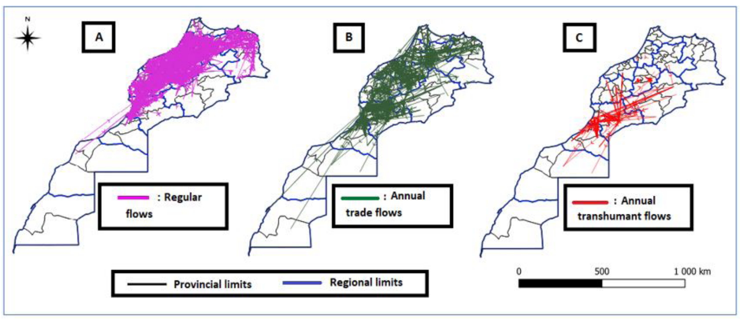
"Negligible" risk (1): Municipality belonging to one of the communities and whose accessibility is negligible, or municipality belonging to one of the communities and whose total density of ruminants is negligible, or municipality belonging to one community and whose bovine density is negligible, or municipality belonging to one community and whose number of incoming links is negligible.

RESULTS AND INTERPRETATIONS

Movements Mapping

Regular movements: Regular movements constitute a dense network ensuring connections between different regions of the country (Figure 2A). These movements represent 84.3% of all movements. They are composed of 71.15% weekly flows, to which are added 27.26% monthly flows, while other flows such as daily, quarterly, and

Figure 2. *Importance and Extent of Flows*



A: *Regular commercial flows.* ***B:*** *Annual commercial flows.* ***C:*** *Transhumant flows.*

bi-weekly movements represent only 1.59% of the total flows.

Annual irregular movements: The annual movements which bring both the movements of commercial preparations for the festivities (Figure 2B) and the periodic transhumance movements (Figure 2C) represent only 15.7% of the total movements. Commercial movements extend over all regions of the Kingdom, they can have large ranges allowing them to reach the southern regions, but also to go up from the provinces located in the extreme south of the country. As for transhumance movements, we distinguish between small amplitude transhumance movements that take place within the same province and which concern four provinces in the northern half of the country, as well as large amplitude transhumance movements of inter-regional scope that go back from the South or which descend from certain arid regions towards the region of "Sous-Massa" which joins the southern half of the country to its northern half.

Network Analysis

a. Global measures

Comparison of descriptive network parameters between festive periods and periods of regular movements

The descriptive parameters of the network during the festive period "R1" and the regular period "R2" are described below, their respective values are recorded in Table 3.

Table 3. *Network Description Parameters during the Fetivity Period R1and during the Regular Period R2*

Paramètre	Value R1	Value R2
Number of nodes/Size (length)	716	636
Number of links	3016	2524
Length (average distance)	4.694	4.755
Diameter	12	13
Density	0.0055	0.0058
Réciprocity	0.265	0.281
Transitivity (Clustering Coefficient)	0.206	0.214
Heterogeneity Coefficient Kappa for indegree»[a]	3.377	3.301
Heterogeneity Coefficient Kappa for outdegree»[a]	2.571	2.528
Weak components number	4	7
Strong components number	398[b]	351[c]
Strong components size	319	286
Modularity Cluster Fast Greedy» (Qcfg)	0.60	0.64
Modularity Edge Betweenness» (Qeb)	0.14	0.214
Cutpoints	68	63

[a]: *Kappa=<K^2>/<k>^2 where < > indicates the mean value and k is both the «indegree» and «outdegree».*
[b]: *Each isolated node not belonging to the 2 groups of strong components is also considered on its own as a strong component (716-(319)=397 isolated nodes+1 strong component=398 strong components).*
[c]: *Strong component «R2» : (636-(286)=350 isolated nodes+1 strong component=351 strong components).*

Number of nodes and links: During preparation periods for the festivities, the network includes 716 municipalities and 3016 links, which are reduced to 636 municipalities and 2524 links during regular periods.

Average distance and diameter: The average distance and diameter, which provide information on the ease of exchange of network nodes, show that the distance traveled by diseases can be relatively shorter during festive periods.

Density: The low density shows that among all the possible links that must be established between all the nodes of the network, there are only 0.55% established during the festive period and 0.58% during the regular period.

Reciprocity: Reciprocity indicates that in 26.5% of cases during festive periods and 28.1% of cases during regular periods, movements between municipalities are in both directions.

Transitivity: Transitivity shows that in 20.6% of cases during the festive period, when a municipality is linked to two others, the latter two are also linked to each other, while this concerns 21.4% of cases during the regular period.

The "Components": During the festive period the network is made up of four (4) "weak components" which means that diseases do not find a path to spread through their components, whereas, within one of these structures, there are municipalities which are strongly connected in subgroups of a size of 319 municipalities which can be reached by movement, corresponding to the "strong component". In regular periods, the composition of the network of seven (7) "weak components" increases its degree of fragmentation, while the size of its "strong component" is reduced to a size of 286 municipalities.

Network type

The distribution of the "indegree" and the "outdegree" centrality indicators is used to characterize networks and determine how connectivity is distributed within the structure. The values of the Kappa heterogeneity coefficient (Table 3) show that these are heterogeneous networks. This reveals that many nodes are weakly connected, while few others concentrate a high number of connections on their own.

b. Local measures

The local measures concerned measurement of "indegree" incoming links, of "outdegree" outgoing links, as well as the measurement of the crossroads importance of the node expressed by the "Betweenness" centrality. Due to the high number of municipalities, only the top ten in the ranking will be discussed.

During festivity and transhumance periods: Figure 3 shows that the municipalities of Timahdite (outdegree=49) and Azrou (outdegree=44) appear as the two largest sheep suppliers in the Kingdom, they are considered the most important "super spreaders" of the

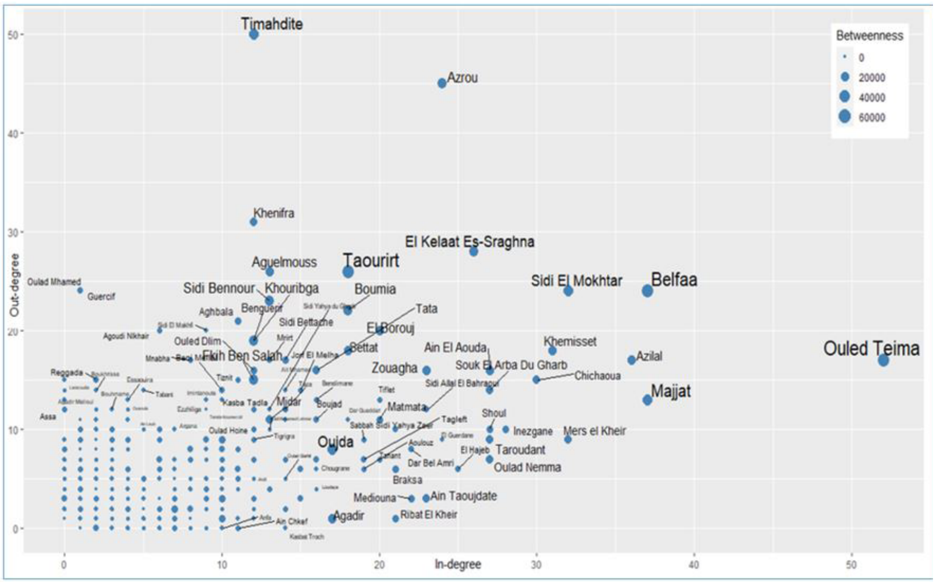


Figure 3. *Representation of Municipalities According to their Outgoing Links "Outdegree", their Incoming Links "Indegree" and their Importance as a "Betweenness" Crossroads*

network in cases of epizootic, they are followed at a distance by the municipalities of Khenifra (outdegree=30), El Kelaa des Sraghna (outdegree=28), Aguelmouss (outdegree=25), Taourirt (outdegree=25), Belfaa (outdegree=24), Guercif (outdegree=24), Sid el Mokhtar (outdegree=23) and Oulad Mhamed (outdegree=23), while the commune of Ouled Teima (indegree=52) represents the most popular destination on the network, followed by Belfaa (indegree=37), Majjat (indegree=36), Azilal (indegree=35), Mers El Kheir (indegree=32), Sidi El Mokhtar (indegree=31), Khemisset (indegree=30), Chichaoua (indegree=29), Inezgane (indegree=27) and Taroudant (indegree=27).

Certain municipalities with high incoming flows and zero or low outgoing flows are the most susceptible to contamination, such as Ain Chkef (indegree=11; outdegree=0), Kasbat troch (indegree=14; outdegree=0), Ribat El Kheir (indegree=20; outdegree=0), Agadir (indegree=17; outdegree=1), Mediouna (indegree=22; outdegree=3), Ain Taoujdate (indegree=22; outdegree=2) and El Hajeb (indegree=25; outdegree=6).

The commune of Belfaa (Betweenness=42582.33) is the largest crossroads in the country, followed by El Kelaa des Sraghna (Betweenness=27392.75), Zouagha (Betweenness=20444.98), Azilal (Betweenness=19860.89), Ouled Teima (Betweenness=18889.08), Azrou (Betweenness=18552.74), Taourirt (Betweenness=17791.34), Settat (Betweenness=16334.98), Khouribga (Betweenness=15990.16) and Sid El Mokhtar (Betweenness=15152.48).

In regular periods: During the regular period, except for the municipality of Ouled Teima which lost 24 incoming links, and Taroudant which lost 10, the other municipalities saw their incoming links reduced from two (2) to six (6) links each, except the commune of Mers El Kheir which maintained its supplies constant during both periods.

Concerning outgoing links, the ranking has almost not changed. The municipalities lost between two (2) and five (5) outgoing links each, except for Ouled Mhamed who lost seven (7), and Boumia who lost none, which allowed the latter to go back to the ranking, while Ouled Mhamed fell in the ranking of suppliers in the regular period. The commune of Boumia therefore manages to supply the communes with which it is in contact with a constant potential during the different periods of the year.

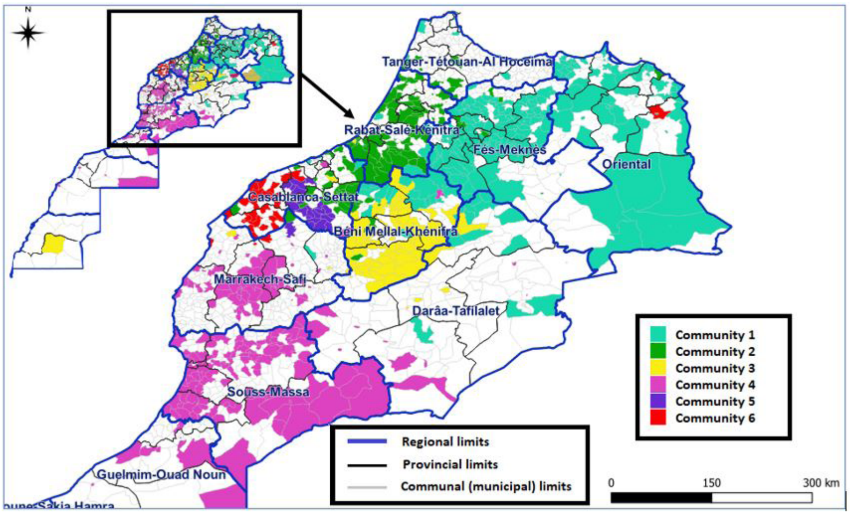
The commune of Belfaa (Betweenness=29500) maintains its status as the largest crossroads in the country during regular periods, followed by Azrou (Betweenness=22500), El Kelaa de Sraghna (Betweenness=22200), Taourirt (Betweenness=15700), Settat (Betweenness=15200), Sid El Mokhtar (Betweenness=15100), Zouagha (Betweenness=14840), Khemisset (Betweenness=14300), Mrirt (Betweenness=13800) and Azilal (Betweenness=13500). The high value of Azrou shows that this municipality is much more essential for journeys during regular periods than during festive periods, while the opposite applies to other municipalities which become much more essential during festive periods, while the commune of Sid El Mokhtar kept the same value during the two periods.

c.Detection of community structures

During holiday and transhumance periods

Six communities of municipalities of epidemiological interest were identified following the analysis (Figure 4):

Figure 4. *Location and Extent of Community Structures during Festive Periods*



Community 1: "*Eastern border and Central Community*": This is the largest community identified, made up of 241 municipalities, almost extending across the provinces of the Oriental region and those from the Fes-Meknès region. It includes neighborhood extensions at the level of two regions including the region of Béni-Mellal-Khenifra (notably through the provinces of Khenifra, Khouribga, and Beni-Mellal), and the region of Draa Tafilalet (notably through its province Midelt). This community also includes extensions with four other geographically distant regions, but immediately connected to it by movement: Tangier-Tétouan-Al Hoceima (Provinces of Tangier, Tétouan and Larache), Rabat-Salé-Kenitra (provinces of Kenitra and Khemisset), Casa-Settat (provinces of Benslimane and Casa) and Marrakech-Safi (Province of El Kelaa des Sraghna).

Community 2: "*Northwest Community*": Represents the second largest community identified in the northern half of Morocco. Its 119 municipalities are mainly located in the region of Rabat-Salé-Kénitra, in continuity with Casa-Settat and Tangier-Tétouan-Al Hoceima as an immediate geographical neighborhood. Its upstream dependencies mix with the community of the "Easter border and Center" in the regions of Oriental (province of Berkane), Fès-Meknès (provinces of Fés, My Yaakoub, and Taounate) and Béni-Mellal-Khenifra (Khouribga province).

Community 3: "*Community of Béni-Mellal-Khenifra*": With its 86 municipalities mainly located in the region of Béni-Mellal-Khenifra, it is the 3rd largest community in the north of the country. Its extensions intersect with other communities in the neighboring regions of Rabat-Salé-Kenitra (province of Skhirate-Temara), Casa-Settat (provinces of Berrechid and Mediouna), Marrakech-Safi (provinces of Safi and El Kelaa) and Draa Tafilalet (provinces of Midelt and Tinghir), while a final extension reaches the region of Dakhla-Oued Eddahab in the extreme south of the country (province of Aousserd).

Community 4: "*Southern Community*": With a size of 180 communes, it extends over the regions of Marrakech-Safi, Sous-Massa, and Guelmim-Oued-Noun, with extensions to the regions of Casa-Settat (provinces of Settat and Mediouna), Beni-Mellal-Khenifra (province of Khenifra), Draa Tafilalet (provinces of Ouarzazate, Zagora and Errachidia) and Laayoun-Sakia El Hamra (provinces of Boujdour, Laayoune and Smara).

Community 5: "*Community of Settat-Berrechid*": This is a community essentially located in the provinces of Settat and Berrechid falling within the region of Casa-Settat, with an extension located in the province of Rehamna in the neighboring region of Marrakech Safi.

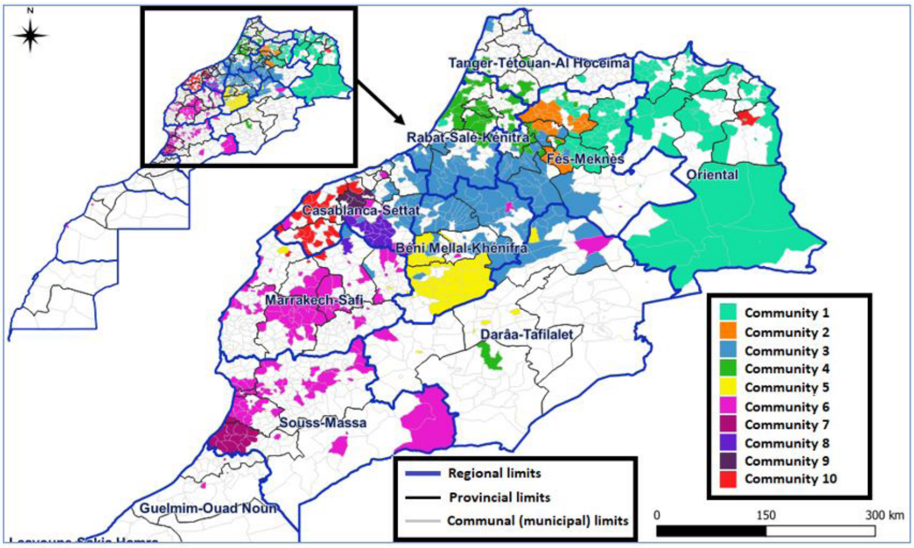
Community 6: "*Community of Sidi Bennour-El Jadida*": Covering the provinces of Sidi Bennour and El Jadida, this community of 31 communes shows extensions to the bordering provinces of Berrechid, Rehamna, Safi and Youssoufiya, while she has a dependency on the province of Jerada in the Oriental region, which puts it in close contact with several municipalities in the "*Eastern border and Center*" community.

In regular periods

During periods of regular movements, we notice that the size of communities has decreased (Figure 5). Indeed, these communities split into independent communities which grow up from six communities during the festivity period to ten communities during the regular period. Thus, ex-community "1" which attracts movements from the Eastern borders, has been reorganized into three new communities (communities "1", "2" and "3"). Its the same for ex-community "2" of the "North-West" which lost municipalities like ex-community "1", in favor of a new emerging community, the current community "3". Concerning the ex-community "5" of Settat-Berrechid, it split into two communities each located in one of these two provinces, the current communities "8" and "9", while the ex-community "4" located further south split into the current communities "6" and "7".

It thus appears that in regular periods, the absence of

Figure 5. *Location and Extent of Community Structures during Regular Periods*



annual movements favors an increase in the number of communities which consequently contribute to limit the diseases spread for relatively longer at their level.

Cohesion structures

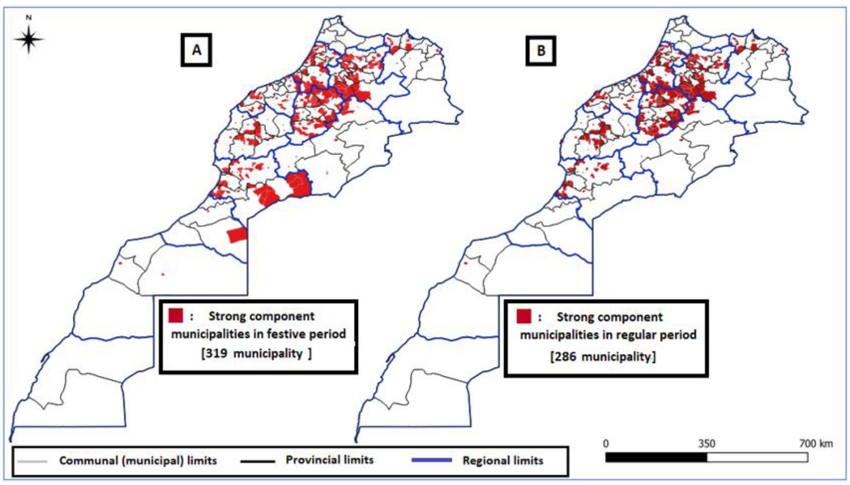
"Strong component": Despite the fact that this cohesive structure for which a movement starting from each node can reach all the others, has lost 33 municipalities of its initial size by moving from the festive period (319 municipalities) (Figure 6A) to the regular period (286 municipalities) (Figure 6B), some towards its center and others towards its southern extent, it appears to keep the same basic structure between the two periods.

Cutpoints: Cutpoints are of great interest in stopping the diseases transmission between communities. They allows to fragment the network by neutralizing the contact points between these structures. As illustrated example in Figure 7, prohibition of exiting movements from Taourirt municipality cutpoint neutralize contaminating flows that can affect communities 2 and 4. During periods of festivities and transhumance, sixty-eight (68) "cutpoints", corresponding to 68 communes, were found (Figure 7), while during regular periods sixty-three (63) "cutpoints" communes were highlited. Action at these cutoff points prevent outbreaks from passing between different communities.

Analysing the 2008 PPR Epizootic Spread in Morocco with Regard to Movement Structures

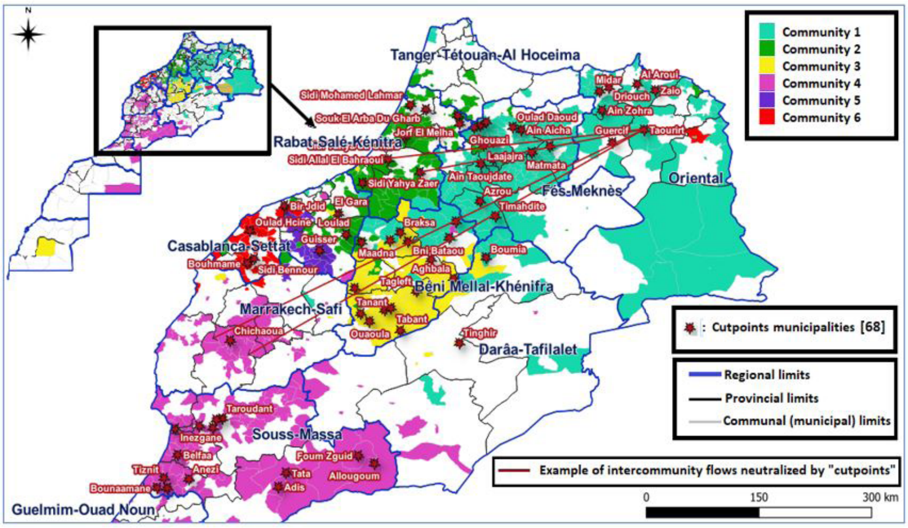
The appearance of the PPR epizootic on July 14, 2008 in Mo-

Figure 6. *Size and Scope of the Strong Component*



***A:** During the festive period. **B:** During regular periods*

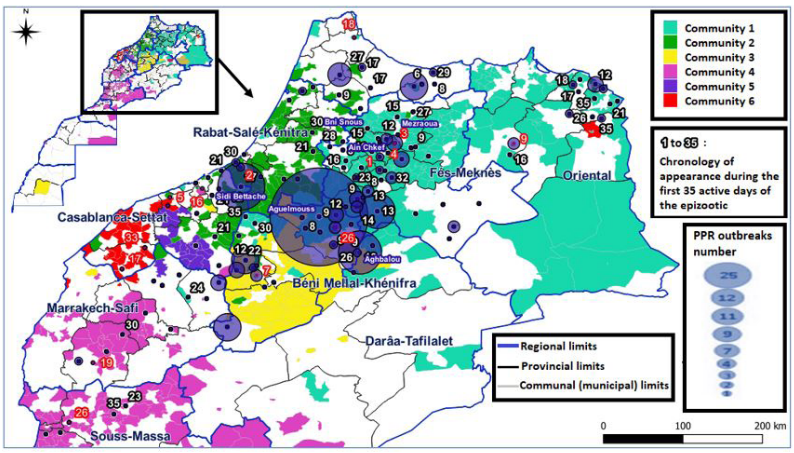
Figure 7. *Location of the "cutpoint" Municipalities of the Movement Network during the Festive Period*



rocco coincided with the period of preparation of breeders for the sheep sacrifice festivity which took place lately in December.[4] This period of preparation is characterized by the establishment of small ruminant's annual movements intended for fattening which are added to other regular movements of the commercial network. This period is also characterized by the establishment of transhumance movements which take place from April to September[5] and which are also added to the network. Consequently, in order to put the epizootic in its 2008 mobility context, the network model during periods of celebration and transhumance was retained for the analysis of the outbreaks.

Chronology of outbreaks and communities: For the sake of map visibility, only the labels of the outbreaks, corresponding to the first 35 active days of the epizootic, were represented for this chronological analysis (Figure 8).

Figure 8. *Chronology of Outbreaks and their Importance at the Community Level*



Thus, in 2008, despite the fact that the PPR epizootic was introduced across the eastern borders of the country, the first outbreak was notified towards the northern center of the Kingdom in the region of Fes-Meknès, commune of Ain Chkef. This municipality (commune) belongs actually to community "1" which is the only community encompassing the eastern border municipalities and therefore the first to have allowed the passage of the disease. The extensions of community "1" to other distant regions allowed the appearance of the second outbreak in the region of Casa-Settat, commune of Sidi Bettache, as well as the outbreak of the 18th active days of the epizootic in the Tangier-Tétouan-Al Hoceima region. The occurence of the 4th outbreak in the Fes-Meknes region within a commune of community "1" with immediate proximity to a commune of community "2" was followed by the appearance of a first outbreak at the level of community "2" in the region of "Casa-Settat" on the 5th active day of the epizootic.

Community "3" showing a broad close relationship with community "1" in the Beni-Mellal-Khenifra region was affected on the 7th day. It was only from the 9th day that the disease broke out in the Oriental region, which nevertheless allowed the initial passage of the disease. Community "4" was affected late on the 16th day at one of its extensions located in the Casa-Settat region and located in the immediate vicinity of a commune belonging to community "2", which allowed the disease to begin to spread further south from the 19th day. Another crossing point towards community "4" located in the Béni-Mellal Khenifra region (Khenifra province), affected on the 26th day, was followed the same day by the declaration of the disease at community "4" in the region of Sous-Massa. As for community "6" which has a dependency in the Oriental region, it only showed outbreaks on the 17th and 33rd day of the epizootic.

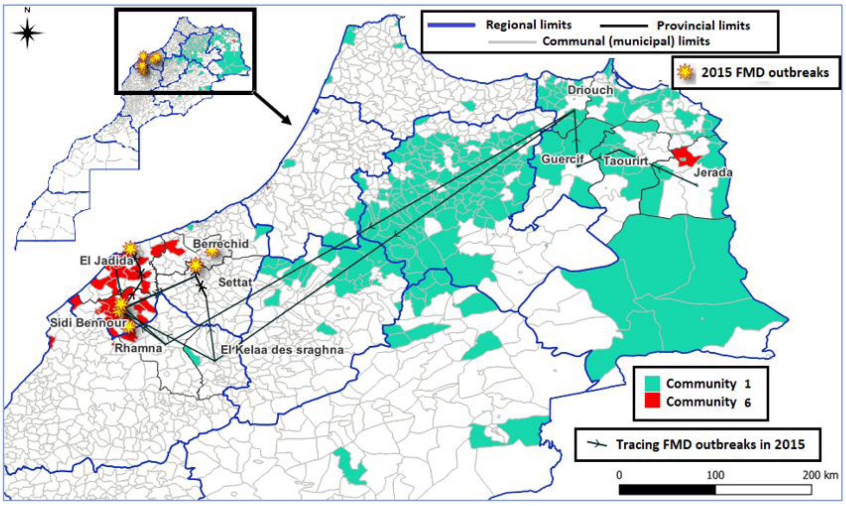
Importance of outbreaks and communities: Figure 8 illustrates the importance of outbreaks at the community level. Thus, among the 257 outbreaks of the epizootic, 74.71% are included in communities, while 21.79% are located in a municipality immediately adjacent to one of the communities, while 3.5% belong to municipalities which are not adjacent to these communities, but the distance separating them does not exceed 1.6 km. Concerning the 192 outbreaks included in the communities, 62.5% of them are included in community "1", 15.6% are in community "3", 13% are in community "2", 7.3% are in community "4", while only 1% and 0.5% are in the respective communities "6" and "5".

Importance of outbreaks and strong component: The strong component of the network, with a size of 319 municipalities during the festive period, includes only 15.36% municipalities reporting outbreaks, hosting half of the outbreaks of the PPR epizootic of 2008 (49.02% of the outbreaks). This structure, which is very united through movement and which communicates with all the other communities, plays an important role in the propagation of epizootics at its level and at the network level through this contact with the different communities.

Analysing FMD Epizootics Diffusion with Regard to Movement Structures

Epizootic of 2015: The 2015 FMD epizootic that appeared on 28 October, affected only bovine species and generated 57 bovine cases, and was characterized by the occurrence of six outbreaks in six municipalities belonging to four provinces very distant geographically from the introduction area of the disease, identified by phylogenetic analysis as being the eastern borders of the Kingdom, without leaving any traces upstream. The tracing of outbreaks *via* the sheep mobility database by the National Office of Food Safety during this year[41] (Figure 9) highlighted the possible paths that could have given rise to these outbreaks, assuming that they were carried out by intermediaries who transported their infected animals from the province of "Jerada" through the markets until the contaminated sheep were able to come into contact with naive animals on farms in the province of Sidi Bennour which is one of the at-risk areas with high bovine concentration.[10]

Figure 9. *Comparison of the Mapping Approach and the Action of Community Structures in Tracing Outbreaks of Foot and Mouth Disease in 2015*



Using the network analysis method, the obtained results of the present study, confirm what was previously found by the movement mapping, as well as the precise origin of the municipality at the origin of the path located in the province of Jerada. The analysis also highlights the overlap of the two communities at its level which gives access to the municipalities of the province of Sidi Bennour.

Epizootic of 2019: The disease, which generated 46 outbreaks in total, was declared in bovine species on January 5, approximately seven months before the feast of the sacrifice which took place on August 12. The extreme contagiousness of this disease associated with livestock movements allow it to spread during the six months of preparation for this religious event until July 25, while widespread vaccination was launched since January 18. The outbreaks affected 36 farms

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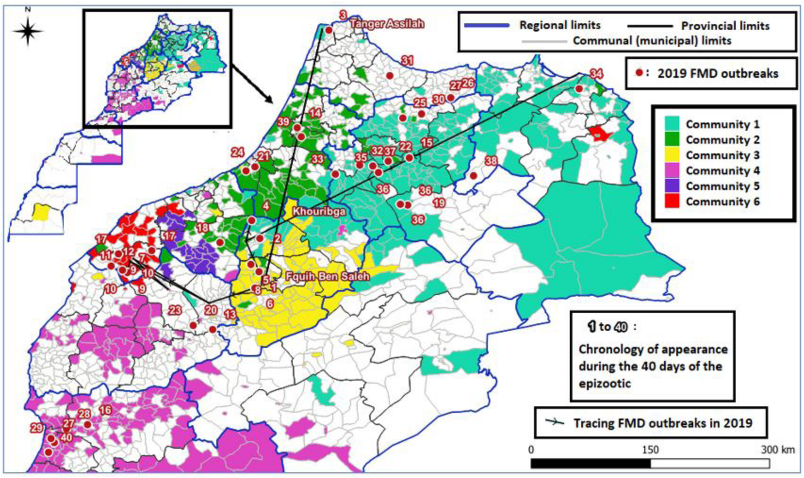
spread across 30 municipalities belonging to 18 provinces with a morbidity rate of 22.86% and a mortality rate of 0.92%. While in the sheep species, the disease was confirmed on May 3, 2019, before it affected the goat species. In small ruminants, the disease affected 10 farms spread across 9 municipalities in 5 provinces with a morbidity rate of 14.91% in sheep and 5.83% in goats, while the mortality rate was 6.68% in sheep and 4.13% in goats.[3]

During the FMD epizootic of 2019, the tracing of the first outbreaks by the National Office of Food Safety[42] (Figure 10) highlighted the only possible route from the Oriental to this region, which elects destination at the level of the province of Khouribga. Indeed, even if the first outbreak was notified in the province of Fquih Ben Saleh, it passed through the province of Khouribga. The occurence of the 2nd and 4th outbreaks at the level of the latter, as well as the chronological propagation profile which followed, including the declaration of the 3rd outbreak at the level of the province of Tangier-Assilah, the passage of other outbreaks at the level of the province of Fquih Ben Saleh (5th, 6th and 8th outbreak) and the transmission of the disease to the province of Sidi Bennour could all be mapped from existing routes which were able to show that the direction of transmission from the Oriental, reached the province of Khouribga, crossing Fquih Ben Saleh before reaching Sidi Bennour.

Figure 10. *Comparison of the Cartographic Approach and the Action of Community Structures in Tracing Outbreaks of Foot and Mouth Disease in 2019*



The results of the network analysis concerning this study support what was found during the tracing of this epizootic, since the province of Khouribga turns out to be the only affected province comprising municipalities belonging to border community "1", but comprising also communes of community "3" which allow the disease transmission to the province of Fquih Ben Saleh by contact. The early affection of the province of Tangier-Assilah is due to the fact that it belongs to border community "1", while the transition to community "6" could have been done through Khouribga or Fquih Ben Saleh which share elements of community "2" which come into contact with community "6", as for the transition to community "4" in the South, it could have been achieved by contact through one of its extensions which is immediately adjacent to the province of Fquih Ben Saleh.

Concerning the strong component, it count only 3.13% of its municipalities reporting outbreaks and was only able to capture 23.91% of outbreaks during this epizootic.

Diseases Risk Mapping

Introduction risk: The risk of introducing diseases through borders, based on the risk of transmission from neighboring countries as well as the risk of external diffusion from border municipalities (ease of road accessibility), reveals a low risk along borders, except for the provinces of Berkane, Oujda-Angad, and Jerada whose border municipalities are accessible to very accessible. This risk, not based on cross-border movements, concerns the risk of the introduction of PPR and FMD through ruminant species, particularly sheep, in the form of illicit journeys facilitated by road accessibility (Figure 11).

Risk of exposure

Exposure risk to PPR: We note that 82.88% of outbreaks are included in municipalities with a high to very high-risk of exposure. Thus, among the 257 outbreaks of the epizootic, 60.70% are included in municipalities with a very high-risk of exposure and 22.18% are in municipalities with a high-risk of exposure, while 13.62% are in municipalities immediately adjacent to municipalities at high or very high-risk or both, while 3.50% are located in municipalities which are not adjacent to the latter, while the distance separating them does not exceed 1.6 km (Figure 12).

Exposure risk to FMD: The exposure risk map to FMD shows that 67.39% of outbreaks are included in municipalities at high to very

Figure 11. *Risk Map for the Introduction of Ruminant Diseases at Borders*

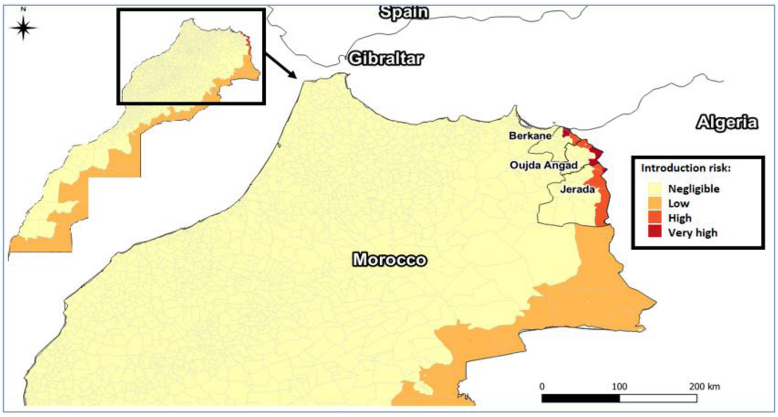
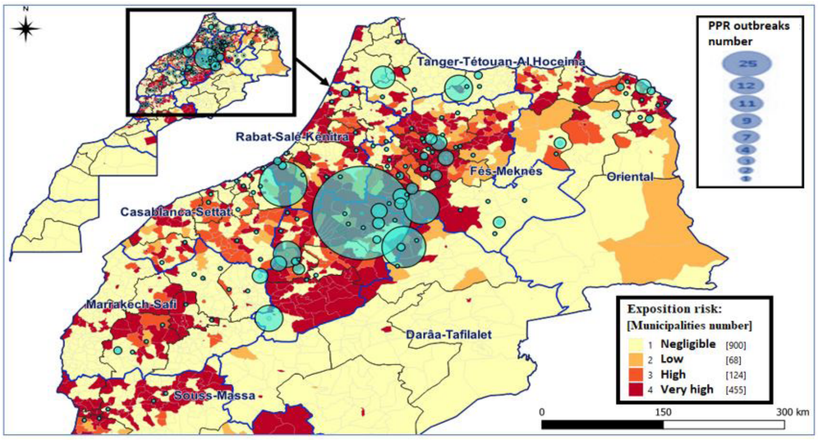
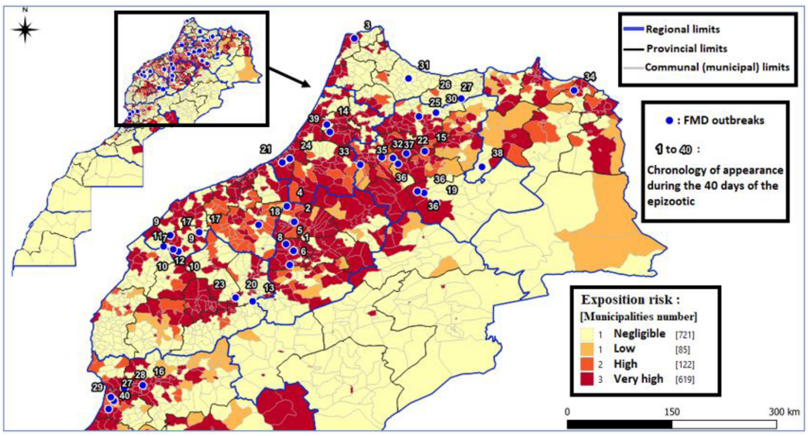


Figure 12. *Risk Map for Exposure to Peste des Petits Ruminants*



high-risk. Indeed, 56.52% of outbreaks are included in municipalities with very high-risk, while 10.87% of these were included in municipalities with high-risk and 23.91% were located in municipalities immediately adjacent to those with high-risk or very high, while only 8.69% of outbreaks were not adjacent to municipalities at risk (Figure 13).

Figure 13. *Foot and Mouth Disease Exposure Risk Map*



DISCUSSION

The sheep movements network in Morocco, in its two periodic forms, shows a heterogeneous structure for which few nodes are connected to many others and strongly influence their movements. Its densities of 0.55% during the festive period (716 nodes) and 0.58% during the regular period (636 nodes) are 3.27 times lower than the density found by Bezeid (1.8%) on the national ruminant network in Mauritania (90 nodes) in 2016,[44] while the values found by Rautureau in 2012 on cattle mobility networks in mainland France (244,097 nodes) were even lower (from 1.40.10-4 to 6.68.10-4).[19] These differences show that in heterogeneous type networks, even if the number of nodes increases, new connections are made preferentially with the nodes which are the most connected,[12] thus leading to a reduction in the network value of density. The network diameter, comprising a value of 12 during the festive period and 13 during the regular period, is wider than that found by Bezaid (d=9),[43] it is however much shorter than the values found by Rautureau which varied from 16-27.[19] Which indicates that in Morocco, diseases have a longer distance to travel before being able to spread to the most distant municipalities compared to Mauritania, but also that in regular periods the spread is less rapid than during the festive period. Reciprocity indicates that contamination can only happen in both directions in 26.5% of cases during festive periods and 28.1% of cases during regular periods due to the unavailability of reverse paths throughout the network, while transitivity shows that in 20.6% of cases during the festive period and 21.4% of cases during the regular period, when a municipality is linked to two others, the latter two are also linked to each other. These latter parameters appear to be weak throughout the network, but can contribute locally to the circulation, persistence and reintroduction of outbreaks in certain municipalities. Finally, the cohesion parameters assessment at the network scale places the latter in the category of heterogeneous networks which can show an early appearance of diseases and a very virulent diffusion of the latter, but for a relatively short duration compared to the others types of networks.[12]

The centrality parameters of certain municipalities make them particularly at risk of being affected by outbreaks, such as the municipality of Ain Chkef which has 11 incoming links and zero outgoing links, which allowed it to host the first outbreak of PPR of the network (two outbreaks in total), and the commune of Ain Kansara which captured the 3rd outbreak of the network with 11 incoming links and a single outgoing link (4 outbreaks in total), while other communes such as Timahdite, Aguelmous and Sidi Bettache manage to capture outbreaks due to their high betweenness centrality values which exceed largely the average of this parameter (m=1177.4). However, it would be important to specify that despite the high centrality values of certain municipalities, the latter are unable to capture outbreaks of epizootics, even though they play an important role in the transmission of diseases on a network scale, this could be explained during field surveys by the fact that local breeders in certain municipalities prefer to obtain supplies from markets other than those of their municipality of origin when this latter drains flows of different origins in order to avoid introducing diseases into their livestock.

The communities of municipalities identified in Morocco, which define themselves as being particularly interconnected and weakly connected to the rest of the network,[44] play a crucial role in the transmission of diseases across the country. There are ten (10) in regular periods, that manage to contain diseases at their level as long as conditions do not allow them to spread to other communities. During periods of festivities and transhumance, they merge under the effect of annual movements, particularly long-range ones, to be reduced to six (6) larger and more extensive communities, in the same way as the degree of fragmentation of the network which goes from 7 to 4 components (weak components). Indeed, among the 257 outbreaks of the PPR epizootic, 74.71% are included in communities, 21.79% are located in a municipality immediately adjacent to a community, and the remaining 3.5% are separated by only 1.6 km. The extent of community "1" which is at the origin of the introduction of diseases from the eastern borders and their dissemination, includes during the festive period three (3) large regions by the immediate geographical proximity of its municipalities, and five (5) other regions more geographically distant, but nevertheless connected by direct movements. This community alone hosted 62.5% of the outbreaks included in the communities during the PPR epizootic of 2008. From the chronology of the PPR outbreaks of 2008[1] and the FMD of 2019,[3] it appears that the disease tends to spread primarily at the level of the community which is at the origin of its introduction, before affecting other municipalities as observed by Valerio et al in 2020,[45] the passage from one community to another is done by proximity at the level of contact communes allowing jumps from one community to another and which can sometimes be carried out over a long distance, this passage is also conditioned by the action of the strong component, called the predictor of the final sizes of epizootics,[17] for which all nodes are strongly connected and can reach each other. For this latter, only 15.36% of municipalities of 319 were concerned by 2008 PPR outbreaks, and only 3.13% of its municipalities were concerned by the 2019 FMD outbreaks even if having extensions to the various identified communities. Indeed, in 2008, in addition to the efforts deployed on the field to control outbreaks by Moroccan veterinary services, including health police around outbreaks and medical prophylaxis measures consisting of perifocal vaccination followed by its generalization, an aid to control this invasive cross-border animal disease was deployed by the Food and Agriculture Organization (FAO) Animal Health Crisis Management Center (CMC-AH).[4] While in 2015 and 2019, the health police measures were much stricter and vaccination was deployed earlier with regard to this extremely contagious disease, including perifocal and generalised vaccination, slaughtering and destruction of infected and cohabiting animals, prohibition on entry and exit of animals susceptible to the disease as well as their products, ban on animal movements, animal gatherings as well as the closure of souks.[2,3] That explains the reason why the strong component was not entirely invaded by outbreaks.

The spread of outbreaks in contaminated communities occurs at a relatively slower speed than the community at the origin of the introduction of the disease which shows a rapid spread of outbreaks. This was observed during the PPR epizootic by Diallo and Campo in 2008[46] in the Middle Atlas, which was identified by this study as belonging to the border community that introduced the diseases.

The identification of border community "1" with its large extent and its extensions gives now much more meaning to the appearance of the first outbreaks of diseases inside the country.[1,3] The same goes for the community "6" of "Sidi Bennour-El Jadida" which was able to ensure the transmission of FMD[2] from the Oriental in 2015 through its only dependency located in the province of Jerada. Tracing the introduction of FMD outbreaks in 2015 and 2019 through movement mapping[41,42] leads to the same conclusions provided by the network analysis method regarding the spread of diseases *via* community structures (Figures 9 and 10).

The results of this study confirm those of our previous study[7] which demonstrated a strong exchange relationship between breeders in the Middle Atlas (Timahdite, Azrou, Khenifra, Aguelmouss, etc.) and fatteners in the commune of Sidi Bettache. Indeed, the breeders of these municipalities who had accumulated around 100 outbreaks alone appear to be deeply linked by the most important structure of network cohesion which is the strong component. The results of this study also allow us to have a more global view of what was found in 2019 since this group of municipalities also turns out to be part of the same large community which is at the origin of the introduction of disease from the eastern borders.

The calculation of the "cutpoints" highlighted 63 strategic municipalities during the regular period and 68 others during the festive period which ensured passage between the different communities. These municipalities represent the strategic points at which action should be taken to neutralize the passage of pathogens between these communities. Indeed, Salathe and Jones, who focused in 2010 on networks with several communities, show that on such networks, intervention strategies targeting individuals bridging several communities are much more effective than those that focus only on the most strongly connected individuals.[47]

The risk of introducing transboundary animal diseases into Morocco appears essentially linked to the possibilities of illicit introductions across its eastern borders, it concerns diseases coming from Africa and those coming from Asia and passing in the form of informal flows across the countries of North Africa.[48] This risk appears to be closely linked to border municipalities dependent on three provinces in the Oriental region. Indeed, the significant road accessibility of the provinces of Berkane, Oujda, and Jerada, compared to all the other border municipalities,[40] means that they are the most at-risk provinces of introducing infected animals from the eastern borders.

The dissemination of contagious diseases among ruminants in Morocco appears to be conditioned by various determinants, including the mobility ruminant network, in particular that of the sheep species which is the most mobile at the national level due to the fact that it represents cash flow that can be easily and quickly mobilized by breeders. The effect of road accessibility allows movements to access municipalities more or less easily, while the effect of animal density allows diffusion depending on the abundance of sensitive or receptive animals at the municipality level. Apart from the effect of animal density and road accessibility, the PPR risk map is based on the movement structures, which take into consideration the different field components, namely the passage through the gathering places represented by markets and the contribution of fattening and transhumant breeders in the network. As a result, and as advised by various authors, it seemed unnecessary to multiply the risk factors which could contribute to minimizing the real risk.[49] Having taken this subtle recommendation into account during our calculations, we see that 82.88% of outbreaks of the disease are included in municipalities at high to very high-risk of exposure. Indeed, it becomes obvious that among the 257 outbreaks of the epizootic, 60.70% are included in municipalities with a very high-risk of exposure 22.18% are in municipalities with a high-risk of exposure, while 13.62 % are in municipalities immediately adjacent to municipalities at high or very high-risk or both at the same time, while 3.50% are located in municipalities which are not adjacent to the latter, but whose distance separating them does not exceed however 1.6 km. These results were much more conclusive than our previous attempts to produce disease exposure risk maps[50] which included several risk factors (markets, fatteners, distance of 3 km and 10 km from a permanent water point, distance of 3 km and 10 km from a non-permanent water point, wells and boreholes, etc.), while some did not apply to the context of the field and others multiplied the risk already taken into account by the indicators and the movement structures.

Concerning the FMD risk map, 67.39% of outbreaks were included in the high to very high-risk strata. Indeed, 56.52% of outbreaks were included in municipalities at very high-risk, while 10.87% of these were included in municipalities at high-risk, and 23.91% were located in municipalities immediately adjacent to those including high or very high-risk. Outbreaks that were not adjacent to municipalities at risk represented only 8.69% of all outbreaks. Although the results were satisfactory with regard to the percentage of outbreaks captured by the model in its high to very high-risk strata, and the percentage of outbreaks which were included in municipalities with high to very high cattle density (76%),[10] which shows the important role of the sheep species in transmission, this also calls into question the fact that even if the sheep species is the most mobile at the national level and that its mobility strongly contributes to the spread of diseases among ruminants alongside the caprine species with which it lives in mixed herds,[7] a minimum knowledge of movements in the bovine species is necessary to achieve a better calibration of the diffusion risk of FMD at the national level.

CONCLUSION

In Morocco, it becomes evident that the sheep exchange network turns denser around festivity and transhumance periods. Indeed, the number of municipalities included in the network as well as the links connecting them greatly increased during this period which allowed the establishment of new movements including those of long range which increased the extent of community structures usually restricted and allowed diseases to be contained at their level.

Certain municipalities whose centrality of incoming activity "in-degree" is high while their centrality of outgoing activity is null or very low, are the most at risk of capturing disease outbreaks when they are also part of the community which was at the origin of its introduction. These are the municipalities of Ain Chkef, Ain Kansara, and Fes-Medina which respectively captured the 1st, the 3rd and the 4th outbreak of PPR in 2008. These municipalities should be subjected to close active surveillance throughout the year, especially concerning the commune of Fes-Medina which is part of the eastern border community throughout the year.

The strong component, commonly studied in network analysis as a predictor of the final sizes of epizootics, showing only 15.36% municipalities of 319 concerned by 2008 PPR outbreaks, indicates that considerable efforts were made by the Moroccan veterinarian's authorities in the field in order to stop the progression of the disease despite the 257 outbreaks declared. As for the 2019 FMD epizootic, the strong component registered only 3.13% of its municipalities concerned by outbreaks, which shows the considerable efforts that were made on the field to abort these epizootics earlier.

The use of disease introduction and exposition risk maps can prove to be of valuable use to decision-makers with a view to establishing targeted active surveillance, allowing them to early detect the introduction of cross-border diseases into the level of risk municipalities. To improve detection, surveillance should be done at shorter intervals during the 6 months of preparation for the festive period, namely Aid al Adha.

In order to prevent the pathogen's circulation between communities, cutpoints prove to be of strategic use in neutralizing the movements ensuring the link between these structures. They can also constitute a practical alternative for implementing active surveillance of PPR and FMD in sheep given their reduced number (68 municipalities during the festive period and 63 municipalities during the regular period) compared to municipalities at risk of exposure to these diseases which are part of the high and very high-risk strata, for which the number has been found be higher.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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