Mapping livestock movements in Sahelian Africa

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In dominant livestock systems of Sahelian countries herds have to move across the territories. Their mobility is often source of conflict with farmers of the crossed areas, and engender the spread of diseases such as Rift Valley Fever. Knowledge of the routes followed by herds is therefore central to guide the implementation of preventive and control measures for transboundary animal diseases, land use planning and conflict management. However, the lack of quantitative data on livestock movements, together with the high temporal and spatial variability of herd movements, has so far hampered the production of fine resolution maps of passage of animals. This paper proposes a general framework for mapping potential paths for livestock movements and identify areas of high potential of animal passage for these movements. The method consists in coupling the information contained in livestock mobility network with landscape connectivity based on different mobility conductance layers. We illustrate our approach with a livestock mobility network in Senegal and Mauritania in dry and wet seasons in 2014.

INTRODUCTION

Every year in West Africa, millions of animal leave the sahelian semi-arid regions, where they bred, toward southern regions looking for better grazing areas or to be sold at consumption markets [1, 2]. Northern regions are, in fact, historically dedicated to extensive livestock farming with important areas of pastoral lands, whereas large crop areas in south hamper the activity of herding during the rainy season. A network of markets has been developed and organized since the middle of the twenty century, where ruminants from northern Sahel are sold and then sent to capital cities of southern countries where most of red-meat is consumed [3, 4]. The animal trade mobility network between the occidental part of Sahel, Mauritania and Senegal concerns up to 1.9 million of bovines [5]. Less than 20% of these animal is conveyed by vehicle, specially commercial requests for religious feasts, the rest travels on foot, over a distance from one to three hundred kilometers [5].

These movements often cause conflicts with farmers, especially during the growing rainy season when animals could invade cultivated plots. These conflicts have become more and more common in the last years, because of the expansion of the cultivated areas and the consequent reduction of the area available for convoy’s passage [6, 7]. Livestock trade mobility is also a key driver of spread of animal diseases. Indeed, along their way, livestock could cross areas with high mosquito prevalence (lowlands, wetlands), that are vectors of diseases. The contact between animals, that occurs when livestock cross each other, also favors the transmission and the spread of diseases. Thus, animals can get infected by a virus at their arrival in a new area, and then introduce the disease into naive areas or promote the re-emergence. The Rift Valley Fever is an example of such transboundary diseases affecting Mauritania and Senegal, responsible for many losses in livestock [8–10].

Mapping movements patterns is thus essential to improve many aspects of the livestock management at regional and national level, as, for instance, the management of natural resources, the positioning of drilling installation, the reduction of conflicts, the control of animal disease [11]. The knowledge of convoys’ trajectories would make possible to develop high resolution maps displaying the risk of introduction and diffusion of infectious diseases. However, the intrinsic complexity of livestock mobility paths makes extremely tricky to map them. Indeed, the conveyance on foot enables to benefit from pastures and crops residues of southern regions in order to continue the fattening of animals along the journey. Thus, herdsmen daily decide the path to follow based on food and water locations. They favor tracks along roads to progress, but could decide several detours to cross pastures, plots with crops residues, ponds and drillings. At the border, large cattle herds will cross at official passage points, but the majority uses non-official points to avoid paying taxes or because they are more accessible [5], increasing the difficulty of mapping their paths.

A way to map livestock spatial distribution consists in working from census or estimation of the num-

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Figure 1. Methodology used to map potential paths livestock movements and identify area with a high potential for livestock movements from mobility network and land uses information.

We recently witnessed the emergence of network-based approach to study livestock movements [5, 11, 14, 15]. It consists in describing livestock movements as a directed and weighted spatial network where nodes represent villages, markets or premises and every link between two nodes represents at least one animal moving from one site to another. The weight of a link is equal to the total number of animals exchanged. In some ideal cases, the spatial pathway of the links is known thanks to a GPS tracking of animals [16], but in sahelian areas, such data is rarely available. Thus, the majority of studies on livestock network analysis do not spatialize animal pathways explicitly; flows give only information on the direction, distance and volume of the movements.

Here we propose a method to map livestock movements, by coupling the information contained in livestock mobility network with a landscape connectivity based approach. We illustrate our approach with a livestock mobility network in Mauritania and Senegal during dry and wet seasons in 2014. The next section introduces the proposed framework and the data used to illustrate our approach. Then, the results are presented, demonstrating the capacity and robustness of our approach to identify potential paths for livestock movement in Sahelian Africa. We finally discuss the advantages and limitations of our approach.

**MATERIAL AND METHODS**

This section describes in details the data and the methodology applied to map livestock movements from mobility network and land uses information (Figure 1).

**Mobility dynamics in Senegal and Mauritania**

Our study area encompasses the Senegal and the Mauritania, where a recent report estimates the total number of cattle to be between 2 and 3 million [17]. In Mauritania, rangelands are predominant, agricultural areas being limited to irrigable or flooded areas along the Senegal River and in oases. In Senegal, livestock farming are mostly located in Ferlo, a region of 70,000 km² in the north-east of the country, where climatic conditions do not allow the development of agricultural activity. A large part of the cattle spends the rainy season in this rangeland area, then move
toward the markets, or towards the crops residues of central and southern regions, especially in the groundnut basin of Senegal.

In Senegal and Mauritania, due to the absence of stocking infrastructures and slaughterhouses, animals are sold alive and moved between markets. Because of this, countries are interested by a continuous flow of animals. Animals traveling on foot often cross large areas before arriving at their final destination. Conveyors usually prefer to use tracks along the asphalted roads, which are often more direct and safer. They chose their pathways so that they can water the animals at least every other day, and go through range-lands or crop residues plots, so that they could continue to fatten the animals along the travel. During the rainy season, they try to avoid humid areas with muddy soils, or areas with high density of cultivated plots that could be damaged by animals.

Livestock mobility network

Livestock mobility data have been collected by field Veterinarian Services in Senegal, Gambia and Mauritania. In these countries, a certificate system based on sanitary movement permit (Sanitary “Laissez-Passer” or LPS) is set up to follow animal mobility and map the main axes of movements in the area. Every time herders move their herds towards markets or other grazing areas, a certificate is issued declaring among other information: the date, the origin and destination of the journey, the species and number of heads, the means of transportation. In this article we consider only information relative to cattle movements, on foot, during 2014. We aggregated data at the timescale of one month providing a representation of the mobility dynamics along the year. We used a network approach to analyze the mobility data where origin and destination locations correspond to nodes, and a link exists between two nodes if at least one animal is exchanged. A link is characterized by the number of heads exchanged (volume) and the month of occurrence. We distinguished the characteristics of the network during the wet (June to October) and the dry season (November to May).

Conductance maps

We used land use/land cover information and transportation features in Senegal and Mauritania to develop conductance maps represented as rasters at 500 meters resolution. Conductance is the reciprocal of resistance and represents therefore a greater ease of livestock movements. We assigned to each pixel of the conductance map a value according to its livestock movements propensity ranging from 0 (low conductance/high resistance) to 1 (high conductance/low resistance). More specifically, we applied an iterative process based on three different levels of information described below. Each geographical layer has been rasterized on the same extent with a pixel dimension of 500 × 500 m².
A walking layer based on land use and land cover information provided by the FAO (data available online at [http://www.fao.org](http://www.fao.org), last accessed 14/06/2019). The original classification has been aggregated in 14 land use types available in Figure 2 and Table 1.

The Senegal, Gambia and Mauritania’s main road network downloaded from OpenStreetMap (data available online at [https://www.openstreetmap.org](https://www.openstreetmap.org), last accessed 14/06/2019). A map of the road network is available in Figure 3.

The administrative border line between Senegal and Mauritania comes from the GADM web platform (data available online at [https://gadm.org/](https://gadm.org/), last accessed 14/06/2019). The border crossing points are based on expert knowledge (red points in Figure 3).

The bottom level of information regarding livestock movements is called walking layer \( W \). On this layer, the conductance is based on landscape features and change according to the season. We rely on expert knowledge to assign a conductance weight to each type of land use (Table 1).

The second level of information is represented by the Senegal and Mauritania’s main road network. It is combined with the walking layer assigning the conductance value 1 (high conductance/low resistance) to any pixels of \( W \) crossed by a road to obtain a new layer \( R \). Note that the influence of \( W \) on \( R \) can be adjusted with the parameter \( \delta_W \in [0, 1] \). More formally, the value \( R_i \) of a pixel \( i \) according to the walking layer \( W \) and \( \delta_W \), is defined as follows,

\[
R_i = \begin{cases} 
1 & \text{if a road cross } i \\
\delta_W W_i & \text{otherwise}
\end{cases}
\]  

Finally, the last level of information is given by the administrative border line. To adjust the permeability of the border line to pixels that are not border crossing points, we introduce the parameter \( \delta_R \in [0, 1] \). The value \( C_i \) of a pixel \( i \) on the conductance map \( C \) according to \( R \) and \( \delta_R \) is given by:

\[
C_i = \begin{cases} 
\delta_R R_i & \text{if } i \text{ is not a border crossing point} \\
R_i & \text{otherwise}
\end{cases}
\]

### Table 1. Land use weights according to the season.

| Type                        | Dry season | Wet season |
|-----------------------------|------------|------------|
| Coastal strip               | 0.5        | 0.5        |
| Mangrove                    | 0.25       | 0.25       |
| Water bodies                | 0.5        | 0.25       |
| Irrigated croplands         | -          | -          |
| Croplands                   | 1          | 0.125      |
| Forest area                 | 0.5        | 0.5        |
| Mosaic croplands & grassland| 1          | 0.5        |
| Open grassland              | 1          | 1          |
| Dune and peneplain pastures | 0.875      | 0.375      |
| Dune and gravel pastures    | 1          | 0.875      |
| Salt land                   | 1          | 0.75       |
| Bare rock                   | 0.75       | 0.75       |
| Urban area                  | 0.125      | 0.125      |
| Major rivers                | -          | -          |

### Livestock movements modeling

This last step consists in assigning a potential route between every couple of markets in our OD matrices using the conductance maps described in the previous section. To do so, we conducted a connectivity analysis based on concepts from electronic circuit theory [18] using the Circuitscape software (v4). This approach has been widely used in wildlife corridor design [19, 20], movement ecology [21, 22] or epidemiology [23].

For each pair of locations, represented by two pixels on the conductance map, Circuitscape computes a map of the total movement resistance accumulated from the origin and destination. This map informs us on the potential for each pixel to be crossed during a livestock movement from the market of origin to the market of destination. We then normalized the map by its highest pixel value.

Finally, we multiply each normalized connectivity map by the ratio of animals concerned (i.e. number of
animals moving from the origin to the destination divided by the total number of animals). We finally sum all the maps. The highest values on this final map indicates the highest potential for livestock movements.

RESULTS

Mobility Network analysis

Figure 5 shows the evolution of the network measures along the year 2014 focusing on the number of links and animal transported each month. As we can see most of the activity are concentrated the months before the rainy season (April-June) when the scarcity of rains impedes the regeneration of pastures and animals are moved looking for better places. During the wet season (shaded area) there is a dramatic reduction of the movements, the number of links abruptly reduce with a global decrease of the animals movements.

Table 2 shows basic network measures according to the period of the year. In terms of number of nodes and links, the two seasonal networks are comparable. A visual representation of the network in the two seasons is displayed in Figure 4, where links colors and thickness correspond to the cumulative volume over the link (expressed in percentage of the total). In both cases, the majority of the links corresponds to movements of small herds and accounts for less than 1% of the total volume. The top 10 links account for 66% of the total volume of animal in wet season and 75% in dry season. The majority of the animal movements takes place in two areas. The first area is located around the Senegalese-Mauritanian border with an important trade activity between important cities in Mauritania (Nbeika, Boutilimit, Aleg, Mbout, Kaedi and Selibabi) and Senegal (Podor, Matam and Kanel). An important part of these movements are trans-boundaries movements between Podor and Mbout or between Matam and Kaedi and Mongel for example. This observation applies to both seasons but the trans-boundary’s activity seems to be higher in wet than in dry season. The second area showing an important activity is located in the south-east of Mauritania close to the border with Mali involving cities like Boustale and Gneiba. It is also important to note that, although more moderate, there is also a trade activity between Senegalese cities furthest from the border such as Kedougou, Diaobe, Tambacounda for the south and Dakar, Diourbel and Touba for the west. This activity is more pronounced during wet than dry season.

The role played by the different locations slightly changes form one season to another. Figure 6 shows...
The different locations highlighted based on their “activity” (number of connections and animals) and centrality (estimated through the betweenness weighted by the distance). Most of locations maintain their “activity” between the two seasons. This is particularly true for the largest market area of Podor, Kaedi, Matam located at the border between Senegal and Mauritania but also for Kedougou in the south of Senegal and Boustale at the border between Mauritania and Mali. They represent major destination for animal movements. We observe in Figure 6e and

### Table 2. Network Characteristics. The volume is expressed in million of heads.

| Season | Nodes | Links | Volume |
|--------|-------|-------|--------|
| All    | 108   | 116   | 0.49   |
| Wet    | 85    | 81    | 0.16   |
| Dry    | 84    | 78    | 0.33   |

Figure 6. Spatial distribution of node centrality. For each node, five centrality indices are displayed for the wet season ((a), (c) and (e)) and the dry season ((b), (d) and (f)): indegree and percentage of incoming animals (a)-(b), outdegree and outcomings animals (c)-(d) and the betweenness (e)-(f). Size of the dot is proportional to the degree (a)-(d) or the betweenness (e)-(f). Color of dots corresponds to the percentage of animals (a)-(d).
Maps based on the parameter values $\delta_W = 0.8$ and $\delta_R = 0.1$.

Mapping potential paths for livestock movements

We plot in Figure 7 the maps of potential paths for livestock movements in wet and dry seasons, obtained with our approach. The value of each $500 \times 500$ m$^2$ pixel displayed on the maps is proportional to the probability of having an animal crossing it (called potential). We run the algorithm described in the method section with the parameter values $\delta_W = 0.8$ and $\delta_R = 0.1$. This means that the walking layer based on land use information accounts for 80% of the road network importance and the border has a very low permeability (10% of the conductance of the road/walking layer $R$), the choice of the parameters being based on expert opinion. Future works will aim to assess their values based on field activities. Therefore, their impact on the potential movement maps are discussed in the next section.

The two maps show different potential movement patterns. For example, the area in the Senegal-Mauritania east border is less permeable in wet than in dry season. The rainy season map, moreover, shows more complex patterns of potential of passage in this area. This is due to the presence of crop plots (see Figure 2) or floodplains that animals must avoid during this season. This highlights the importance of an explicit mapping of the network links according to the landscape conductance in order to spatially translate the connectivity. For both seasons, the highest potential passage are located around the roads. This is even more pronounced for the rainy season, during which some areas cannot be crossed and animals are forced to use tracks along the roads. Whatever the season, the two maps show one big core area with high potential of crossing located at the eastern side of the border between Senegal and Mauritania. Areas located in the south of Senegal (Kedougou) and in the south-east of Mauritania (Boustaile) show a low potential of passage, while they clearly appear as central nodes of the spatial network (Figure 6). On the contrary, certain areas located around the Podor-Kaedi-Matam axis exhibit a high potential of passage, while it does not contain any origin or destination nodes. It is typically

Figure 7. Map of the potential paths for livestock movements according to the season. (a) Wet season. (b) Dry season.
an area where animals pass through and crossbreed that our methodology allows to identify and delimit. This demonstrates that the explicit spatialization of network links is a pertinent tool for the identification of areas with a high potential for livestock movements.

In animal health programs, land-use planning or management of conflicts between farmers and herders programs, it is essential to be able to prioritize intervention zones. To do so, we spatially aggregate the potential at regional level for Senegal, Gambia and Mauritania using data downloaded from the GADM web platform https://gadm.org/index.html. We thus obtain a distribution of values informing us on the level of activity within each administrative unit. We also compute the level of activity in each administrative unit based on the information provided by the mobility network alone (total of out- and in- coming number of animals) to use it as benchmark. We plot in Figure 8 the distribution of activity obtained with the different methods (potential or network) in dry and wet seasons. For each distribution, the values are normalized by the maximum and the x-axis represents the rank of the administrative units according to the activity measured with the potential paths in dry season (red squares). We observe that there is an important difference between administrative units’ rankings obtained with the potential and network approach whatever the seasons. This is not really surprising since the two types of activity are not based on the same information but it highlights the importance of potential paths spatial mapping to identify active areas in terms of animal movements. In particular, there are several units with no activity according to the mobility network that are in the top 10 regarding the activity measured with the potential. A map of the spatial distribution of activity measured with the potential and the in- and out- strengths of the mobility network in dry season is available in Figure 9. To quantify these differences more rigorously, we compute the correlation between the different distribution of activity with the Kendall’s $\tau$ coefficient [24]. The coefficient matrix available in Table 3 confirms the results shows in Figure 8.

Finally, in order to assess the impact of $\delta_W$ and $\delta_R$ on the resulting potential maps, we compare the reference distribution of activity obtained with the parameter values $\delta_W = 0.8$ and $\delta_R = 0.1$ in dry season (display in Figure 8 and 9) with the ones obtained with different couples of values ranging between 0 and 1. The results obtained with the Kendall’s $\tau$ coefficient as similarity metric are displayed in Figure 10. This sensitivity analysis indicates that $\delta_R$ has almost no impact on the activity at a global scale. Note that the effect of this parameter is probably higher at a local scale since it only affect areas close to the Mauritanian-Senegalese border. The impact of $\delta_W$ adjusting the importance of the walking layer compared to the road layer is more complex. Indeed, while the similarity decreases slowly when $\delta_W$ is getting lower than the reference value, we observe a strong gap when $\delta_W = 1$. In this particular case, the results are no longer driven by the road network leading to an important modification of the potential movement patterns at a global scale. It is however worth noting that whatever the couple of $\delta_W$ and $\delta_R$ values the re-
results are more or less consistent with the ones obtained with the reference values with a Kendall’s $\tau$ coefficient ranging from 0.88 to 1.

DISCUSSION

The precise description of livestock movement patterns has a central role in many applied questions. This is particularly true in Sahelian semi-arid regions where it has become a crucial requirement to help decision-makers to deal with conflicts between herders and farmers or regarding the spread of animal diseases. Until now, the mapping of the potential livestock presence has been done only from census data of “sedentary” herds [12], without taking into account livestock mobility on a larger scale. The originality of the approach proposed in this article lies in the fine mapping of animal flows by weighting a conductance map by the number of animal heads. The resulting raster map reflects the potential for livestock movement of each pixel according to its landscape connectivity and its position relative to the livestock mobility network. We illustrated our approach with a livestock mobility network in Senegal and Mauritania in dry and wet seasons in 2014 that we combined with different land uses information (land cover, roads and border). Our results demonstrate the robustness of our approach to identify and rank areas according to their potential for livestock movement.

Limitations of the study

However, one should keep in mind that our approach is highly dependent on the data being used and their resolution. The resolution of the conductance map, 500 meters in our study, depends on the resolution of the land cover map and might not allow to consider very fine paths. Our results show that the potential map is mostly driven by the road network, this can also represent an important source of uncertainty.

Many factors drive mobility dynamics: landscape configuration, roads quality, needs for food, needs for watering points, border crossing, religious feasts etc. The conductance map has to include all these mobility driven factors. For this study, we were able to collect most of the geographical layers for each of these factors, except that of the watering points (drillings and ponds). Therefore, the maps obtained in this study do not take into consideration the need to pass through water points, especially during the dry season. This is an important drawback counterbalanced by the fact that Senegal and Mauritania have a very dense mesh of drillings.

Another difficulty is the reliability of the mobility data. Mobility data has been collected using two different approaches in Senegal and Mauritania. For the Mauritanian case, a synthetic survey was conducted by National Livestock and Veterinary Research Centre (CNERV) and compared with health certificate collected by Veterinarian Offices. In the case of Senegal, paper copies of sanitary movement permit (LPS) were collected by ad-hoc activities. These certificates provide information about origin and destination, and we do not know if during the journey the herd’s composition change due to animal sales. Furthermore there is no proof that the herds actually reach their destination. Another bias in the data is linked to the fact that this data set do not include no declared movements (for herds that do not have LPS).

Finally, the construction of the conductance map, that is the basis of the proposed methodology, relies on resistance weights given by experts. Note that the main purpose of this article is to propose a methodology and we did not try to increase the number of experts or test different weights combinations. To use the presented method for operational purposes, a concerted reflection on the weights to be assigned as well as a sensitivity analysis of these weights should be integrated into the approach.

Concluding remarks

The identification of high potential for livestock movement is a central issue for decision-makers, whether in the field of animal health or territorial planning. Our approach opens interesting perspectives for the modeling of potential animal passage in semi-arid region experiencing a lack of specific data on livestock movements. It is however important to note that a large part of the livestock remains in its zone of origin. These sedentary animals are often in contact with transhumant animals that cross their territory. This information should be added to complete
the map of potential for livestock movement provided in this study.

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AUTHOR CONTRIBUTIONS

CJ and ML designed the study, analyzed the data and wrote the paper. AA and IT processed and analyzed the data. BS, IS, CSD and CC collected the data and contribute to the definition of weights. CC and RL coordinated the study. All authors read, commented and validated the final version of the manuscript.
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