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Abstract

Transhumants move their herds based on strategies simultaneously considering several environmental and socio-economic factors. There is no agreement on the influence of each factor in these strategies. In addition, there is a discussion about the social aspect of transhumance and how to manage pastoral space. In this context, agent-based modeling can analyze herd movements according to the strategy based on factors favored by the transhumant. This article presents a reductionist agent-based model that simulates herd movements based on a single factor. Model simulations based on algorithms to formalize the behavioral dynamics of transhumants through their strategies. The model results establish that vegetation, water outlets and the socio-economic network of transhumants have a significant temporal impact on transhumance. Water outlets and the socio-economic network have a significant spatial impact. The significant impact of the socio-economic factor demonstrates the social dimension of Sahelian transhumance. Veterinarians and markets have an insignificant spatio-temporal impact. To manage pastoral space, water outlets should be at least 15 *km* from each other. The construction of veterinary centers, markets and the securitization of transhumance should be carried out close to villages and rangelands.

Keywords (separated by '-') Multi-agent system - Agent based modeling - Distributed artificial intelligence - Sahel - Pastoral mobility

Footnote Information

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RESEARCH ARTICLE

Agent-Based Model for Analyzing the Impact of Movement Factors of Sahelian Transhumant Herds

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Abstract

Transhumants move their herds based on strategies simultaneously considering several environmental and socio-economic factors. There is no agreement on the influence of each factor in these strategies. In addition, there is a discussion about the social aspect of transhumance and how to manage pastoral space. In this context, agent-based modeling can analyze herd movements according to the strategy based on factors favored by the transhumant. This article presents a reductionist agent-based model that simulates herd movements based on a single factor. Model simulations based on algorithms to formalize the behavioral dynamics of transhumants through their strategies. The model results establish that vegetation, water outlets and the socio-economic network of transhumants have a significant temporal impact on transhumance. Water outlets and the socio-economic network have a significant spatial impact. The significant impact of the socio-economic factor demonstrates the social dimension of Sahelian transhumance. Veterinarians and markets have an insignificant spatio-temporal impact. To manage pastoral space, water outlets should be at least 15 *km* from each other. The construction of veterinary centers, markets and the securitization of transhumance should be carried out close to villages and rangelands.

Keywords Multi-agent system · Agent based modeling · Distributed artificial intelligence · Sahel · Pastoral mobility

Abbreviations

ABM	Agent-based model
UML	Unified modeling langage

1 Introduction

Transhumance is a livestock farming system practiced on rangelands or pastures [1, 2]. Transhumance is a common practice in the Sahel due to the high climatic variability of the region [2–4]. Transhumants move their herds according to strategies that simultaneously consider vegetation quality, watering outlets, veterinarians, markets and perturbators. Herds are moved in areas where: (1) transhumants have socio-economic relationships with people; (2) security conditions are satisfied [5, 6]. Although it is recognized that these factors are all simultaneously involved in herd movement strategies, there is no agreement on the influence of each factor in movement strategies. For some authors, the movements of transhumant herds are explained by the spatiotemporal distribution of rainfall and vegetation. For them, most other variables such as markets, veterinarians, thieves (perturbators) and socio-economic networks are just noise [5, 7]. For other authors, variables such as markets, veterinarians, thieves (perturbators), and the socio-economic network are not noise [8–10]. This raises the question of hierarchizing the influence of herd movement factors in the design of herd movement strategies. A hierarchy of factors

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could facilitate the design of a transhumance model whose processes could be close to those of reality.

Agent-Based Modeling allows to model a real phenomenon by considering the strategies or agents involved in that phenomenon with the features they have in reality [11, 12]. An Agent-Based Model (ABM) can model herd movements according to the movement strategies of their transhumants. These strategies may be based on one or a combination of environmental and socio-economic factors [13–15]. An ABM can be designed from a reductionist or holistic point of view [16, 17].

A holistic ABM is designed based on empirical observations and considers a large number of interrelated factors in the studied problem [16, 18]. A holistic ABM considers the majority of agents and their strategies. The aim is for the model to be a subjective image of reality. This approach is called distributed artificial intelligence. For example in [19], Bah et al. model the multiuse of pastoral resources around the Thieul borehole. This model considers pastoralists, farmers, and agropastoralists and their interactions with crop fields, natural pastures and water outlets (boreholes, lakes, ponds, etc.) located around the Thieul borehole. The large number of entities and interactions considered simultaneously in this model complicates the identification of the significant or non-significant impact of entities or interactions on the results. Furthermore, as the model is based on the realities of a borehole, it is not reproducible and cannot be used for decision-making elsewhere. The multitude of factors considered in holistic ABMs masks the individual impact of each factor [16, 20]. This class of model cannot provide decision-makers with pastoral land management scenarios based on precise and explicit herd movement factors.

A reductionist ABM is designed from a strict subset of entities or interactions considered important by the modeler. Such a construct, commonly known as artificial life, enables the modeler to test hypotheses in a virtual world [18, 20]. For each hypothesis, the modeler performs one or more microsimulations. Then, the model results will be compared with empirical data or results to draw conclusions applicable to the real world [16, 20, 21]. For example, Traore et al. [22] determine the spatiotemporal distribution of transhumant herds based on the presence of the socio-economic network of transhumants and veterinary centers. In this model, the socio-economic network of transhumants aggregates access to vegetation and water.

Most models addressing herd mobility and pastoral land management issues are holistic, focusing on the dynamics of herd mobility around pastoral resources or infrastructures [23, 24]. Despite knowledge of herd movement factors, it is difficult to know where a set of herds will be during their outward or return transhumance phases. It is therefore difficult for: (1) decision-makers, non-governmental organizations and veterinarians to plan their interventions in pastoral land use, and (2) Sahelian states to secure pastoralists and their herds.

Based on human behavior algorithms and microsimulations, this article has two purposes. On the one hand, to determine (qualitatively) the influence of each herd movement factor can have on the movement strategies of the transhumants. On the other hand, to provide Sahelian decision-makers with pastoral land management scenarios based on a specific transhumant herd movement factor. Ultimately, this article will indicate: (1) where it could be efficient to install boreholes, markets, veterinary centers or prohibited areas for herds; and (2) how to secure the movements of transhumant herds. To achieve these purposes, agent-based microsimulations conceptualize and simulate transhumant herd movement strategies. These strategies are based on a single movement factor: vegetation quality, water outlets (boreholes, antennas), veterinarians, markets, perturbators (thieves, bandits, troublemakers), and people helping the transhumant (socio-economic network). This article is conceptualized at a high level of abstraction to ensure reproducibility.

2 Material

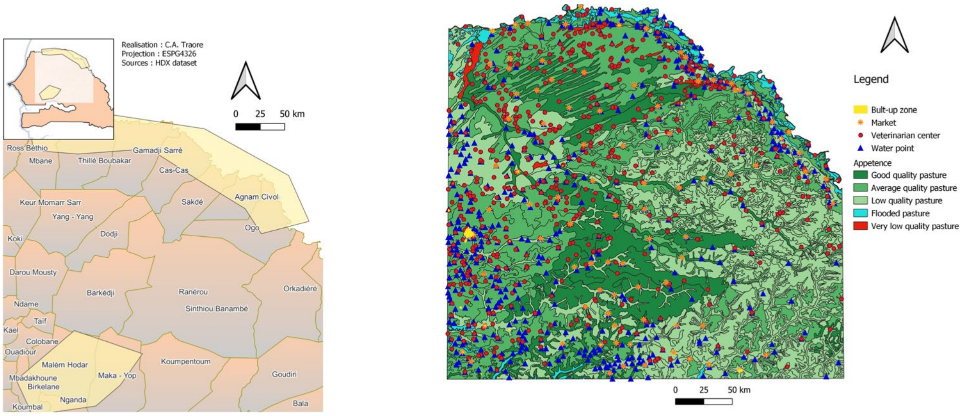
2.1 Study Area

The study area (Fig. 1) is the part of Senegal that covers an area of 121000 km^2, extending from part of the Ferlo silvo-pastoral zone (in the north) to the groundnut basin (in the center).

2.2 General Description of Transhumance of Sahelian Herds

Transhumance is the seasonal environmental and socio-economic mobility of herds moved by transhumants [23, 26]. The purpose of transhumance is to feed the herds at a low cost while ensuring a decent income for the transhumants and their families. Transhumance consists of long and short movements of herds [2, 27]. The long movements occur between: (1) the terroir of origin and the host terroir of the herd, and (2) between two host terroirs. Short movements occur within a terroir of the herd. These movements

Fig. 1 Study area in (a) the terroir of origin is the top orange polygon and the host terroir is the bottom orange polygon



(a) The terroirs of the herds [25]

(b) Input data

are called daily movements. This article focuses on the long movements of herds which can be subdivided into the outward phase and the return phase towards a terroir.

Herd movements depend on the pastoral environment and its management. In our study area, the outward phase of transhumance extends over $40 - 70$ days, and the return phase over $30 - 50$ days. Transhumant herds move around $15\ km$ per day during the outward phase and $17.5\ km$ per day during the return phase [28, 29]. In review [27], Turner and Schlecht compared African herd daily mobility and long mobility between two terroirs. They conclude that herd spatio-temporal distribution is not significant around base locations (camps, villages, water outlets) but a significant spatio-temporal distribution for mobility like transhumance.

Every day the transhumant moves his herd to secure areas where pastoral resources (vegetation quality, water) are available and where he can care for or sell animals without having to travel long distances [7, 26, 27]. The transhumant determines the transhumance path after gathering information on the state of pastoral resources (vegetation, water), the availability of markets and veterinarians, and security conditions. Transhumants move their herd to veterinary centers and pastoral markets close to their paths to reduce the distances to cover. In addition, they build and maintain socio-economic relations with individuals living in the areas they cross. These individuals constitute his socio-economic network. The socio-economic network facilitates the access of the herd to pastoral resources. In certain areas where a transhumant has no socio-economic network, he may have to pay exorbitant sums to access pastoral resources, sometimes leaving these areas [2, 10]. According to [10] transhumance would be impossible without the socio-economic network. The transhumants are sometimes affected by robberies and thefts of animals in the crossed areas [10, 30].

In many Sahelian countries, herds move through areas defined or not by legislation [30, 31]. These movements distribute the herds across a broad spatial scale between the origin and the host terroirs to benefit as much as possible from the vegetation, water outlets and markets [8, 10, 19].

The use of non-legally defined areas during transhumance is essentially due to the increase in cropland and the lack of representation of herding communities in state regulations or local land-use agreements [6, 19]. The very good quality of some pastures outside the regulatory area motivates transhumants to use non-pastoral areas such as protected areas, which are prohibited to herds [10, 26].

During their movements, herds interact with the environment by grazing, trampling grasses and shrubs, defecating and urinating [32, 33]. Herbivores excrements and the gases they emit during digestion are sources of greenhouse gases sequestered by vegetation and soils [33, 34]. Microfauna consume part of the excrement of herbivores. A broad spatio-temporal distribution of herds favors better sequestration of Greenhouse gases by soils and vegetation, and the emergence of biodiversity through the wide distribution of seeds. During the dry season, transhumant herds of cattle, sheep and goats eat no more than a third of the available herbaceous biomass and less than 5% of the leaves of trees and shrubs in a pastoral region [22, 33, 35]. We would point out that, in pastoral regions, the dynamics of water outlets (Eq. 1) and vegetation (Eq. 2) condition short-distance mobility and camp changes. In the Sahel, water outlets are either permanent (boreholes, antennas) or temporary (ponds, lakes). In Eq. 1 described in [36], Python et al. establish the dynamics of temporary water points in the Sahel.

$$\dot{w}(t) = p(t)a(t) - r_0(t) + r_i(t) - [c + e_r(t) + i_r(t)].w(t) \quad [36]. \tag{1}$$

In Eq. 2 described in [22], Traore et al. establish the dynamics of Sahelian vegetation as a function of the impact of herds.

$$\begin{cases} r(t+\Delta t) &= r(t) - \gamma(t).r(t).\Delta t \\ r(t_0) &= (\alpha.P + \beta).\lambda \end{cases} \quad [22] \qquad (2)$$

where r represents vegetation in $kg.ha^{-1}$ [37]. According to studies of the PPZS (Pole Pastorale Zone Seche), for our study area $\alpha = 4.1,\ \beta = -515$. P represents the annual rainfall in mm. λ represents the vegetation cell area. γ represents the amount of vegetation ingested by the herd's animals.

3 Methods

ABM is an approach to modeling social or environmental systems. In an agent-based model, the interactions of system elements are formalized in mathematical or computational (UML, algorithm) form or both [17, 38, 39]. These formalisms use reductionist or holistic paradigms (presented in the introduction). For example, if the formalizations of an ABM are based on the reductionist paradigm, the model is said to be reductionist. We notice the existence of a third formalization paradigm: globalism. This paradigm is a combination, based on expert knowledge, of reductionism and holism. These paradigms allow ABM to model complex systems at various spatial and temporal scales. In addition, the holistic paradigm permits us to consider many agents and the maximum complexity of interactions between agents. The agents of an ABM are the entities of the studied system. In ABM, an agent can be either cognitive or reactive [21, 38]. A cognitive agent has formalisms that enable it to change and adapt its strategies over time. A reactive agent, on the other hand, can only apply a set of rigid, predefined strategies. The results of these strategies are generally known in advance. In this article, the modeling paradigm is reductionist and the agents are reactive.

The formalization (approach, paradigm), agents, or interactions considered in the agent-based model depend on the modeler's purpose(s). Many ABMs of pastoral mobility are based on computational formalization (UML, algorithm) [39, 41]. These formalizations consider empirical observations implemented in simulators such as Gama, Mason or Netlogo [40]. However, mathematical formalizations based on graphs, Bayesian networks or differential equations can be observed in ABM (Eqs. 1 and 2) [42, 43].

According to many authors, ABM is an efficient approach to model pastoral systems [24, 40, 41]. It allows researchers to build artificial pastoral systems that permit the examination of complex interactions between households, herds, and pastoral resources or infrastructures over long periods and broad spatial scale [19, 24, 40]. For example, Rouchier et al. use an agent-based model to analyze the creation of market relations through exchanges between farmers and transhumants. They have designed simulations of artificial life in northern Cameroon and in the host terroirs of transhumants. These simulations are reductionist and involve computer and operations research formalizations of commercial interactions between farmers and transhumant herders. Farmers and transhumants are reactive agents in their model. The rest of this section describes our ABM.

3.1 Overview

3.1.1 Purpose

The purpose of the model is to formalize and simulate the movement strategies of transhumant herds. These strategies are based on a single movement factor: vegetation quality, water outlets (boreholes, antennas), veterinarians, markets, perturbators (thieves, bandits), and people helping the transhumant (socio-economic network).

The model is destined for use by modelers to provide them with a tool for testing hypotheses concerning the movement of transhumant herds. The model is also destined for pastoral researchers and decision-makers to inform their environmental and socio-economic discussions and decision-making.

3.1.2 Entities, State Variables and Scale

The entities of the model are organized into the "Transhumant_herd", "Socio_ecosystem", "Environment" and "Infrastructure" modules. These modules and the relations between their entities are illustrated in a UML class diagram (Fig. 2).

The "Transhumant_herd" module contains the "Transhumant_herd" entity, which represents the transhumant with his herd. The herd is a mix of cattle, sheep and goats. The state variables of this entity are: the position of the herd, the position of the camps in the origin and host terroir, the numbers of each herbivore species, and the speed of movements.

The "Socio-ecosystem" module contains the "Perturbator" and "Socio_economic_network" entities. The "Perturbator"

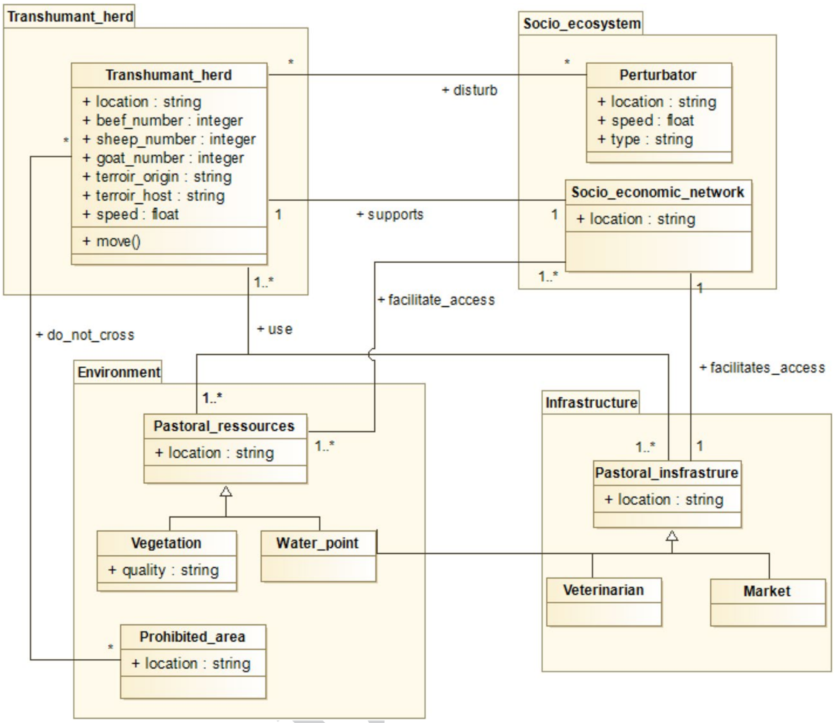


Fig. 2 Class diagram of model entities

entity represents any individual hindering the transhumance of a herd. It could be a farmer who doesn't want any herd to cross or pass near his farm. In this case, the speed of this entity is equal to zero, and its position is considered a prohibited area. The perturbator can also be a cattle rustler or a bandit on the move. The "Socio_economic_network" entity represents the transhumant's socio-economic network. This entity has its location as the unique state variable.

The "Infrastructure" module contains the "Pastoral_Insfrastructure" entity. This entity generalizes the "Veterinarian", "Market" and "Water_point" entities representing respectively the veterinary centers, markets and water outlets used by pastoralists. This entity has its location as the unique state variable.

The "Environment" module contains the "Pastoral_ressources" and "Prohibited_area" entities. The "Pastoral_ressources" entity generalizes the "Vegetation" and "Water_point" entities. The "Vegetation" entity represents the vegetation required to feed transhumant herds. Its state variable is vegetation quality represented by appetence. The 'Water_point' entity represents water outlets (boreholes or antennas). The "Prohibited_area" entity represents parts of the area forbidden to herds (Fig. 3). There are no water outlets, veterinarians, or markets in prohibited areas. All entities of the "Environment" module have their position as a state variable.

The model is formalized on the spatial scale of the Sahel and simulated at the scale of the study area. The simulation space is discretized into grid cells of $9,6\ km \times 9,6\ km$ with Moore's topology [24, 44]. This size of the grid cells is close to the minimum distance ($8 - 12\ km.day^{-1}$) covered by a transhumant herd on a half day [5, 28]. Furthermore, this grid size allows us to stay within the herd's impact zone, despite any unexpected events the transhumant might confront.

(a) One prohibited area in red (b) Two prohibited areas in red

Fig. 3 Grid of simulation space with prohibited areas for herds [25]

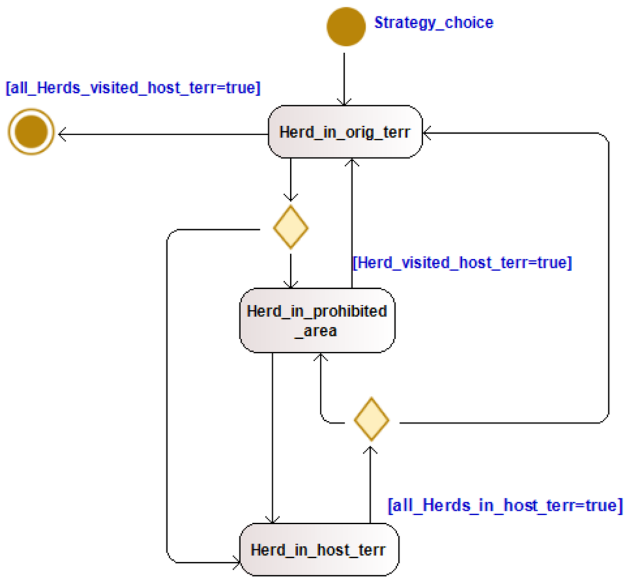


Fig. 4 Activity diagram of transhumant herd movements

The time step of the model is six hours because transhumant herds have two daily phases of movement with a total duration of twelve hours. This time step allows us to monitor herds' presence at pastures or water outlets during the morning and afternoon. The model has a time horizon of 10 months to consider the outward phase of transhumant herds in their host terroir and the return phase in their terroir of origin. Transhumance is carried out from October to July [5, 13].

3.1.3 Process Overview and Scheduling

Herds move from the terroir of origin to the host terroir and vice versa according to a strategy based on a movement factor and prohibited areas (Fig. 4). A movement factor can be quality vegetation, water outlets, veterinarians, markets, perturbators, or socio-economic networks. A herd can leave the host terroir only when all the other herds have arrived. When a herd is in a prohibited area, it launches a process to leave it. Herd movement strategies are formalized and described in detail in Sect. 3.3.4. The model design assumes that there is enough vegetation and water on rangelands. Transhumants gather information daily before determining the paths of their herds. As a result, they will not choose paths where pastoral resources are lacking.

3.2 Design Concept

3.2.1 Sensing

The herd is sensitive on a distance d (such that $d \in \{d_{veg}, d_w, d_v, d_m, d_{rs}\}$) to the movement factor considered. The herd is also sensitive to prohibited areas.

3.2.2 Interaction

Transhumant herds interact with pastoral space, resources and infrastructure. Pastures, water outlets, veterinarian centers and markets are places where herds are concentrated [8, 45]. Herds also interact with perturbators by avoiding them. Perturbators can be mobile or non-mobile. Mobile perturbators are cattle rustlers or thieves. Non-mobile perturbators are farmers or people who do not want herds to cross an area.

3.2.3 Collectives

All water outlets in the model are considered permanent. Movements to host or origin terroirs occur when surface water outlets have water. All herds move by using the same strategy and have the same origin and host terroirs. The minimum speeds for the outward and return phases of the herd are respectively 13.5 $km.day^{-1}$ and 15 $km.day^{-1}$.

3.2.4 Heterogeneity

Herds differ by their vaccination status and time interval of movement to markets. Grid cells differ by vegetation quality, presence of water outlets, markets, perturbators, veterinarians, or socio-economic network elements that they contain.

3.2.5 Stochasticity

Herd movement speeds during the outward and return phases follow the normal distributions. The time between animal sales follows a uniform distribution on the range 1 to 14 days.

3.2.6 Observation

The spatiotemporal distribution of transhumant herds emerges from the movement factor and strategy considered. For each movement strategy, we observe:

Table 1 Initialization parameters ($\mathcal{N}(a, b)$: normal distribution with mean a and standard deviation b)

Description	Value	Reference
Number of herds	200	Empirical
Percentage of herds vaccinated	$\simeq 70\%$	[2]
Herd speed	$\mathcal{N}(15.5, 2)\ km.day^{-1}$ (Outward phase) $\mathcal{N}(17.5, 2)\ km.day^{-1}$ (Return phase)	[28] [10, 28]
Number of perturbators	20	Empirical
Percentage of mobile perturbators	$\simeq 35\%$	Empirical

- The duration of the outward and return phases of transhumance;
- the proportion of space used by herds;
- the spatio-temporal impact of prohibited areas on herd distribution.

From the spatio-temporal distribution of transhumant herds, transhumance corridors may emerge. This emergence is a feature of spatial auto-correlation of herd positions. We use Moran indicators to observe whether herd positions are spatially auto-correlated. Moran indicators are of three types: I, z-score and p-value [46, 47]. Moran's I index satisfies hypotheses H_0 and H_1. H_0: spatial patterns are random ($I = 0$); H_1: spatial patterns are clustered/uniform ($I \neq 0$) [46, 47]. Moran's z-score and p-value are used with Moran's I to facilitate analysis. For example, for $I \neq 0$ and $z - score > 2.58$, we have a strong spatial concentration. Moran's p-value determines the significance of the cluster.

3.3 Details

3.3.1 Implementation Details

The model is implemented in the Gama simulator. Simulation results are analyzed in a Python notebook. The model data and Python scripts are available at https://www.comses.net/codebase-release/f0ad8a58-acc9-414b-b7e7-4ff279a48bcb/.

3.3.2 Input Data

The input data are geographic information systems (Fig. 1b). The locations of water outlets, veterinarians and markets are georeferenced as points in shapefiles. The vegetation quality layer and built-up areas are georeferenced as polygons in a shapefile.

3.3.3 Initialisation

Model initialization is based on algorithm 1 and Table. 1.

Algorithm 1 Model initialization

```
begin
    To read the input data (Sect. 3.3.2);
    To create a grid that covers the simulation space;
    To create the entities of the model except the
      "Social_network" entity;
    To Initialize the parameters of the
      transhumant_herd entity;
    To determine the location of the camps of the
      transhuman_herd in the terroir of origin and in
      the host terroir;
    To determine the beginning date of the
      transhumance of each herd.
```

3.3.4 Submodels

This section describes each herd movement strategy formalized by using algorithms.

Sub-model* 1: *herd movements based on vegetation quality This movement strategy is formalized by algorithm 2. In this algorithm, the herd researches any grid cell located at most a distance d_{veg} in the direction of the target terroir and containing the best vegetation quality. Thus, the herd will research: (1) a cell containing vegetation of good quality, (2) a cell containing vegetation of average quality, (3) a cell containing vegetation of poor quality. Finally, during the return phase, grid cells containing flooded vegetation (first loop while). When the herd is in a prohibited area -P_{area}- (Fig. 3), it moves towards the cell closest to its location, in the direction of the target terroir and where the vegetation is grazeable.

Algorithm 2 Herd movements based on vegetation quality

```
Input:
point : target_terroir ;                                  /* location of target terroir */
grid : $G$, $P_{area} \subset G$ ;                         /* set of cells, set of prohibited cells */
float : $d_{veg}$ ;
Variables:
point : location, target_location ;                       /* current and target location of the herd */
point : cell_location ;
string : cell_veg_quality ∈ {'good','average','low','flooded','not grazeable'};
string : phase ∈ {'outward', 'return'} ;                   /* the herd transhumance phase */
begin
    while location ≠ target_location and location ∉ $P_{area}$ do
        if one of cell_veg_quality='good' and distance(cell_location,location) ≤ $d_{veg}$ then
            target_location←cell_location ;
        else if one of cell_veg_quality='average' and distance(cell_location,location) ≤ $d_{veg}$ then
            target_location←cell_location ;
        else if one of cell_veg_quality='low' and distance(cell_location,location) ≤ $d_{veg}$ then
            target_location←cell_location ;
        else
            if phase='outward' then
                target_location←target_terroir ;
            else
                if one of cell_veg_quality='flooded' and distance(cell_location,location) ≤ $d_{veg}$ then
                    target_location←cell_location ;
                else
                    target_location←target_terroir ;
    while location ∈ $P_{area}$ do
        if one of nearest cells with cell_veg_quality !='not grazeable' then
            target_location←cell_location ;
```

Sub-model* 2**: ***herd movements based on water outlets This movement strategy is formalized by algorithm 3. In this algorithm, the herd moves from water outlet to water outlet until it reaches its target terroir. It can only move to a water outlet at most d_w from its location (first loop while). When a herd is in a prohibited area, it moves to the nearest water outlet outside this area (second loop while).

Algorithm 3 Herd movements based on water outlets

```
Pre-condition: This algorithm does not consider water points located in areas where houses are built
Input:
point : target_terroir ;                                  /* location of herd target terroir */
grid : $G$, $P_{area} \subset G$ ;                         /* set of cells, set of prohibited cells */
water point : $W$ ;                                        /* set of water points */
float : $d_w$ ;                                            /* herd distance to water point */
Variables:
point : location, target_location ;                       /* current and target location of the herd */
water point : $w$ ;                                        /* such as $w \in W$ */
point : $w$_location ;                                     /* water point location */
begin
    while location ≠ target_terroir and location ∉ $P_{area}$ do
        if distance(location, $w$) ≤ $d_w$ then
            target_location ← $w$_location ;
        else
            target_location ← target_terroir ;
    while location ∈ $P_{area}$ do
        target_location←nearest $w$_location ;              /* nearest water point location */
```

Sub-model* 3: *herd movements based on veterinarians and markets The herd movement strategy based on veterinarians is formalized by algorithm 4. In this algorithm, the herd moves toward the target terroir if a veterinarian is at most d_v distance from it, then it moves to that veterinarian. It stays j_v days at the veterinarian's location, then resumes its movement towards its target terroir. The movement strategy based on markets is formalized by algorithm 5. Every j_m day, the herd is moved to a market located at most a distance d_m from its location.

Algorithm 4 Herd movements based on veterinarians

```
Pre-condition: This algorithm does not consider veterinarians located in areas where houses are built
Input:
point : target_terroir ;                                  /* location of herd target terroir */
$V = \{v\}$ ;                                             /* set of veterinarians */
float : $d_v$ ;                                           /* herd distance to veterinairan */
int : $j_v \leftarrow rand(1, 7)$ ;                       /* number of waiting days for each herd */
bool : vac_status ;                                       /* herd vaccination status */
Variables:
point : location, target_location ;                       /* current and target location of the herd */
veterinarian : $v$ ;                                      /* such as $v \in V$ */
point : v_location ;                                      /* veterinarian location */
begin
    while location ≠ target_terroir do
        if there is a veterinarian at a maximum distance $d_v$ and vac_status=false and phase='outward'
         then
            while distance(location,v_location) ≠ 0 do
                target_location ← v_location ;
                if target_location=v_location then
                    stay $j_v$ day at this location;
                    vac_status← true ;
                    target_location ← target_terroir ;
```

Algorithm 5 Herd movements based on markets

```
Pre-condition: This algorithm does not consider markets located in areas where houses are built
Input:
point : target_terroir ;                                  /* location of herd target terroir */
$M = \{m\}$ ;                                             /* set of pastoral market */
float : $d_m$ ;                      /* herd distance to market $0 \leq d_m \leq$ one day of walking */
int : $j_m \leftarrow rand(1, 14)$ ;                      /* time between two sales */
Variables:
point : location, target_location, m_location ; /* current and target location of the herd, market
location */
begin
    while location ≠ target_terroir do
        if there is a market at a maximum distance $d_m$ then
            target_location ← m_location ;
            while distance(location,m_location) ≠ 0 do
                if $J_m \equiv 0[j_m]$ then
                    target_location ← m_location ;
                $J_m \leftarrow J_m + 1$ ;
                if target_location = m_location then
                    target_location ← target_terroir ;
```

Sub-model 4: ***herd movements based on perturbators*** This movement strategy is formalized by algorithm 6. The herd moves towards its target terroir; if a mobile perturbator is at most a distance d_p from its location, the herd stays at this location for j_p days. If the perturbator is sedentary, the herd moves to an adjacent cell to the cell containing this perturbator.

Algorithm 6 Herd movements based on perturbators

```
Input:
point : target_terroir, perturb_location ;
string : type_perturb ∈ {'mobile','sedentary'} ;              /* type of perturbator */
float : $d_p$ ;                                  /* distance between herd and perturbator */
int : $j_p$ ;                                   /* 0 < nb_day < 3, number of waiting days */
Variables:
point : location, target_location ;            /* current and target location of the herd */
begin
    while location ≠ target_terroir do
        if distance(location,perturb_location) ≤ $d_p$ and type_perturb='mobile' then
            wait $j_p$ day at this location ;
        if distance (location,location_perturb) ≤ $d_p$ and type_perturb='sedentary' then
            target_location ← neighbors_of perburb_location ;   /* herd will go into a neighborhood
             of the perturbator */
```

Sub-model 5: ***creation of socio-economic network elements*** The socio-economic network elements are created by using algorithm 7. Each herd creates $N_{rs} = 10$ socio-economic network elements so that these elements are spaced approximately 20 *km* from each other. The abscissas of the socio-economic network elements are at most a distance d_{rs} from the abscissa of the initial location of their transhumant herd.

Algorithm 7 Creation of socio-economic network elements

```
Input:
$S = \{s\}$ set of socioeconomical elements with $|S| = N_{rs}$;
grid : $G$, $P_{area} \subset G$ ;                      /* set of cells, set of prohibited cells */
float : $d_{rs}$ ;      /* $d_{rs} \in [75km, 125km]$, creation distance from the herd's initial position */
Variables:
point : s_location ;                                     /* socio-economic element location */
point : init_location ;                                       /* initial location of the herd */
bool : creation←true;
int : k ;
begin
    if creation=true then
        for k=0 to |S| do
            create s in $G \setminus P_{area}$ and s_location ∈ $[init\_location.x - d_{rs}, init\_location.x + d_{rs}]$ ;
        creation←false ;
```

Sub-model* 6: *herd movements based on socio-economic network This movement strategy is formalized by algorithm 8. In this algorithm, the herd moves from the socio-economic network element to the socio-economic network element until it reaches the target terroir. At a socio-economic network element, it stays j_{rs} days (first loop while). When the herd is in a prohibited area, it moves to a grid cell located outside this area and close to its location (second while loop).

Algorithm 8 Herd movements based on socio-economic network

```
Input:
$S = \{s\}$ set of socioeconomical elements with $|S| = N_{rs}$;
grid : $G$, $P_{area} \subset G$ ;                    /* set of cells, set of prohibited cells */
point : init_location, target_terroir ;    /* herd's initial location and target terroir location */
float : $d_{rs}$ ;     /* $d_{rs} \in [75km, 125km]$, creation distance from the herd's initial position */
int : $J_{rs}$ ;                                  /* $0 < J_{rs} \leq 6$, length of stay in days */
Variables:
point : s_location, location, target_location ;    /* socio-economic element, and herd's current and
target location */
bool : creation←true;
list : V ;                             /* elements of the socio-economic network visited */
int : k, $j_{rs} \leftarrow rand(0, J_{rs})$ ;                 /* $j_{rs}$ herd's length of stay in days */
begin
    while location $\neq$ target_terroir and location $\notin P_{area}$ do
        if location=s_location then
            wait $n_{rs}$ days at this location
        else if nearest $s \notin V$ and $|V| \leq |S|$ then
            target_location← nearest s_location ;
            V←V+[s] ;
        else
            target_location←terroir_location ;
    while location $\in P_{area}$ do
        target_location←near cell_location where cell $\notin P_{area}$ ;
```

4 Results

The movements of transhumant herds are simulated by using scenarios presented in Table 2. The results are based on 50 replications of each scenario. Figure 5 and the transhumance empirical data in Sect. 2.2 will be used as references to estimate the efficiency of our scenarios. In the analysis of exploration scenarios, a temporal gradient strictly inferior to three days is insignificant and significant otherwise. A spatial gradient strictly inferior to 10% is insignificant and significant otherwise.

Table 2 Exploration scenarios

Herds movements factor	Parameter(s)	Reference
Vegetation quality	$d_{veg} \in [12, 26]$ *km* (distance herd to vegetation)	[25, 28]
Water outlets	$d_w \in [10, 25]$ *km* (distance herd to water outlets)	[28, 45]
Veterinarians	$d_v \in [14, 26]$ *km* (distance herd to veterinarians)	Empirical
	$j_v \in [\![0, 6]\!]$ (length of stay in days)	[10, 25]
Markets	$d_m \in [1, 25]$ *km* (distance herd to markets)	[8, 25]
	$j_m \in [\![1, 14]\!]$ days (time between animal sales)	[23]
Perturbators	$d_p \in [0, 19]$ *km* (distance herd to perturbators)	Empirical
	$j_p \in [\![0, 4]\!]$ (number of waiting days)	Empirical
Socio-economic network	$j_{rs} \in [\![2, 6]\!]$ (length of stay in days)	[10, 25]
	$N_{rs} \in [\![5, 11]\!]$ (Number of elements)	[22]
	$d_{rs} \in [75, 125]$ *km* (distance between the social network element and the initial position of its herd)	Empirical

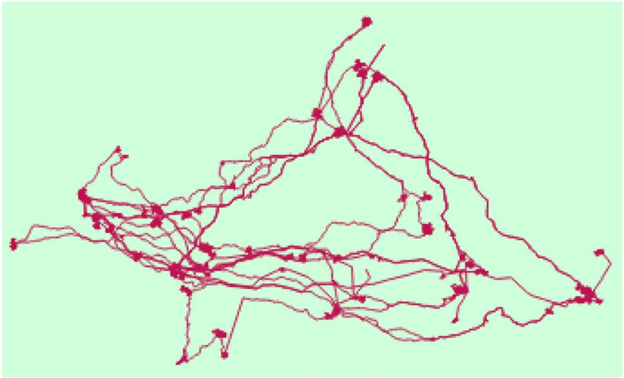


Fig. 5 Transhumance paths based on GPS data from nine cattle herds in Senegal

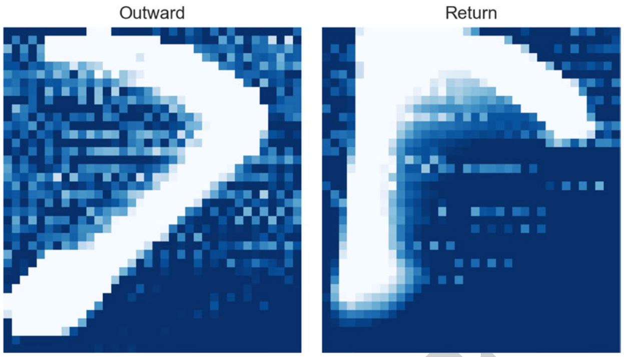


Fig. 7 Spatial distribution of herds based on vegetation quality in the full space ($d_{veg} = 25\ km$) d_{veg}: maximum distance between herd location and quality vegetation

4.1 Herd Movements Based on Vegetation Quality

Fig. 6a shows significant gradients in the duration of outward and return transhumance phases. These gradients are null when transhumant herds move to locations where the vegetation is at a distance of more than 20 *km*. In addition, a prohibited area reduces the duration of transhumance phases. However, two prohibited areas increase the duration of transhumance phases.

Figure 6b shows insignificant gradients in the space used by herds with or without prohibited areas. This gradient is more significant in the outward phase than in the return phase. Figures 7 and 8 illustrate the spatial distribution of herds (in white). Herds respect prohibited areas in the return phase but not in the outward phase. Moreover, there is a tendency for herds to use the same places for their movements, which will destabilize the ecosystem (overgrazing, etc.) and is inconsistent with empirical studies in [1, 2, 10]. Access to vegetation quality is therefore not a significant factor in the movement of transhumant herds.

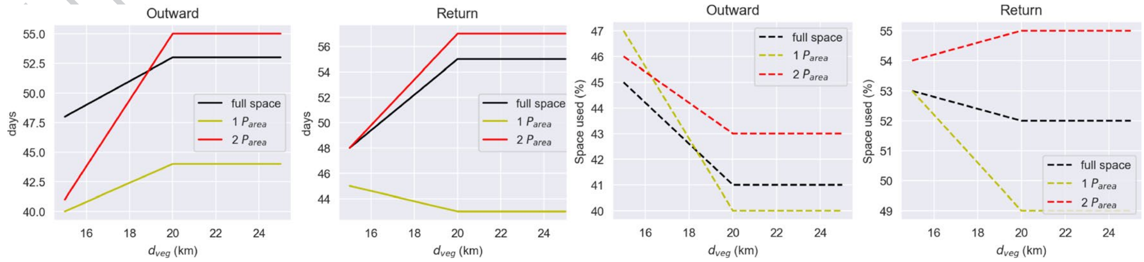
4.2 Herd Movements Based on Water Outlets

Fig. 9a shows significant gradients in the duration of the outward and return phases of transhumance. These gradients are higher when the herds move to water outlets at a distance at most 20 *km* away. In addition, prohibited areas increase the duration of transhumance phases. A prohibited area in the middle of a pastoral region increases the duration of the return phase compared to two prohibited areas.

Figure 9b shows insignificant gradients in the space used by herds. These gradients are higher outward phase than in the return phase and when water outlets are at most 20 *km* away.

Prohibited areas significantly reduce the proportion of space used by transhumant herds. However, during the outward phase, when transhumant herders move to water outlets located between 18 *km* and 22 *km* from their location, prohibited areas cause more use of space.

Figures 10 and 11 show the spatial distribution of transhumant herds. The significant spatial distribution of herds in areas with abundant water outlets is consistent with

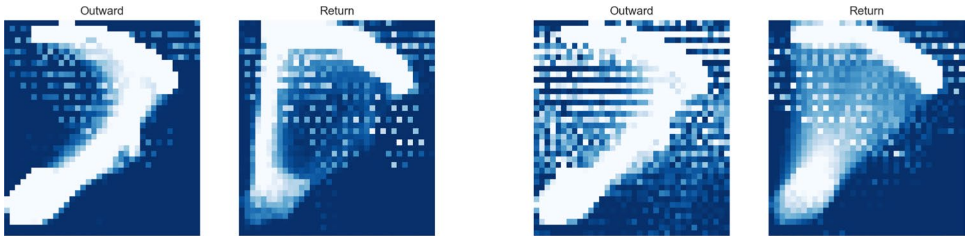


(a) Average duration

(b) Average proportion of space used

Fig. 6 Average duration of transhumance phases and proportion of space used by herds during their movements based on vegetation quality P_{area}: Prohibited area; d_{veg}: maximum distance between herd location and quality vegetation

Fig. 8 Spatial distribution of herds based on vegetation quality with prohibited area(s) ($d_{veg} = 25\ km$). d_{veg}: maximum distance between herd location and quality vegetation



(a) One prohibited area (b) Two prohibited areas

reality. Thus, water outlets are a significant factor in the movement of transhumant herds.

Figure 12 results from a change in the location of water outlets. A comparison of Figs. 10 and 12 reveals the sensitivity of the spatial distribution of herds about the location of water outlets.

4.3 Herd Movements Based on Veterinarians and Markets

Figures 13, 14 and 15a show insignificant gradients in the spatio-temporal distribution of transhumant herds when their movements based on veterinarians and markets. These movements are similar to unconstrained movements from their terroir of origin to their host terroir and vice versa (Fig. 16). Thus, veterinary centers and markets are not significant factors in the spatio-temporal distribution of transhumant herds.

4.4 Herd Movements Based on Perturbators

Figure 17 shows insignificant gradients in the spatiotemporal distribution of transhumant herds when the movement strategy is based on perturbators. When the perturbators are located at most 7 km (respectively 10 km) away, they have no impact on the duration of the outward (respectively return) phase of transhumance (Fig. 17a).

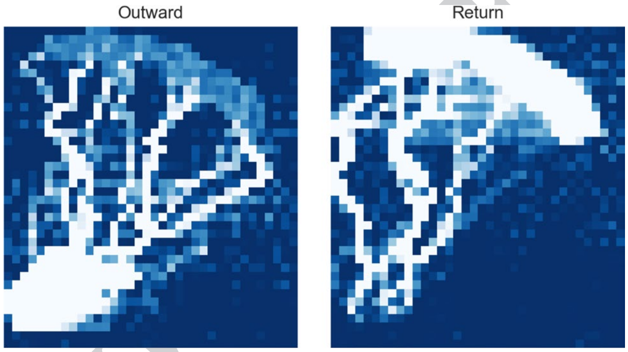
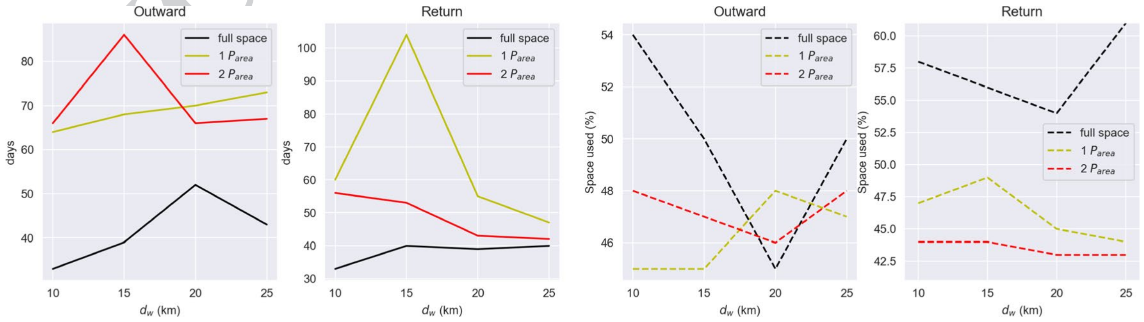


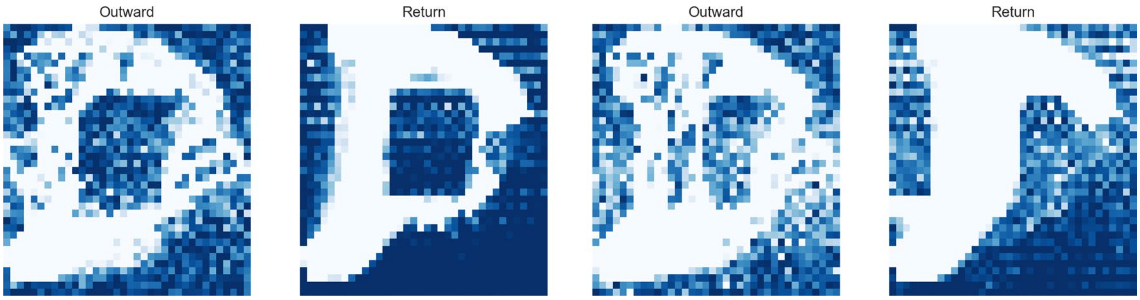
Fig. 10 Spatial distribution of herds based on water outlets in full space ($d_w = 20\ km$) [25] d_w: maximum distance between herd location and water outlet

Figure 15b shows that the number of waiting days due to a perturbator has no significant impact on the temporal distribution of transhumant herds. The influence of a perturbator (disgruntled farmer, robber) is insignificant for the spatio-temporal distribution of the herds. Their movements are similar to unconstrained movements from their terroir of origin to their host terroir and vice versa (Fig. 18).



(a) Average duration (b) Average proportion of space used

Fig. 9 Average duration of transhumance phases and proportion of space used by herds during their movements based on water outlets [25]. P_{area}: Prohibited area; d_w: maximum distance between herd location and water outlet



(a) One prohibited area

(b) Two prohibited areas

Fig. 11 Spatial distribution of herds based on water outlets with prohibited area(s) ($d_w = 20\ km$) [25]. d_w: maximum distance between herd location and water outlet

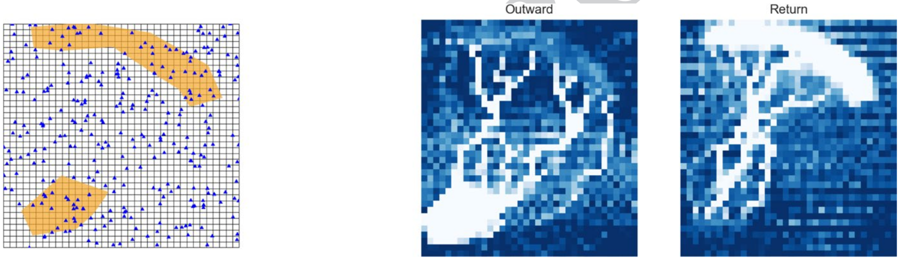


Fig. 12 Spatial distribution of herds based on water outlets in another distribution of water outlets d_w: maximum distance between herd location and water outlet

(a) New distribution of water outlets

(b) Spatial distribution of herds ($d_w = 20\ km$)

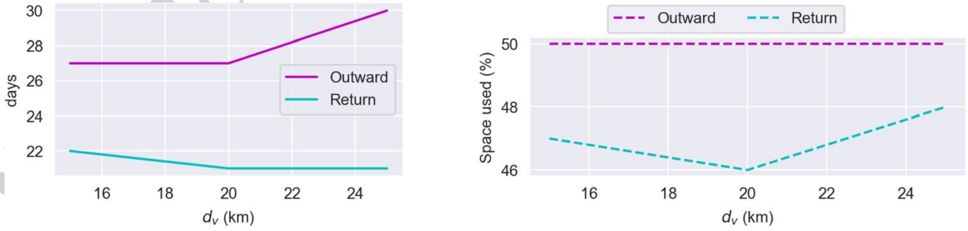


Fig. 13 Average duration of transhumance phases and proportion of space used by herds during their movements based on veterinarians. d_v: maximum distance between herd location and veterinarian

(a) Average duration

(b) Average proportion of space used

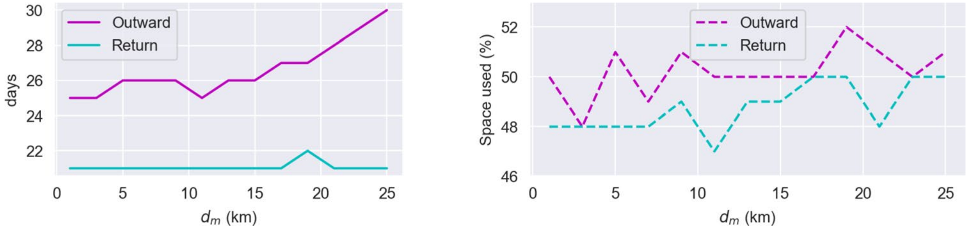
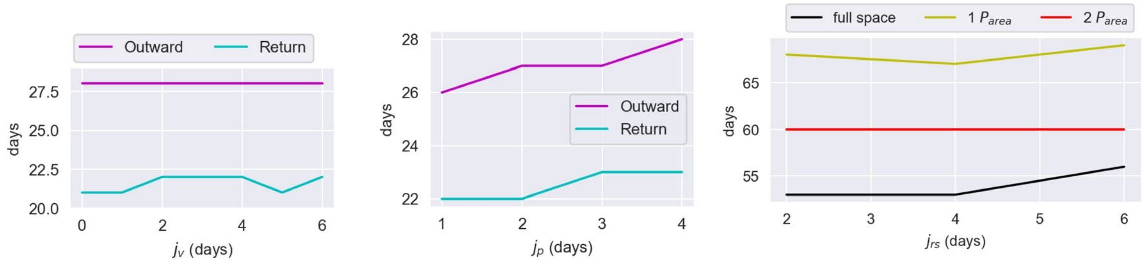


Fig. 14 Average duration of transhumance phases and proportion of space used by herds during their movements based on markets. d_m: maximum distance between herd location and market

(a) Average duration

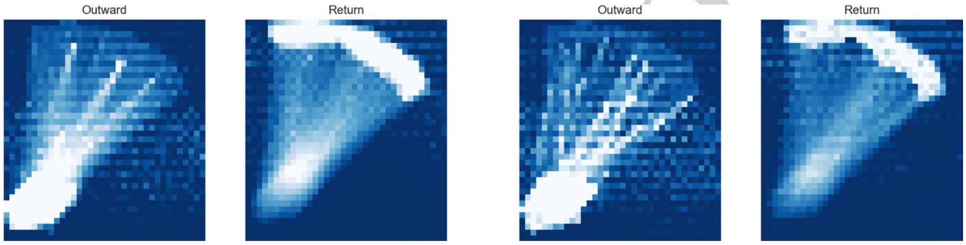
(b) Average proportion of space used



(a) Due to veterinarians (b) Due to perturbators (c) Due to one of element of socio-economic network

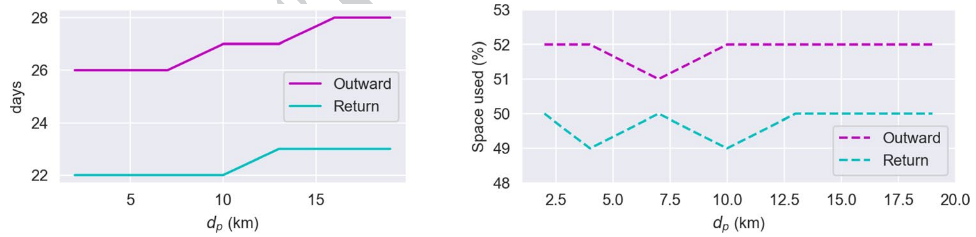
Fig. 15 Impact of waiting days (duration) on transhumance phases. j_v,j_p,j_{rs}: length of waiting days due respectively to veterinarian, perturbator, one of the elements of socio-economic network

Fig. 16 Spatial distribution of herds based on veterinarians and markets in full space ($d_v = d_m = 25\ km$). d_v: maximum distance between herd location and veterinarian; d_m: maximum distance between herd location and market



(a) Based on veterinarians (b) Based on markets

Fig. 17 Average duration of transhumance phases and proportion of space used by herds during their movements based on perturbators. d_p: maximum distance between herd location and perturbator



(a) Average duration (b) Average proportion of space used

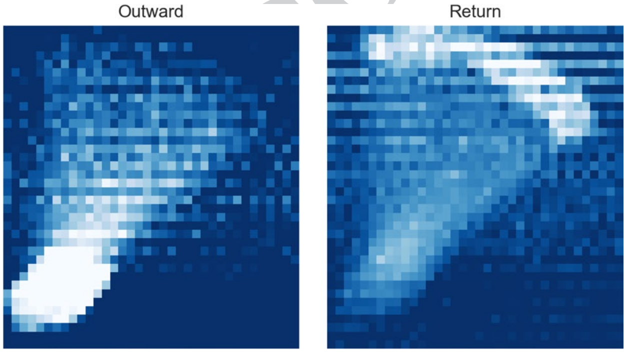
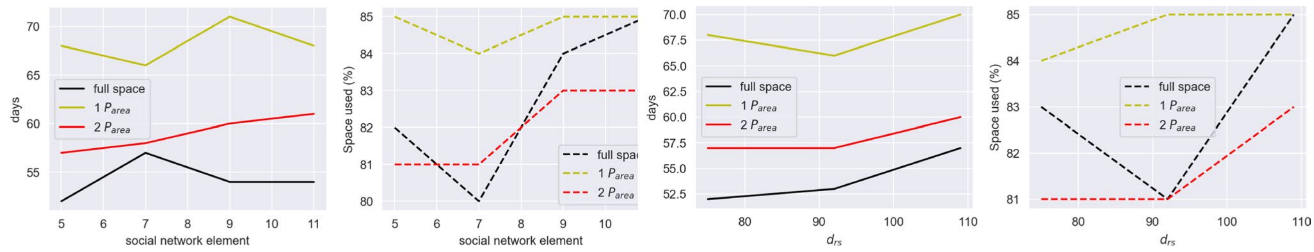


Fig. 18 Spatial distribution of herds based on perturbators ($d_p = 10\ km$). d_p: maximum distance between herd location and perturbator

4.5 Herd Movements Based on Socio-Economic Network

Figures 15c and 19 show insignificant gradients in the spatio-temporal distribution of transhumant herds. These distributions are slightly affected by the number of socio-economic network elements (Fig. 19a), how they are created (Fig. 19b), or the number of waiting days at a socio-economic network element (Fig. 15c).

Figure 20 shows that transhumant herds are widely distributed in space and do not cross prohibited areas. Thus, the socio-economic network is a significant factor in herd movements. These results are in line with empirical



(a) Number of the elements

(b) Average distance between elements

Fig. 19 Average duration and proportion of space used by herds based on the number of elements in the socio-economic network and the distance between these elements. P_{area}: Prohibited area; d_{rs}: maximum distance between herd location and one of the elements of the socio-economic network

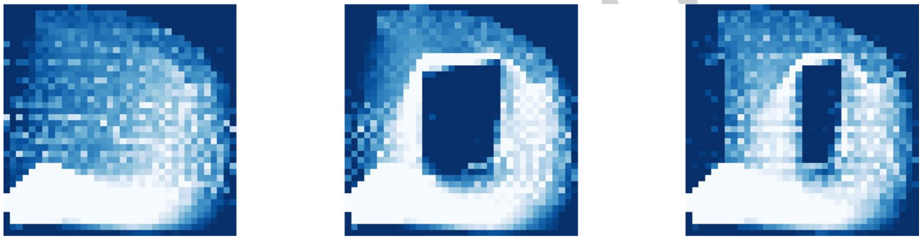


Fig. 20 Spatial distribution of herds based on socio-economic network ($d_{rs} = 100\ km, N_{rs} = 10$) d_{rs}: maximum distance between herd location and one of the elements of the socio-economic network N_{rs}: number of the elements of the socio-economic network

(a) Without prohibited area

(b) One prohibited area

(c) Two prohibited areas

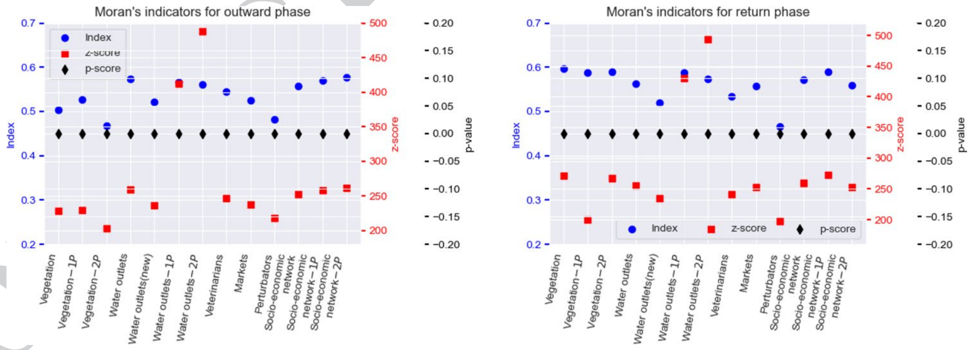


Fig. 21 Moran's indicator results for herd movement strategies (αP means α Prohibited area(s))

studies in [2, 10] relating the socio-economic network of transhumants and sahelian herd movements.

4.6 Moran's Spatial Auto-Correlation

Fig. 21 shows that herd positions are spatially auto-correlated. This auto-correlation leads to the emergence of transhumance corridors or clusters as $I \neq 0$ and $z - score > 2,58$ (Figs. 7, 8, 10, 12, 11, 16, 18 and 20). As the $p - value = 0 < 0,05$, the spatial distribution of herds according to the exploration scenarios is not random but respects the strategy considered (Table 2).

4.7 Results Validation and Interpretation

Compared with the results of other models, Moran's spatial auto-correlation analysis and empirical studies (Sect. 2.2), the microsimulations provide reliable and valid results—in the sense of Sim and Arnell [48]– [2, 10, 28]. A comparison of the model results and the paths illustrated in Fig. 5 shows that transhumants cannot move their herds according to one factor. This factor will not allow them to move their herds from one terroir to another, feeding and keeping them healthy, and safe while selling animals. These needs lead transhumants to use a combination of movement factors in their strategies to obtain the best for their herd or themselves. However, the results of microsimulations provide alternative explanations to those proposed by empirical studies.

Pastoral resources located at a maximum distance of 20 *km* from the location of the herds could have a significant impact on the spatio-temporal distribution of transhumant herds (Figs. 6 and 9). This distribution explains why transhumants seek out pastoral resources on distances ranging from 10 *km* to 20 *km*.

The insignificant impact of quality vegetation on long herd movements would explain why transhumants avoid using the same rangelands as their predecessors. Frequently used rangelands are often overgrazed and conducive to disease contagion.

Water outlets and transhumant socio-economic networks are significant factors in herd movements. Several transhumance corridors emerge when herd movements based on water outlets (Figs. 10, 11, 12).

The spatiotemporal distribution of transhumant herds is not significantly affected by veterinarians, markets, and perturbators because transhumants rarely change their initial path due to these factors. The construction of pastoral infrastructures and transhumant herd movements securitization must be carried out closest to their usual paths.

The prohibited areas to herds have an insignificant impact on their spatio-temporal distribution. However, they also create a concentration of herds in certain areas. This concentration of herds may cause overgrazing or a change in movement strategy to accommodate the needs of both herds and transhumants (Figs. 8a, b, 11a, b).

5 Discussion

The simulations designed in this article analyze the influence of social and environmental factors on the movement dynamics of transhumants. On the one hand, the microsimulations allowed us to determine the impact of each herd movement factor on the decision-making processes of transhumants. Thus, we were able to establish the significant role of the socio-economic network of transhumants. This significant impact of this network gives Sahelian transhumance a social dimension. A dimension that some pastoral researchers deny. On the other hand, these microsimulations allow us to study the impact of water outlets, prohibited areas for herds on their movements and where these areas should be located.

Water outlets are a significant factor in herd movements and should be located in the least-used areas to distribute herds more widely. The location of a new water outlet (borehole or antenna) must consider the location of existing water outlets. A concentration of water outlets in an area could create a concentration of herds. However, if water outlets are close together, the herds will be more widely distributed in space. A wide spatial and temporal distribution of herds reduces the risk of overgrazing and the carbon footprint of herbivores.

The prohibited areas have an insignificant impact on the spatio-temporal distribution of transhumant herds. These areas require careful selection of their size and location to avoid the risk of not achieving their objectives. Indeed, they could also lead to a concentration of herds in undesirable locations. This concentration of herds could create overgrazing or conflicts. Such areas should be located where there are no water outlets (human-made) and where transhumants have few socio-economic relations.

In the context of Sahelian security, where armed groups occupy and evict populations from their living spaces. The prohibited areas could be areas occupied and emptied of their population by armed groups. According to the results, unless these areas are the only ones with water outlets in their neighborhood, transhumants should not cross them. Based on model results, efforts to secure pastoral areas should focus on villages, pastoral infrastructures or transhumant paths.

6 Conclusion

This article develops microsimulations based on each factor of the movements of transhumant herds. The results show that transhumance cannot be based on a single factor. Pastoral resources (vegetation, water outlets) and the socio-economic network of the transhumant have a significant temporal impact on transhumance. Water points and socio-economic networks have a significant spatial impact. The significant role of the socio-economic network of transhumants demonstrated by simulation confers a social dimension to Sahelian transhumance. Pastoral infrastructures (veterinarians, markets) have an insignificant spatial and temporal impact on transhumance.

A pastoral land-use plan, which would increase interaction between the pastoral ecosystem and transhumant herds, would install water outlets no more than 15 *km* from each other. Such land-use plans could optimize the carbon footprint of herbivores through wider spatialization of their movements. In addition, the construction of veterinary centers, livestock markets, and the securitization of pastoral areas should be carried out close to villages and rangelands.

In a perspective of modeling the decision-making processes of Sahelian transhumants, this article allows us to: (1) consider that the water requirement of the herd is twice that of vegetation; (2) to materialize the impact of the socio-economic network of the transhumant by reducing the cost of buying water, selling herbivores on markets and avoiding conflicts. For our future work, we hope to model the movements of transhumant herds by using a strategy that simultaneously considers all movement factors weighted by their influence.

Author Contributions The first author contributed in concept, experiments, and writing. The other authors assisted with report improvement and review. All authors examined the results and approved the manuscript version.

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Availability of Data and Materials Model data and scripts are available since October 11, 2023 at https://www.comses.net/codebase-release/f0ad8a58-acc9-414b-b7e7-4ff279a48bcb/.

Declarations

Conflict of Interest The authors have no Conflict of interest to declare that are relevant to the content of this article.

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