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TIQUES ET MALADIES ASSOCIEES CHEZ LES BOVINS TRANSHUMANTS ENTRE LE BURKINA FASO ET LA REPUBLIQUE DU BENIN : ASPECTS SOCIO-EPIDEMIOLOGIQUES

TICKS AND TICK-BORNE DISEASES IN TRANSHUMANT CATTLE BETWEEN BURKINA FASO AND REPUBLIC OF BENIN: SOCIO-EPIDEMIOLOGICAL ASPECTS

Olivier Mahuton ZANNOU

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Ticks and tick-borne diseases in transhumant cattle between Burkina Faso and Republic of Benin: socio-epidemiological aspects

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Tiques et maladies associées chez les bovins transhumants entre le Burkina Faso et la République du Bénin: aspects socio-épidémiologiques

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Résumé - Abstract

Résumé

L'élevage tient une place importante dans l'économie de l'Afrique de l'Ouest. La principale stratégie d'élevage en Afrique de l'Ouest est le pastoralisme incluant la transhumance. Cette stratégie adaptative vise à optimiser l'accès du bétail à l'eau et aux pâturages. Cependant, elle peut favoriser la propagation transfrontalière d'agents pathogènes et de vecteurs avec de nombreuses conséquences sanitaires et économiques pour les pays concernés.

A l'aide d'un questionnaire et d'une modélisation statistique, la première étude a exploré la perception des éleveurs sur les tiques et maladies à tiques (TMT) chez les bovins, leurs pratiques de contrôle des tiques et les groupes sociaux impliqués dans l'élevage bovin dans l'est du Burkina Faso (46 troupeaux sélectionnés aléatoirement) et dans le nord du Bénin (44 troupeaux sélectionnés aléatoirement). Les résultats montrent que la plupart des éleveurs (79%) appartiennent au groupe social des Peuls. Les activités principales et secondaires des éleveurs sont respectivement l'élevage et l'agriculture. L'âge moyen des pasteurs se situe entre 40 et 50 ans et 60% des troupeaux enquêtés pratiquent la transhumance interne ou transfrontalière. Les éleveurs ont une connaissance claire des différents genres de tiques à l'exception du genre *Rhipicephalus*. Leur connaissance des maladies à tiques (MT) est très limitée. L'amitraz est le principal acaricide utilisé par les éleveurs pour lutter contre les tiques (68%) mais son utilisation est inappropriée et son approvisionnement se fait à plus de 50% par le marché non réglementé. Toutes ces pratiques peuvent induire une résistance aux acaricides, d'autant plus que l'inefficacité de l'amitraz contre *Rhipicephalus microplus* a déjà été signalée dans des études antérieures. De tels résultats aideraient à élaborer des stratégies adaptées de contrôle et de prévention des TMT au Burkina Faso et au Bénin.

La deuxième étude visait à caractériser les zones de départ et d'arrivée de la transhumance entre le Burkina Faso et le Bénin et modéliser le risque de propagation de *R. microplus* dans la zone. Des dispositifs GPS (*global positioning system*) ont donc été remis à 27 éleveurs pour suivre une saison complète de transhumance entre l'Est du Burkina Faso et le Nord du Bénin. Les GPS ont révélé quatre corridors principaux et cinq zones de pâturage utilisés par les troupeaux de bovins pendant la transhumance. L'indice de végétation et les précipitations étaient significativement plus élevés au Bénin qu'au Burkina Faso, tandis que la température était significativement plus basse. Le modèle de score de risque montre un risque plus élevé dans les communes du Bénin par rapport à celles du Burkina Faso. Les fréquents mouvements des troupeaux transhumants entre les zones infestées et non infestées augmentent le risque d'introduction de *R. microplus* dans les zones favorables encore indemnes. Les intrusions fréquentes du bétail transhumant dans les réserves fauniques constituent un autre risque d'échange de vecteurs et de pathogènes entre les animaux domestiques et sauvages.

La troisième étude de cette thèse visait à identifier les modèles épidémiologiques développés par les chercheurs pour comprendre la dynamique de la propagation des TMT. Une revue systématique a été faite avec le protocole PRISMA (*Preferred Reporting Items for Systematic reviews and Meta-Analysis*) dans deux bases de données en ligne (Scopus et PubMed). Les articles sélectionnés ont été classés selon le pays, le type de modèles épidémiologiques utilisés et l'objectif de la modélisation. La sensibilité, la spécificité et la précision de ces modèles ont été étudiées en utilisant une méta-analyse. L'analyse des 100 articles sélectionnés indique que c'est le genre de vecteur *Ixodes* spp et le genre de pathogène *Borrelia* spp qui sont les plus étudiés. Les modèles les plus fréquemment utilisés sont le modèle linéaire généralisé - GLM (26,67%) et le modèle d'entropie maximale - MaxEnt (24,17%). Un focus sur la modélisation des TMT en Afrique a montré que les genres *Rhipicephalus* et *Theileria* étaient les plus modélisés. Une méta-analyse sur la performance de 20 modèles a révélé que les modèles MaxEnt, Linear Discriminant Analysis (LDA) et Ecological Niche Factor Analysis (ENFA) avaient respectivement la sensibilité, la spécificité et l'aire sous la courbe les plus élevées parmi tous les modèles sélectionnés. La modélisation des TMT est très pertinente pour prévoir leur distribution et prévenir leurs effets néfastes sur la santé animale et humaine et sur l'économie. Les résultats de ces analyses sont utiles pour élaborer des programmes de prévention et/ou de contrôle par les autorités vétérinaires et de santé publique.

L'objectif de la quatrième étude était de modéliser la distribution de l'habitat de *R. microplus*. Les occurrences de tiques ont été rassemblées à partir de dix études différentes menées dans six pays d'Afrique de l'Ouest au cours de la dernière décennie. Six modèles statistiques (Maximum Entropy MaxEnt, Generalized Linear Model GLM, Generalized Additive Model GAM, Random Forest RF, Boosted Regression Tree BRT et Support Vector Machine SVM) ont été appliqués pour prédire la distribution de l'habitat de *R. microplus* en Afrique de l'Ouest. Le modèle de MaxEnt a été utilisé seul à et les cinq autres ont été utilisés dans un modèle d'ensemble (*ensemble modelling*). Les modèles sélectionnés se sont avérés précis selon les valeurs des AUC (Area Under the Receiver Operating Characteristic Curve) et TSS (True Skill Statistic), respectivement supérieures à 0,9 et 0,5. Les prédictions des modèles montrent que les pays côtiers d'Afrique de l'Ouest sont les zones les plus adaptées pour l'habitat de *R. microplus*. Les pays non encore infestés et se trouvant dans les zones adaptées à la tique doivent améliorer leurs stratégies de contrôle. La sensibilisation et la formation des différents acteurs doivent être renforcées pour améliorer la prévention ou le contrôle de cette tique dans ces différents pays en fonction de leur statut.

L'objectif de la cinquième étude était d'évaluer l'impact clinique et économique des TMT dans les troupeaux de bovins et les bénéfices du contrôle de ces parasites. A partir des données d'une enquête acarologique et épidémiologique menée en 2017 dans l'est du Burkina Faso et le nord du Bénin et des données collectées dans différents articles, un modèle déterministe a été développé. Ce modèle nous a permis d'évaluer l'impact clinique et économique des tiques et des maladies transmises par les tiques sur les troupeaux. Six scénarios ont été élaborés selon que les animaux étaient traités uniquement avec des acaricides ou avec des acaricides et contre les maladies transmises par les tiques. Les résultats de ces scénarios ont été comparés dans une régression linéaire pour mettre en évidence les différences significatives. Les analyses ont révélé un gain significatif de 871 euros à l'échelle du troupeau ($P<0,05$)

avec les scénarios de traitement aux acaricides, par rapport aux pertes si aucun traitement n'est effectué. Lorsque le traitement préventif des agents pathogènes transmis par les tiques est combiné à un traitement acaricide, il y a un gain supplémentaire significatif de 254 euros (P<0,001). Il est donc opportun de mettre en place des stratégies de lutte adaptées à la spécificité de chaque zone. L'élaboration de ces stratégies et leur mise en œuvre doivent être consensuelles et participatives pour leur réussite.

En conclusion nous pouvons dire que notre thèse a atteint globalement son objectif général en mettant à la disposition des autorités compétentes de précieux et pertinents outils d'aide à la décision (modèles épidémiologiques et économique) pour réduire l'incidence des tiques et maladies à tiques. En conséquence nous recommandons ce qui suit :

- A la CEDEAO : une meilleure gestion des médicaments vétérinaires afin de réussir la lutte contre les tiques et maladies associées et le renforcement des accords sous-régionaux existants sur la transhumance transfrontalière;
- Aux Services vétérinaires : le renforcement de leurs capacités techniques et en ressources humaines compétentes pour faire face au défi des tiques et maladies associées et de la transhumance;
- Aux éleveurs : une plus grande responsabilité dans l'approvisionnement et l'utilisation des acaricides et une meilleure gestion de leur troupeaux en tenant compte du niveau d'infestation de tiques et maladies à tique dans leurs milieux respectifs.

Abstract

Livestock plays a key role in the macro economy of West Africa and provides livelihoods for millions of people. The main cattle rearing strategy in West Africa is pastoralism, including transhumance: i.e. a seasonal migration of cattle with their cattle holders. This adaptive strategy aims to optimize livestock access to water and pastures. However, it can favour pathogens and vectors transboundary spread with many medical and economic consequences to the affected countries.

Using a questionnaire survey and statistical modelling, the first study explored the perception of cattle holders about ticks and tick-borne diseases (TTBD) in cattle, their practices in tick control and the social groups involved in cattle farming in eastern Burkina Faso (46 randomly selected herds) and in northern Benin (44 randomly selected herds). Results show that most of the cattle holders (79%) are from the Fulani social group. The principal and secondary activities of cattle holders are respectively cattle farming and agriculture. The mean age of pastoralists is between 40 and 50 years and 60% of the surveyed herds practice internal or transboundary transhumance. Cattle holders have a clear knowledge of different genus of ticks except for the genus *Rhipicephalus*. Their knowledge of tick-borne diseases (TBD) is very limited. Amitraz appears to be the main acaricide compound used by cattle holders for tick control (68%) but its use is inappropriate and its source is frequently the unregulated market. All of these findings can induce acaricide resistance especially since the inefficacy of amitraz against *R. microplus* has already been reported in previous studies. Such results would help to elaborate suitable strategies of control and prevention of TTBD in Burkina Faso and Benin.

The second study aimed to highlight, firstly the corridors and grazing areas used by Burkina Faso transhumant cattle herds going to Benin, secondly the characteristics of departure and arrival areas of transhumance and thirdly, the risk score related to the introduction and spread of the invasive tick species, *Rhipicephalus microplus*, in free areas. Therefore, GPS (Global Positioning System) devices were given to 27 cattle holders to monitor a full transhumance season between East Burkina Faso and North Benin. GPS devices revealed four main corridors and five main grazing areas used by cattle herds during transhumance. Normalized Difference Vegetation Index (NDVI) and rainfall are significantly higher in Benin than in Burkina Faso whereas temperature is significantly lower. Additionally, using biotic and abiotic parameters, a risk-scoring model was developed to predict the presence of *R. microplus* at the municipality level. The invasiveness and adaptability of *R. microplus* added to the frequent stays of transhumant herds in infested areas suggest its potential introduction and establishment in free areas soon. Moreover, frequent intrusions of the transhumant cattle in the wildlife reserves is another risk of vectors and pathogen exchange between domestic and wild animals.

The third study of this thesis aimed to identify epidemiological models developed by researchers to understand the dynamics of TTBD spread. A literature search was implemented with PRISMA (*Preferred Reporting Items for Systematic reviews and Meta-Analysis*) protocol in two online databases

(Scopus and PubMed). The selected articles were classified according to country, type of epidemiological models used and the objective of the modelling. Sensitivity, specificity and accuracy available data of these models were investigated using meta-analysis approaches. Results relied on 107 studies in which seven tick genera were modelled, with *Ixodes* spp. the most studied. Thirteen genera of tick-borne pathogens were modelled, with *Borrelia* spp. the most frequently modelled. Twenty-four different models were reviewed and the most frequently used are the Generalized Linear Model (GLM) representing 26.67% and the Maximum Entropy (MaxEnt) model representing 24.17%. A focus on TTBD modelling in Africa showed that respectively genus *Rhipicephalus* and *Theileria* were the most modelled. A meta-analysis on the quality of 20 models revealed that MaxEnt, Linear Discriminant Analysis (LDA), and the Ecological Niche Factor Analysis (ENFA) models had respectively the highest sensitivity, specificity, and area under the curve effect size among all the selected models. Modelling TTBD is highly relevant for predicting their distribution and preventing their adverse effect on animal and human health and the economy. Related results of such analyses are useful to build prevention and/or control programs by veterinary and public health authorities.

The objectives of the fourth study are to develop models to forecast the habitat distribution of *R. microplus*. Tick occurrences were assembled from ten different studies conducted in six West African countries in the past decade. Six statistical models (Maximum Entropy MaxEnt, Generalized Linear Model GLM, Generalized Additive Model GAM, Random Forest RF, Boosted Regression Tree BRT et Support Vector Machine SVM) were applied to predict the habitat suitability of R. microplus in West Africa. MaxEnt was used alone and the other five models were used in an ensemble model. The selected models resulted as accurate according to the AUC (Area Under the Receiver Operating Characteristic Curve) and TSS (True Skill Statistic) metrics, respectively above 0.9 and 0.5. The models' predictions show coastal countries of West Africa as more suitable areas for the habitat of *R. microplus*. We stress the importance of vector surveillance and control in those countries that have not yet detected the tick but are in the areas predicted to host suitable habitats. Indeed, awareness-raising and training of different stakeholders must be reinforced for better prevention and control of this tick in these different countries according to their status.

The objective of the fifth study is to evaluate the clinical and economic impact of ticks and tick-borne diseases in cattle herds and the benefits of controlling these parasites. Using data from an acarological and epidemiological survey conducted in 2017 in eastern Burkina Faso and northern Benin and data collected from various articles, we developed a deterministic model. This model allowed us to evaluate the clinical and economic impact of ticks and tick-borne diseases on herds. Six scenarios were developed depending on whether the animals were treated with only acaricides or with acaricides and against tick-borne diseases. The results of these scenarios were compared in a linear regression to highlight the significant difference. Linear regression revealed a significant gain of 871 euro at herd level ($P<0.05$) with the acaricide treatment scenarios, compared to the losses if no treatment is done. When preventive treatment of tick-borne pathogens is combined with acaricide treatment there is a significant additional gain of 254 euro (P<0.001) compared to the losses if no treatment is applied at all. It is therefore opportune to set up control strategies adapted to the specificity of each area. The development of these strategies and their implementation must be consensual and participatory for their success.

In conclusion, we can say that this thesis has achieved its overall objective by providing the competent authorities with valuable and relevant decision support tools (epidemiological and economic models) to reduce the incidence of ticks and tick-borne diseases. We, therefore, recommend the following:

- To ECOWAS: better management of veterinary drugs to successfully control ticks and associated diseases and strengthening existing sub-regional agreements on cross-border transhumance;
- To Veterinary Services: strengthening their technical and human resource capacities to face the challenge of ticks and associated diseases and transhumance;
- To livestock keepers: greater responsibility in the supply and use of acaricides and better management of their herds taking into account the level of tick infestation and tick-borne diseases in their respective environments.

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List of Abbreviations

ANCOVA	Analysis of covariance
ANOVA	Analysis of variance
ARES	Academy of research and higher education
ASF	African swine fever
AUC	Area under the curve
BI	Boyce index
BRT	Boosted regression tree
CART	Classification and regression tree
CHELSA	Climatologies at high resolution for the earth's land surface areas
CIRDES	International centre for livestock research and development in sub-humid zones
CSAO/SWAC	Sahel and west Africa club
CVD	Village development committee
DE	Livestock directorate
DEM	Digital elevation model
DGSV	General directorate of veterinary services
DSER	Sociology and rural economy department
ECF	East coast fever
ECOWAS	Economic community of west african states
ENFA	Ecological niche factor analysis
ENM	Environmental niche model
ESA CCI	European space agency climate change initiave
FA	Factor analysis
FAO	Food and agriculture organization
FARAH	Fundamental and applied research for animal and health
GAM	Generalized additive model
GDP	Gross domestic product
GIS	Geographic information system
GLM	Generalized linear model
GLW3	Gridded livestock of the world
GPS	Global positioning system
HCPC	Hierarchical principal component classification
IncMSE	Increase of the mean squared error
INSD	National institute of statistics and demography
IRR	Incidence rate ratio

LDA	Linear discriminant analysis
LEMV	List of veterinary medicines expert
LERE/DES	Laboratory for rural studies on environment and economic and social development
LSD	Lumpy skin disease
MaxEnt	Maximum entropy
MCA	Multiple correspondence analysis
MCDA	Multi-criteria decision analysis
MODIS	Moderate resolution imaging spectro-radiometer
NASA	National aeronautics and space administration
NDVI	Normalized difference vegetation index
NGM	Next generation matrix
OECD	Organisation for economic cooperation and development
OIE	World organisation for animal health
PBR	Pendjari biosphere reserve
PCR	Polymerase chain reaction
PNP	Pendjari national park
PRD	Research for development project
PRISMA	Preferred reporting items for systematic reviews and meta-analysis
QGIS	Quantum geographic information system
ReSurEp	National epidemiological surveillance network
RF	Random forest
ROC	Receiver operating characteristic
RVMC	Regional veterinary medicine committee
SDM	Species distribution models
SIR	Susceptible-infectious-recovered
SIS	Susceptible-infectious-susceptible
SSC	Sub-saharan countries
SVM	Support vector machine
SWA	Sahel and West Africa
TBD	Tick-borne disease
TSS	True skill statistic
TTBD	Ticks and tick-borne diseases
UEMOA	West African economic and monetary union
UFR	Education and research unit
ULB	Libre university of Brussels
UMaVeB	Vector-borne diseases and biodiversity unit

URMaT	Communicable disease research unit
USD	United states dollar
VIF	Variance inflation factor
WAHIS	World animal health information system
WAP	W-Arly-Pendjari
WofE	Weight of evidence method

Table of content

General introduction

Benin and Burkina Faso in West Africa

Benin and Burkina Faso are two West African countries, which share a 386 km borderline.

The Republic of Benin is located between 6°10' and 12°25' north latitude and between 0°45' and 3°55' east longitude. It covers an area of 112 620 km^2 (Cheke, 2001). Potentially cultivable land is estimated at 7 million hectares or almost 63 per cent of the total area. Benin is generally self-sufficient for cereals (with the notable exception of rice) and roots and tubers but is highly dependent on imports of animal and fish products (Aregheore, 2009a). The contribution of livestock to agricultural GDP increased by 2.88 points from 15.5% in 2011 to 18.5% in 2014. The livestock in 2016 was estimated at 2 339 000 cattle, 2 751 000 small ruminants, 466 000 pigs and 19 215 000 poultry. The products from these stocks, in particular meat, milk and eggs, do not guarantee complete coverage of animal protein needs. According to FAO standards, the meat requirements are 21kg/capita/year and eggs 1kg/capita/year. Current levels of animal production cover on average only 8.41 kg/capita/year for meat and 0.6 kg/capita/year for eggs. FAO requirements are thus not covered.

Burkina Faso belongs to the tropical climates characterised by two seasons: a dry season (October-May) and a rainy season called wintering (June-September). Four variants specify the climate of Burkina: a wet period from June to September, dry and hot from September to November, dry and cool from December to March and hot from March to June. Three climatic zones can be distinguished in the country:

- a Sahelian climate zone in the north: there are 3 months of rainfall with less than 600mm of water/year, extreme temperatures ranging from 10 to 45 °C ;
- a North Sudanese climate zone in the centre: 4 to 5 months of rainfall, 600 to 1000mm of water/year, temperatures between 13 and 40 °C;
- a southern Sudanese climate zone in the south: 6 months of rainfall, 1000 to 1300mm of water/year, temperature extremes 12 to 38 °C (Kabore et al., 2017).

Benin and Burkina are part of the West African sub-region. West Africa is composed of 16 countries, which are Benin, Burkina Faso, Côte d'Ivoire, Cape Verde, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone and Togo. This region has a variety of landscapes, agro-ecological zones and a cattle herd that varies according to the country. These ruminants are raised using strategies that vary according to the environment (Hopkins, 2019).

West Africa landscapes

The region's landscapes have been transformed by agricultural activity. The West African Sahel is one of the original centres of world food production. Plants and animals were cultivated and raised here long before these practices developed on the fertile plains of Europe (CSAO and SWAC, 2007).

West African rural areas can be classified according to the type of settlement (villages or camps), the major food and commercial productions, and the agro-ecological systems that shape the landscape. Geographers subdivide the West African region into three zones: the Sahelian zone, the Sudanian zone and the Guinean forest zone (Ly et al., 2010). This classification is based on the abundance or scarcity of rainfall and the vegetation formations: grassy savannahs, shrublands and trees, and secondary forest (**Figure 1**).

The Sahel-Sudanese populations have domesticated the savannas, from their desert banks to the forest edges. They delimited the grazing area for pastoral societies, the land to be inhabited and cultivated, the bush for hunting and the collection of firewood. This was the civilization of millet and granaries. The landscape was shaped by the selection and adaptation of food crops (millet, sorghum, maize) and useful trees (e.g. *acacia albida*, shea, néré, tamarind, gum and mango) (Boffa and Nations, 1999; Weber and Hoskins, 1983). The immense "Fulani arc" unfolds the richness of the movement of herds over contracted grazing areas.

The populations of the Guinean forest have developed techniques for penetrating this closed environment: harvesting agriculture (gathering), slash-and-burn clearing. This is the civilization of cassava and plantain, yams, kola, palm oil, lowland and mangrove rice. It is pioneer agriculture that settles in the forest space and modifies it by creating clearings to camp and cultivate in the middle of insects (Devèze, 2011).

Despite the introduction of commercial crops by colonization, which included cotton, peanuts and cocoa, existing agrarian systems were not destroyed. These populations have therefore integrated monetization with its new potential and possible unfair exchanges. Plantations were created only in the coastal zone, such as rubber, pineapple, palm and sugar cane (CSAO and SWAC, 2007).

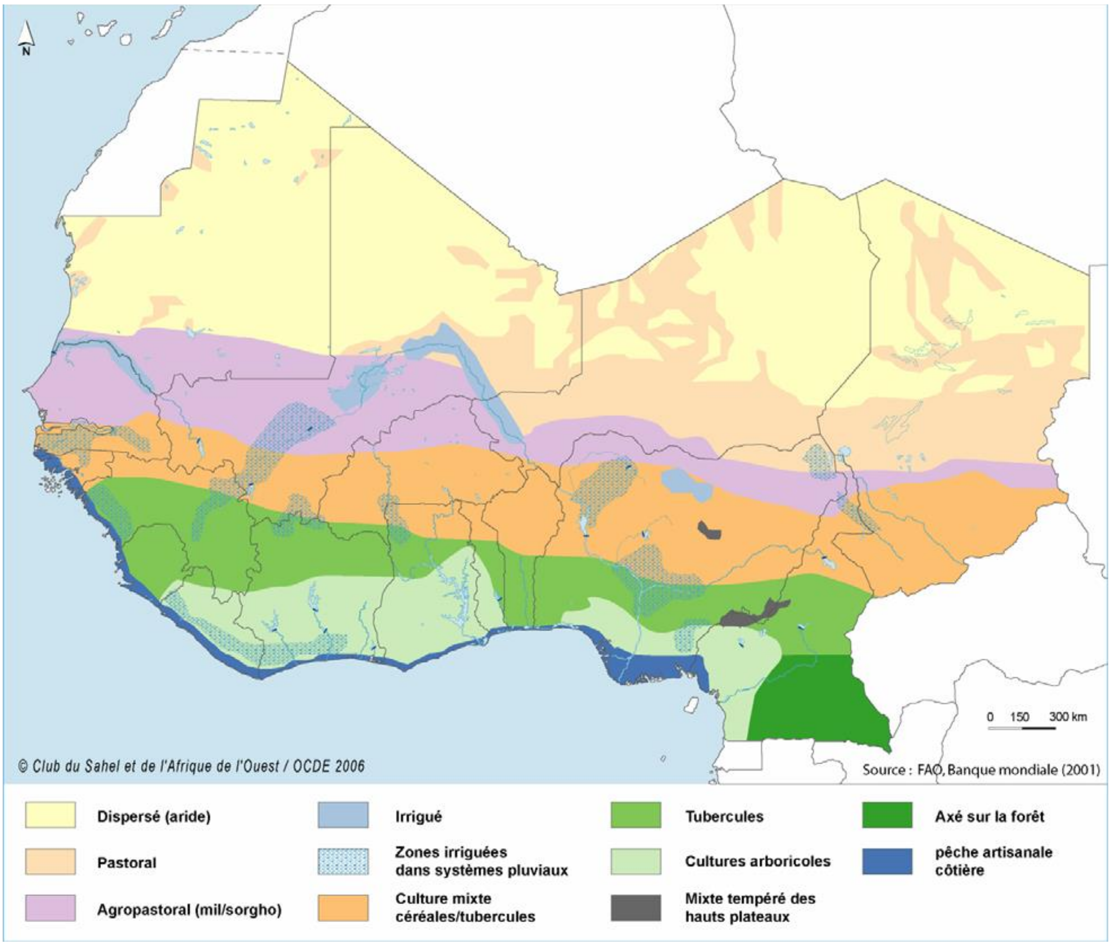

Figure 1. West African farming systems (Source: (CSAO and SWAC, 2007)

West Africa's main agro-ecological zones

Sub-Saharan Africa has six agro-ecological zones, the distribution of which is shown in **Figure 2**. Five of these agro-ecological zones are found in West Africa. These are the desert, arid, semi-arid, sub-humid and humid zones (FAO, 2003).

The Sudano-Sahelian Zone is composed of countries such as Burkina Faso, Cap Vert, Erythrée, Gambie, Mali, Mauritanie, Niger, Sénégal, Somalie, Soudan and Tchad. The Sudanian savanna zone is generally considered to be humid semi-arid and the Sahelian zone is considered to be dry semi-arid. In both zones, water availability tends to be the critical factor in determining which production systems-crop and livestock are appropriate, and water availability depends on soil and landscape factors as well as rainfall (Hountondji, 2008).

The sub-humid zone is composed of some west and central African countries. In West Africa, near the coast, there is a transition from tropical rainforest to a semi-deciduous forest and from a mosaic of savanna and forest to savanna woodland grasslands as the length of the dry season increases and rainfall decreases (FAO, 2003).

The largest wetlands in sub-Saharan Africa are in central and western Africa. Rainfall occurs for more than nine months, with totals exceeding 1,500 mm per year. The main soils are acidic with low levels of fertility. One of the key issues in this area is the management of organic matter, as most of the nutrients are associated with it and are thus concentrated in the upper horizon. Thus, during cultivation, when organic matter is lost through oxidation or erosion, fertility decreases rapidly. The presence of tsetse flies has prevented animals from making any significant contribution to the production system. In traditional shifting cultivation systems, the soil was mostly protected from the erosive force of rainfall by trees and crops (FAO, 2003).

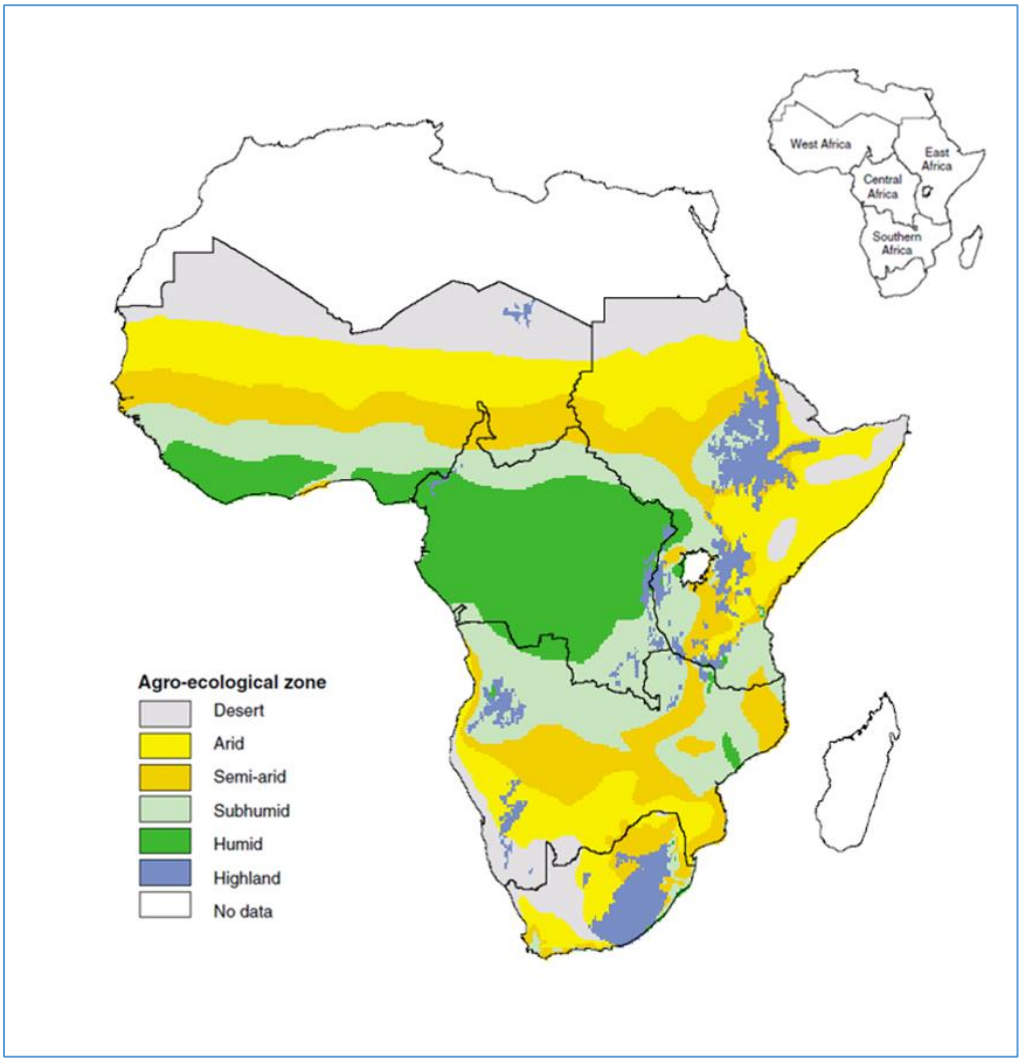

Figure 2. Map of main agro-ecological zones in sub-Saharan Africa (**Source:** FAO, 2003)

Three major river basins also link this West African area: the Senegal, Niger and Lake Chad basins (**Figure 3**).

Joint water management also immediately became a necessity. As early as 1963, nine countries met within the Niger Basin Authority, in 1964 it was the turn of the Lake Chad Basin Commission, then the Organisation for the Development of the Gambia River in 1967, the Organisation for the Development of the Senegal River in 1972 (CSAO and SWAC, 2007).

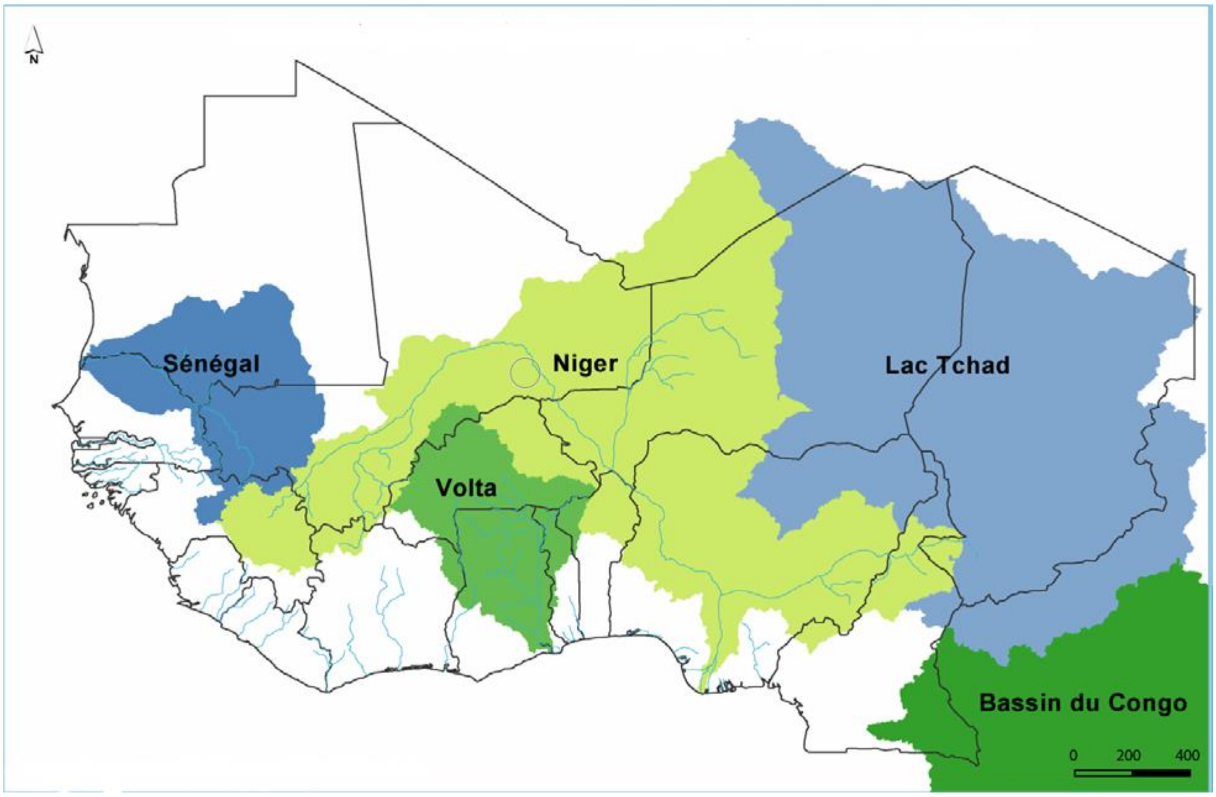

Figure 3. West Africa's major watersheds (Source: CSAO and SWAC, 2007; Copyright: CSAO/OCDE 2006)

West African cattle population and management

In 2019, the West African cattle population was 79 419 666 head (FAO, 2021). This cattle population is concentrated more in the Sahelian zone than in the more humid coastal zone, which is more suitable for agriculture (**Figure 4**). This cattle population is not raised in the same way in the various agro-ecological zones of the West African sub-region (**Figure 5**).

Based on the factors of production we can distinguish two livestock production system in West Africa. The modern system with a large capital requirement and employ substantial amounts of hired labour, and the traditional systems mainly rely on family labour and the extensive use of land (Otte and Chilonda, 2002). In West Africa, the traditional livestock systems are far more prevalent than modern systems.

Traditional ruminant production systems include pastoral and mixed systems practised in lowland and upland areas. Pastoral systems are practised in areas that are too dry for agriculture to provide a livelihood base and where ruminant grazing is the predominant form of land use. Pastoral systems are mainly found in arid and semi-arid areas (with rainfall less than 600 mm per year) of West Africa. Pastoral systems are not widespread in the humid zone and are only seasonal in the subhumid zone (Otte and Chilonda, 2002). The main determining factor in pastoral systems is average rainfall, its reliability and distribution. Three types of pastoral systems can be identified. In the range of rainfall below 400 mm per year, are nomadic pastoralism and transhumant pastoralism. In areas where annual rainfall is between 400 and 600 mm, are agropastoralism, where livestock is associated with cultivation in dry or rainy areas and the animals move over short distances (Jahnke, 1983).

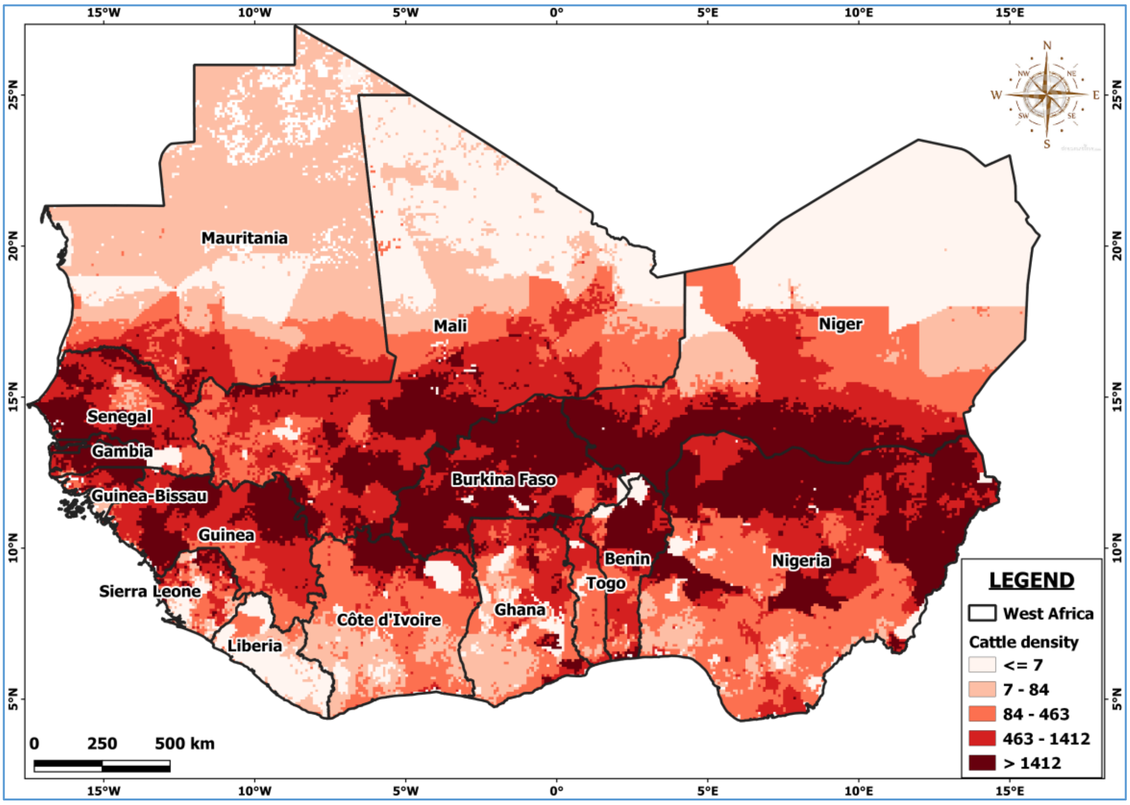

Figure 4. West Africa cattle density; Data source: GLW3 *(Gilbert et al., 2018; Nicolas et al., 2016)*

Mixed systems are found in semi-arid, sub-humid, humid and mountainous areas of West Africa. According to Jahnke (Jahnke, 1983). The term "mixed systems" has a dual meaning. Firstly, it refers to farming systems based on livestock production practised alongside or associated with other farming systems. Second, it refers to livestock systems that integrate agriculture and livestock production. The first type is the most common in West Africa and is characterized by a long tradition of seasonal movement into wetter areas, with movements southward during the dry season and northward during the rainy season. However, most animals in the semi-arid, sub-humid and humid zones are raised in the second type of system, integrated agriculture and livestock. Jahnke (1983) proposes four criteria to characterize these systems: i) agroclimatic conditions, especially rainfall and cropping pattern, ii) human population pressure, expressed by cropping intensity, iii) tsetse challenge and overall livestock importance, expressed by densities and animal species. Trypanosomiasis acts as an increasing constraint on cattle farming as one moves from the semi-arid to the humid zone. Thus, in West and Central Africa, in the humid zone, trypanotolerant breeds of cattle, sheep and goats are replacing the trypanosensitive breeds of the semi-arid zone.

Modern production systems or Ranching systems consist of labour-intensive enterprises specializing in one or more livestock species and producing primarily live animals for slaughter (for meat, hides and skins), but also wool and milk. Grazing occurs within fixed, well-delineated boundaries. Ranching systems occur sporadically in the drier regions of West Africa. Ranches are also found in the wetlands of West Africa. They are not a predominant form of land use in this region. There are also some ranches in the highlands. Ranches generally represent improved management of livestock, grazing and water (Otte and Chilonda, 2002).

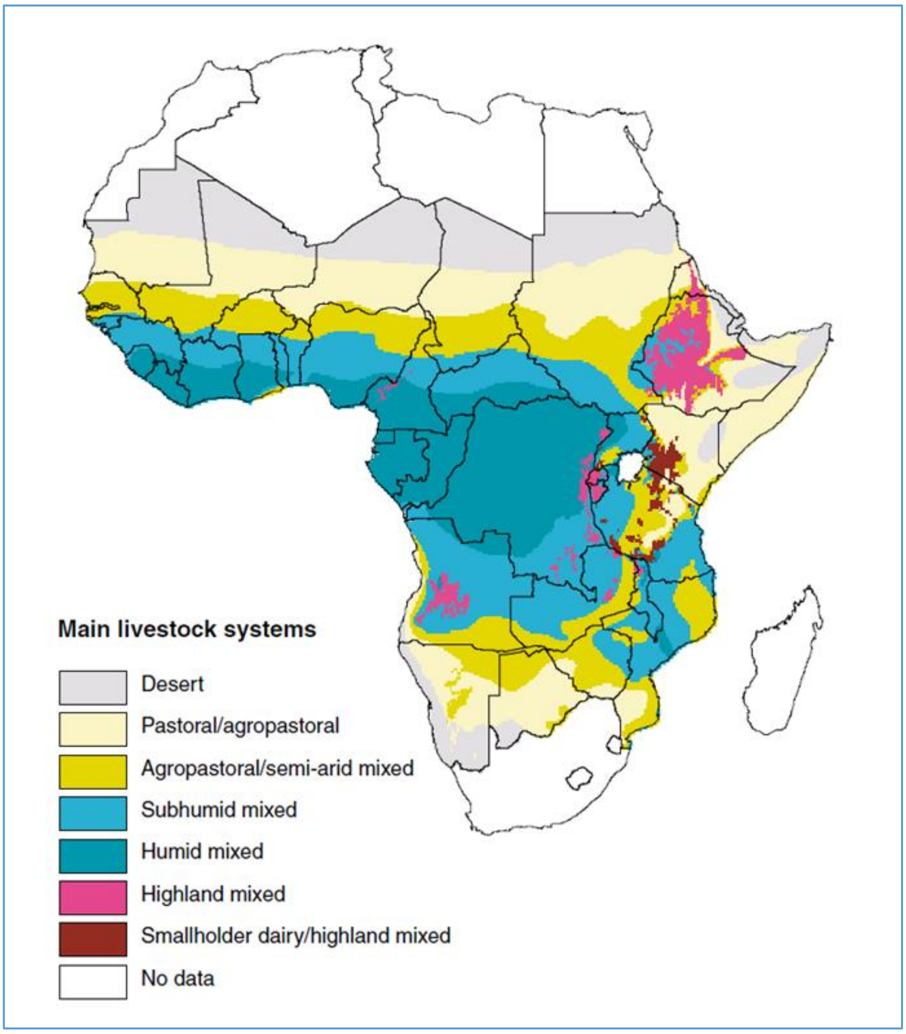

Figure 5. Ruminant production systems in sub-Saharan Africa (Source: Otte and Chilonda, 2002)

Ticks and tick borne diseases, an overview of the systematic, the biology and their medical importance

1.1. Ticks (Acari: Ixodida)

Ticks are all obligate hematophagous arthropods. They parasitize vertebrates at least during part of their life cycle. They are found almost everywhere on the globe, from the warmest to the coldest areas. They belong to the class Arachnida, suborder Ixodida. There are two main families of tick species in this taxonomic group which are " Ixodidae" and "Argasidae". These two major families of ticks parasitize humans, domestic animals and a wide range of wild hosts (McCoy, 2016). Their bites create significant direct damage to their hosts: anaemia, superinfection of bites, injection of toxins causing paralysis, tropical dyshidrosis or allergic reactions. Ticks also transmit numerous infectious agents such as bacteria, viruses and parasites. Some of these transmitted agents are of major health and socio-economic importance, such that ticks are currently among the most important diseases vectors in human and veterinary medicine (**Table 1**). The emergence of several tick-borne diseases and the observation of significant changes in the abundance and distribution of several species has advanced research on these arthropods in recent years. The number of tick species is certainly underestimated at present, because of the bias of studies focused mainly on species that affect humans and the animals they live with directly. Other vertebrates, less close to humans, surely have their own set of ectoparasites including ticks, many of which remain to be discovered (Duvallet et al., 2017).

Table 1: Main diseases transmitted by ticks (Sources:*(Duvallet et al., 2017; Rochlin and Toledo, 2020; Shi et al., 2018)*

Disease or condition	**Pathogen [main vector]***	**Geography**	**Prevalence† and comments**
Viral			
***Flaviviridae*/*Flavivirus* (tick-borne encephalitis group)**			
Tick-borne encephalitis (TBE)	TBE virus complex (*I. ricinus*, *I. persulcatus*)	Europe, Asia, Middle East	Common and widespread
Powassan encephalitis (POW)	POW virus (*I. scapularis*, *I. cookei*)	Northeastern USA/ adjacent Canada, Russian Far East	Rare, increasing
Other TBEs: Omsk haemorrhagic fever (OHF), Kyasanur Forest Disease (KFD), louping ill, others	OHF, KFD, other viruses (*Ixodes*, *Dermacentor*, *Haemophysalis* sp.)	Europe, Russia, China, Japan, India, Southeast Asia, Middle East	Rare to common within localized range; some increasing
Bunyavirales/*Orthonairovirus*			
Crimean–Congo haemorrhagic fever (CCHF)	CCHF virus (*Hyalomma marginatum*, other tick sp.)	Europe, Central Asia, India, Africa	Common and widespread; increasing
Bunyavirales/*Phlebovirus*			
Severe fever with thrombocytopenia syndrome (SFTS)	SFTS virus (*H. longicornis* and *R. microplus*)	China, Korea, Japan	Uncommon, increasing
Heartland virus	(*A. americanum*)	Mid-western and southern USA	Rare

Disease or condition	**Pathogen [main vector]***	**Geography**	**Prevalence† and comments**
Bhanja virus	(*Dermacentor*, *Haemophysalis* sp.)	Africa, Central Asia, southern Europe	Rare
Orthomyxoviridae*/*Thogotovirus			
Thogoto (THOV), Dhori (DHOV) and Bourbon virus	(*Hyalomma*, *Amblyomma*, *Rhipicephalus* sp.)	Africa, Asia, Europe (THOV and DHOV), USA (Bourbon)	Rare; Bourbon virus isolated from *A. americanum*
Reoviridae*/*Coltivirus			
Colorado tick fever (CTF)	CTF virus (*D. andersoni*)	Western USA and Canada	Rare
Eyach virus	(*I. ricinus*)	Central Europe	Rare
Bacterial			
Spirochaetales/*Borrelia* spirochetes (borreliosis and relapsing fever)			
Lyme disease	*Borrelia burgdorferi* (*I. ricinus* complex)	Temperate North America, Europe, Asia	Common, widespread
Relapsing fever borreliosis	*B. miyamotoi* (*I. ricinus* complex)	Temperate North America, Europe, Asia?	Rare
Relapsing fever borreliosis – tick-borne relapsing fever (TBRF)	Relapsing fever *Borrelia* (*Ornithodoros* and *Carios* sp.)	Worldwide (except Australia), mostly tropical and desert regions	Rare to common locally
Southern tick-associated rash illness (STARI)	Unknown (*A. americanum*)	Southern and eastern USA	Rare
Rickettsiales/*Rickettsia* (spotted fever and tick typhus)			
Rocky Mountain spotted fever (RMSF)	*Rickettsia rickettsii* (*D. variabilis*, *D. andersoni*, *R. sanguineus*)	Western hemisphere	Common
Rickettsiosis	R.parkeri (*A. maculatum*)	Southern and mid-Atlantic USA, South America	Rare, emerging in South America
Pacific Coast tick fever (PCTF)	*R. philipii* (*D. occidentalis*)	California, Pacific coast	Rare
Mediterranean spotted fever	*R. conorii* complex (*Rhipicephalus sanguineus*)	Europe, Africa, Middle East, Asia	Uncommon, imported
African tick bite fever	*R. africae* (*Amblyomma* sp.)	Africa, West Indies, Oceania	Uncommon, imported
Rickettsiales/*Anaplasmataceae* (anaplasmosis and ehrlichiosis)			
Human granulocytic anaplasmosis (HGA)	*Anaplasma phagocytophilum* (*I. scapularis*, other sp.)	Northeastern and central USA	Common; emerging in Europe and Asia
Human ehrlichiosis	*Ehrlichia chaffeensis*, *E. ewingii* (*A. americanum*)	Eastern USA	Common
Human ehrlichiosis	*E. muris eauclairensis* (*I. scapularis*)	Minnesota and Wisconsin	Rare
Neoehrlichiosis	*Ca*. *N. mikurensis* (*Ixodes* sp.)	Europe, Asia	Rare
Other bacterial			
Tularaemia	*Francisella tularensis* (*Amblyomma*,	North America, Europe, Asia	Uncommon by tick bite; other

Disease or condition	Pathogen [main vector]*	Geography	Prevalence† and comments
	Dermacentor Ixodes and Haemaphysalis)		routes of exposure
Q fever or Coxiellosis	*Coxiella burnetii* (*Rhipicephalus* spp. and *Dermacentor* spp)	Comopolitan	Common
Parasites (Protists)			
Human babesiosis	*Babesia microti*, *B. divergens*, (*I. ricinus* complex)	Northeastern and Midwestern USA Europe, China	Common; emerging in Europe and Asia
Human babesiosis	*B. duncani* (WA-1 type parasite) (*D. albipictus*, *I. pacificus*?)	Pacific Coast of North America	Emerging
Theileriosis	*Theileria annulata* (*Hyalomma* spp)	Europe, Asia, Africa	
Theileriosis	*Theileria parva* (*Rhipicephalus* spp)	Africa	
Tick bite associated (non-pathogenic)			
Alpha-gal syndrome (red meat allergy)	(*A americanum*, *H. longicornis*, *Ixodes* sp.)	Worldwide	Uncommon, increasing
Tick paralysis	Various species	USA, Australia, other countries	Rare
Disease or condition	Pathogen [main vector]*	Geography	Prevalence† and comments
Viral			
***Flaviviridae*/*Flavivirus* (tick-borne encephalitis group)**			
Tick-borne encephalitis (TBE)	TBE virus complex (*I. ricinus*, *I. persulcatus*)	Europe, Asia, Middle East	Common and widespread
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Other TBEs: Omsk haemorrhagic fever (OHF), Kyasanur Forest Disease (KFD), louping ill, others	OHF, KFD, other viruses (*Ixodes*, *Dermacentor*, *Haemophysalis* sp.)	Europe, Russia, China, Japan, India, Southeast Asia, Middle East	Rare to common within localized range; some increasing
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Bunyavirales/*Phlebovirus*			
Severe fever with thrombocytopenia syndrome (SFTS)	SFTS virus (*H. longicornis* and *R. microplus*)	China, Korea, Japan	Uncommon, increasing
Heartland virus	(*A. americanum*)	Mid-western and southern USA	Rare
Bhanja virus	(*Dermacentor*, *Haemophysalis* sp.)	Africa, Central Asia, southern Europe	Rare
Orthomyxoviridae*/*Thogotovirus			
Thogoto (THOV), Dhori (DHOV) and Bourbon virus	(*Hyalomma*, *Amblyomma*, *Rhipicephalus* sp.)	Africa, Asia, Europe (THOV and DHOV), USA (Bourbon)	Rare; Bourbon virus isolated from *A. americanum*

Disease or condition	**Pathogen [main vector]***	**Geography**	**Prevalence† and comments**
Reoviridae*/*Coltivirus			
Colorado tick fever (CTF)	CTF virus (*D. andersoni*)	Western USA and Canada	Rare
Eyach virus	(*I. ricinus*)	Central Europe	Rare
Bacterial			
Spirochaetales/*Borrelia* spirochetes (borreliosis and relapsing fever)			
Lyme disease	Borrelia burgdorferi (*I. ricinus* complex)	Temperate North America, Europe, Asia	Common, widespread
Relapsing fever borreliosis	B.miyamotoi (*I. ricinus* complex)	Temperate North America, Europe, Asia?	Rare
Relapsing fever borreliosis – tick-borne relapsing fever (TBRF)	Relapsing fever *Borrelia* (*Ornithodoros* and *Carios* sp.)	Worldwide (except Australia), mostly tropical and desert regions	Rare to common locally
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Rocky Mountain spotted fever (RMSF)	*Rickettsia rickettsii* (*D. variabilis*, *D. andersoni*, *R. sanguineus*)	Western hemisphere	Common
Rickettsiosis	R.parkeri (*A. maculatum*)	Southern and mid-Atlantic USA, South America	Rare, emerging in South America
Pacific Coast tick fever (PCTF)	*R. philipii* (*D. occidentalis*)	California, Pacific coast	Rare
Mediterranean spotted fever	*R. conorii* complex (*Rhipicephalus sanguineus*)	Europe, Africa, Middle East, Asia	Uncommon, imported
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Human ehrlichiosis	*Ehrlichia chaffeensis*, *E. ewingii* (*A. americanum*)	Eastern USA	Common
Human ehrlichiosis	*E. muris eauclairensis* (*I. scapularis*)	Minnesota and Wisconsin	Rare
Neoehrlichiosis	*Ca. N. mikurensis* (*Ixodes* sp.)	Europe, Asia	Rare
Other bacterial			
Tularaemia	*Francisella tularensis* (*Amblyomma, Dermacentor Ixodes and Haemaphysalis*)	North America, Europe, Asia	Uncommon by tick bite; other routes of exposure
Parasites (Protists)			
Human babesiosis	*Babesia microti*, *B. divergens*, (*I. ricinus* complex)	Northeastern and Midwestern USA Europe, China	Common; emerging in Europe and Asia

Disease or condition	Pathogen [main vector]*	Geography	Prevalence† and comments
Human babesiosis	*B. duncani* (WA-1 type parasite) (*D. albipictus*, *I. pacificus*?)	Pacific Coast of North America	Emerging
Tick bite associated (non-pathogenic)			
Alpha-gal syndrome (red meat allergy)	(*A americanum*, *H. longicornis*, *Ixodes* sp.)	Worldwide	Uncommon, increasing
Tick paralysis	Various species	USA, Australia, other countries	Rare

*Generic tick names abbreviated in (): *A.*, *Amblyomma*; *D.*, *Dermacentor*; *H.*, *Haemophysalis*; *I.*, *Ixodes*; *R.*, *Rhipicephalus.*
†Prevalence, reported annual number of human cases (approximate): rare, <10; uncommon, >10–1000; common, >1000; common and widespread, ≈several thousands.

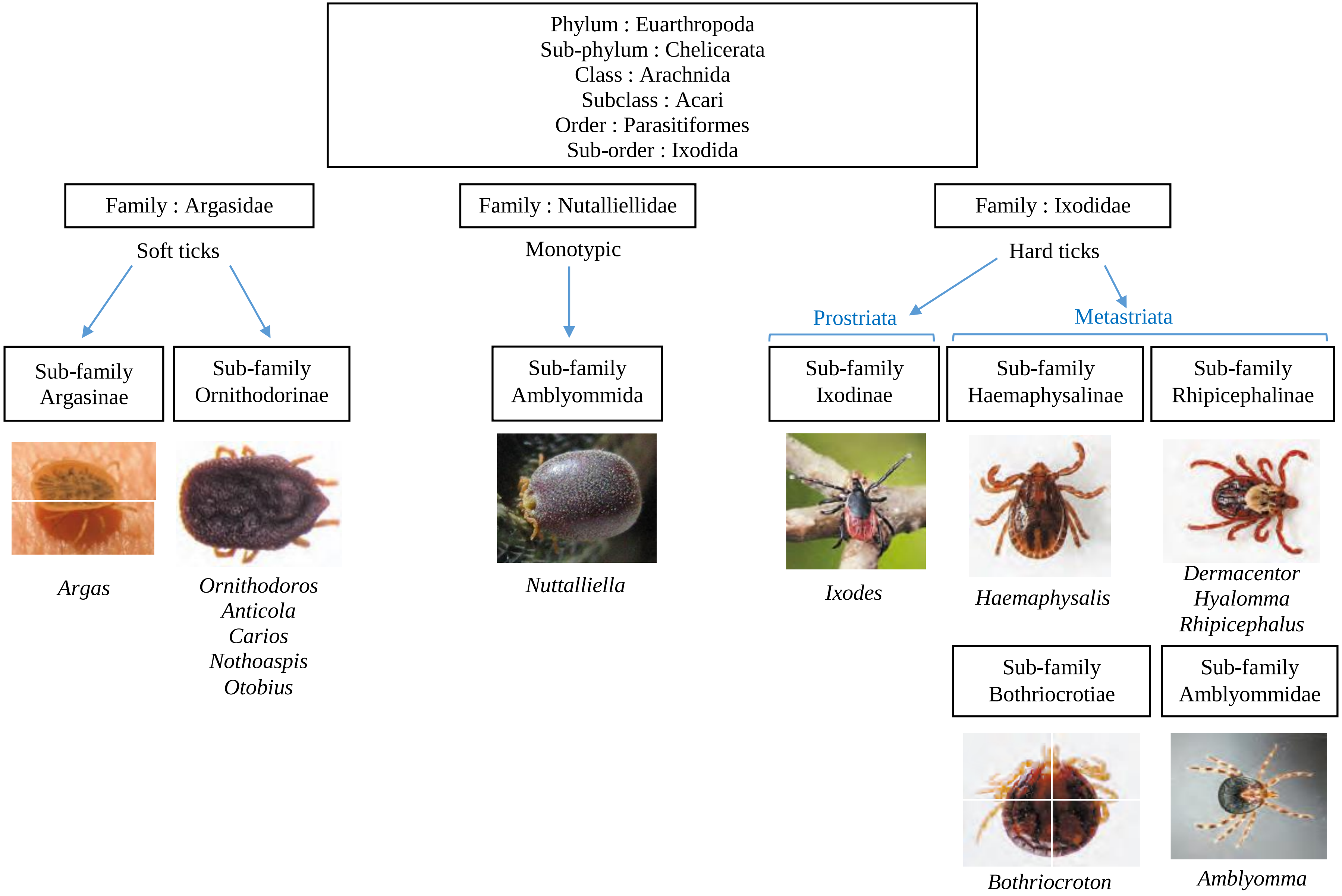
*Generic tick names abbreviated in (): *A.*, *Amblyomma*; *D.*, *Dermacentor*; *H.*, *Haemophysalis*; *I.*, *Ixodes*; *R.*, *Rhipicephalus.* †Prevalence, reported annual number of human cases (approximate): rare, <10; uncommon, >10–1000; common, >1000; common and widespread, ≈several thousands.

1.2. Systematic

Ticks belong to the phylum Euarthropoda, and the sub-branch Chelicerata (**Figure 6**). During evolution, they have diverged from insects, which are part of the sub-branch Mandibulates. Indeed, ticks are part of the class Arachnida and are thus more related to scorpions and spiders (Lecointre and Le Guyader, 2001). They are members of the subclass Acari, which is divided into two orders: the Acariformes - most mites - and the Parasitiformes, which includes hematophagous species such as ticks. Ticks are therefore large mites that can measure up to 3 cm in length. They are all grouped in the suborder Ixodida, which has about 900 species. This suborder is subdivided into three families: the family Ixodidae (hard ticks) composed of about 700 species, the family Argasidae (soft ticks) with 200 species and the family nutalliellidae with one known species (Guglielmone et al., 2010). This last species, *Nuttalliella namaqua*, relatively unknown, has the particularity of borrowing characters from the two other families of ticks. It is considered the closest species to the common ancestor of all ticks (Mans et al., 2012). While systematics at the family level and beyond remain relatively stable, they change at lower levels in important ways depending on the school of thought. Advances in molecular biology may introduce major revisions in tick systematics (Duvallet et al., 2017). The systematics presented here is that of the classification of Guglielmone et al. (2010).

The taxonomy of the Ixodidae has been better developed than that of the Argasidae. The vast majority of the scientific community agrees on the systematic position of the genera of this family. The family Ixodidae is now considered to include the genera *Ixodes, Haemaphysalis, Amblyomma, Rhipicephalus, Dermacentor, Hyalomma, Anomalohimalaya, Bothriocroton, Cosmiomma, Margaropus, Nosomma,* and *Rhipicentor* (plus the fossil representatives *Compluriscutula* and *Cornupalpatum*). On the other hand in the family Argasidae, the situation is different. There is a battle of the schools with totally different taxonomies between the western and eastern currents and a third group (Estrada-Peña, 2015).

Figure 6. Classification of hard and soft ticks (Adapted from Duvallet et al., 2017) *Ornithodoros capensis* (© M. Dupraz), *Ixodes ricinus* (© E. Léger), *Haemaphysalis leporispalustris* and *Dermacentor occidentalis* (© P. j. Bryant), *Bothriocroton hydrosauri* (© ICPS-GSu/H. Seabolt), *Amblyomma variegatum* (© université d'Edimbourg/R. Matthews et A.R. Walker), *Nuttalliella Namaqua* (doi: 10.1371/journal.pone.0023675)



1.3. Biology-Ecology

Ticks are obligatory temporary parasites of vertebrates. They are characterized by a complex development cycle. That consists of three stages (other than eggs), namely the larva, the nymph and the adult (male and female). How these stages develop and how long the tick life cycle lasts depends on the tick family. Ticks from the Ixodidae and Argasidae families have different life cycles. Ixodidae feed for several days, while Argasidae feed for only a few minutes, usually at night when the animals are resting in their burrows. Ticks that restrict themselves to the shelters of their hosts have an "endophilic" behaviour, as they live near a suitable blood source and their development is not influenced by weather conditions outside the burrow. All argasid ticks and some ixodid ticks exhibit “endophilic” behaviour (Gray et al., 2013). The feeding stages of species that have evolved this survival strategy fall off the host inside the nest or burrow. This increases their chances of survival, as they moult in the shelter, in a protected environment. The opposite type of behaviour, called "exophilic," involves the ticks waiting for a suitable host outside the burrow, exposed to the weather. Weather variables regulate the behaviour of these ticks as they actively search for a host. The ixodid life cycle typically includes the larva (which hatches from the egg), the nymph, and the adult. Ixodid ticks feed once in each active stage and ingest massive amounts of blood. Ticks may use different host groups for each active stage. Immature stages (larvae and nymphs) typically feed on small hosts, such as rodents and/or birds, while adults typically feed on large animals, including carnivores and ungulates. However, this rule does not apply to all tick species. Some species are very specific of a particular type of host. The absence of this key host(s) in a given area may prevent the appearance of ticks that feed specifically on it.

Pathogen transmission begins approximately 24 hours after the tick begins to feed on its host. After each blood meal, the ticks detach, fall to the ground and moult. The engorged females do not moult but lay thousands of eggs in decaying vegetation in protected sites. The immature stages (larvae and nymphs) usually feed for three to six days, while the adults may feed for up to two weeks. After the blood meal, the tick will moult. Then it will actively search for a new host. The diagram in **Figure 7** shows the different stages of a three-host cycle. In this type of life cycle, the tick feeds on a different host at each stage. Some species complete their life cycle by feeding on only two hosts. Other species may complete their entire life cycle on a single host. These different types of life cycles play a determining role in the survival of ticks. As the climate is very important in the development of ticks (mortality during moulting phases), ticks that complete their cycle in fewer stages (i.e. fewer moults) are less dependent on the environment. These factors are also very important for the transmission of pathogens. A tick-borne pathogen can only be transmitted to a host when the infected tick survives all stages of its cycle in the environment (Kahl et al., 2002). The dynamics of a pathogen in the field, therefore, depend strongly on both the survival and activity rates of the tick and the composition of the host community (Estrada-Peña et al., 2013). Ticks spend long periods between meals in the environment, during which they are exposed to the weather.

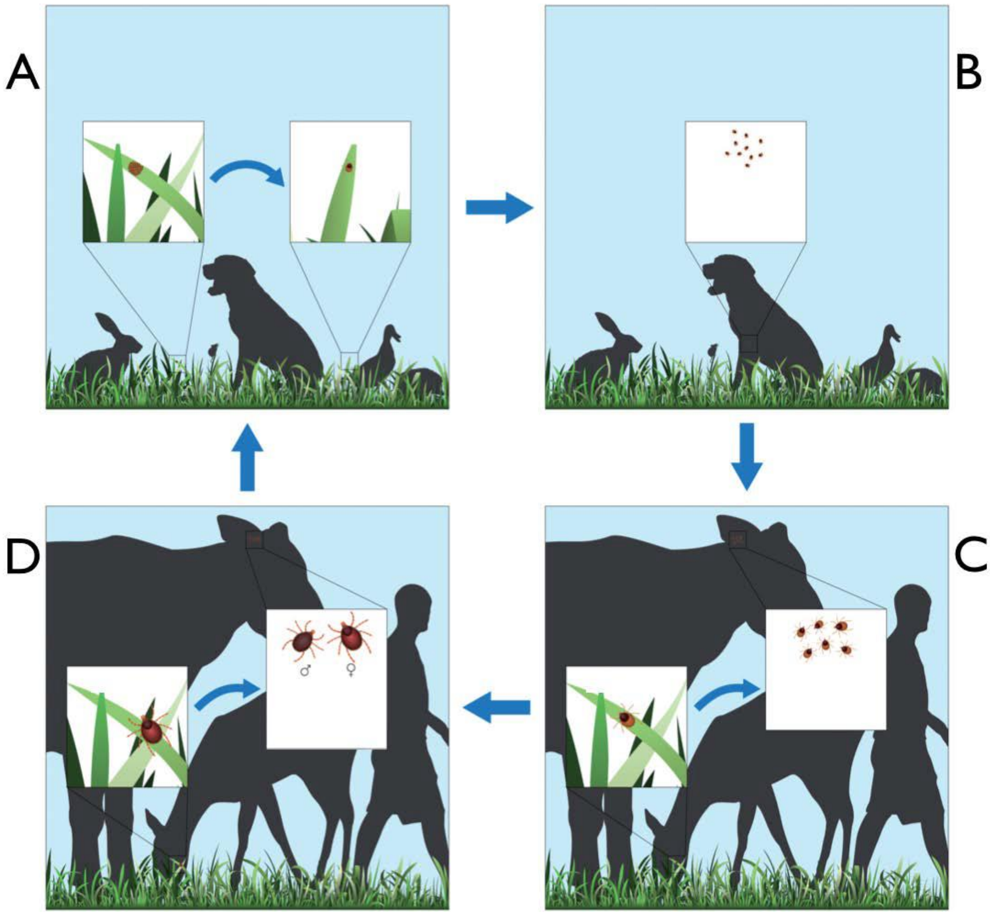


Figure 7: The life cycle of a three-host tick (Source: Image prepared by Alex McAuley, University of Texas Medical Branch, Galveston, United States of America)

Legend: Larvae hatch from eggs, and quest in the vegetation for a host (A). After attachment and feeding (B), the larvae drop to the ground to moult, a process regulated by temperature and the availability of water. The nymphs quest again after moulting (C) and feed upon a second host. These engorged nymphs again drop to the ground for a final moult to the adult stage, which again quests, finds a suitable host, and drops to the ground to lay eggs (D).

1.4.Tick-borne diseases of animal and/or human medical importance

Ticks are major vectors of infectious agents (Moutailler et al., 2015). In veterinary terms, they are the most important vectors ahead of mosquitoes. In human medicine, ticks are second to mosquitoes in terms of importance. The knowledge of vector-borne diseases has greatly evolved in recent years thanks to molecular and cellular biology, diagnosis and environmental epidemiology. The pathogens transmitted by ticks are very diverse. They include bacteria (e.g. spirochetes, Rickettsia, Ehrlichia, etc.), viruses (e.g. flaviviruses, orthonairoviruses, phleboviruses, and thogotoviruses) and also parasites (e.g. *Babesia* spp. and *Theileria* spp.) (**Table 1**). The diseases caused by these different organisms are mostly zoonoses. Humans accidentally contract these diseases through the bites of infected ticks. This happens when visiting tick-infested biotopes (e.g. forestry, hunting, and recreational activities). Some tick-borne diseases seem to be on the increase, others are described as emerging. Migratory flows and globalization have favoured the appearance of certain pathologies in new geographical areas (e.g. Crimean-Congo fever, African swine fever, Lyme disease). These new appearances are made through the introduction of their vectors by the movement of livestock (e.g. *Rhipicephalus microplus* and babesiosis) (de la Fuente et al., 2008). Local emergences are related to more varied factors such as human-induced socioeconomic and environmental changes (Kilpatrick and Randolph, 2012). It should be noted, however, that the evolution of knowledge of the cycles of these vector-borne diseases and the improvement of diagnostic techniques, particularly by molecular biology (Polymerase Chain Reaction, PCR), allow for a better diagnosis of affected people and animals. All these elements put together can also explain why some of these diseases seem to be emerging. Climate change may also explain the increased incidence of tick-borne diseases in some parts of the world. For example the expansion and the increase of the abundance of *Ixodes ricinus* in Sweden was correlated with climate change (Gray et al., 2009). These climate changes may contribute to the disappearance of certain species in certain environments where they were abundant and thus the decline of the diseases they transmit (E. Léger et al., 2013).

Transhumance

Transhumance (internal and cross-border) is one of the most important livestock production strategies in West Africa. It enables the feeding of an increasingly important Sahelian livestock population. It also contributes to sub-regional integration and the supply of ruminant products to an increasingly large population. However, it is causing more and more problems due to the often deadly farmer-cattle holder conflicts it causes and the spread of diseases (Adum et al., 2019; Adzande, 2019).

2.1. An ancestral animal production strategy to increase resilience

Transhumance is an ancestral animal production system characterised by regular seasonal movements between complementary ecological zones, under the care of a few people, with the bulk of the group remaining sedentary. It is a livestock system based on practical and economically viable management of pastoral resources that have enabled pastoral people such as the Peulhs, the Tuaregs and the Moors to survive the major ecological and climatic crises that periodically occur in the Sahel countries. Transhumant herds generally move from environments in disequilibrium and where grazing is scarce to areas considered to be still well supplied with grazing. In this context, transhumance in West Africa can be seen as a form of adaptation to these environments and as a way of exploiting the ecological complementarities between Sahelian and Sudanian regions (Alidou, 2016; Kamuanga et al., 2008; SWAC/OECD, 2007). During this seasonal and traditional migration, herds travel hundreds of kilometres within or across national borders and a transhumance season can last from 3 to 8 months (Ayantunde et al., 2014). The speed and duration of these seasonal movements depend on the region, the year, and can be correlated with many local conditions. These include the length of the rainy and dry seasons; the number of animals in the herd; the availability of other herds; the population density; the extent of cropland and the availability of appropriate markets where dairy products can be sold (Stenning, 1957).

The main factors that determine transhumant pastoralism in the West African region are twofold: environmental factors and socio-economic factors. The environmental factors are mainly climate change/variability, drought and the resulting seasonal shortage of pasture and water, and animal diseases. Socio-economic factors are changes in land use, population pressure resulting in the progressive loss of grazing land, social relationships and networks (Ayantunde et al., 2014).

The conceptual frameworks that underpin transhumance in West Africa include the mobility paradigm, the modernization paradigm, the stimulus-response concept, the migration drift paradigm and the ecological rationality of transhumance. These frameworks allow us to understand the socio-ecological concepts and debates concerning livestock mobility in the region. It is important to note that there is no single conceptual framework that can be used to explain transhumance in West Africa.

During cross-border transhumance, certain equipment and infrastructures are necessary for its smooth running. These include, in particular, water points, grazing areas, markets, salt pans, fords, resting places and passage tracks. Lodges and tracks are important to make way for animals to pass through cultivated areas or to reach water points without damages (FAO and ECOWAS, 2012). The corridors play an important role in the peaceful conduct of transhumance between cattle holders and farmers. However, the corridors are occupied by fields. Despite the usefulness of these corridors, which is recognised by the various stakeholders, some farmers sometimes occupy them with their crops. The markers of these corridors are sometimes removed by farmers (FAO and ECOWAS, 2012). Sometimes it is the pastoralists who allow their animals to leave the corridors and cause damage in the surrounding fields. This is most often due to the lack of monitoring and the failure to consult the local population. A corridor is a strip of land reserved for the passage of livestock to graze, to a watering-place or to a pastoral infrastructure (livestock market, vaccination park, holding pen, from one area to another, transhumance for example) (FAO and ECOWAS, 2012; Maman Moutari and Giraut, 2013). The characteristics of a passageway are:

- the width varies between 50 and 100m depending on the level of pressure on the land resource;
- variable direction and direction depending on the path of the livestock, the layout of pastoral resources and infrastructure and the occupation of the land by crops;
- straight, curved or straight trajectory depending on the detours required;
- a corridor is most often marked by signs specific to the locality (e.g. painting on trees, planting, markers, and plaques) (Alidou, 2016).

A grazing area is an area identified, demarcated and reserved primarily for grazing. It may be developed or undeveloped. It must have good quality pasture and be able to accommodate a significant number of livestock. It must not be crumbled by crop fields or closed vegetation formations (e.g. dense dry forests).

The area must take great account not only of the quantity and quality of the pasture but also of its carrying capacity (Alidou, 2016).

2.2. Economical and sociological aspects

Transhumant pastoralism is important in the SWA's livestock sector and involves 70-90% of the Sahel's cattle and 30-40% of its sheep and goats. Experts agree that it protects the environment and is profitable and competitive, as well as allowing some West African communities, especially the Peulhs, to affirm their cultural identity. Transhumant pastoralism supplies about 65% of cattle meat, 40% of mutton and goat meat and 70% of milk.

Transhumance contributes to the development of the local economy through the expenses incurred by transhumant cattle holders throughout their journey. These expenses, estimated at 687 Euro per herd and per transhumance season, cover the costs of human and animal health, cattle feed, food and accommodation for the cattle holders and other social needs. It also contributes to regional trade through the connection between the people of the Sahel and those of the coastal countries, as these host countries serve as outlets for the sale of animals and animal products. By enabling the development of inter-zonal complementarities in the community space, it thus strengthens regional integration as promoted by the regional economic communities - RECs (ECOWAS, UEMOA) (FAO, 2012a).

Despite its importance, it still faces serious obstacles that threaten its potential production.

During the transhumance, the herds move through several regions, including agricultural and protected areas. Sometimes herds can cause damages by grazing in fields, harvests and protected areas. Some of them can get lost. The distances and amplitudes of the movements are very variable. Conflicts between farmers and cattle holders can arise during these movements because of damage caused by the animals in the farmers' fields. To avoid these conflicts following damage, legislative and legal texts have been adopted at the regional level (ECOWAS). We can cite, among others, the decision A/DEC.5/10/98 regulating transhumance between the ECOWAS Member States. These laws aim to define the corridors for the passage of grazing areas and other management infrastructures for transhumant livestock. These pastoral facilities contribute to improving the practice of transhumance.

2.3. Epidemiological and animal and/or human health aspects

Apart from the social conflicts that transhumance causes between cattle holders and farmers, resulting in the loss of human lives each year, this type of livestock farming also contributes to the epidemiological map of several human and animal diseases in the sub-region.

During transhumance, people and their livestock pass through and spend most of their time in areas where there is little veterinary, medical, educational or livestock infrastructure. The diseases present are often not recorded and control strategies are rarely implemented. The epidemiology of different diseases in transhumant communities is furthermore dependent on particular husbandry practices, livestock species, close contact between humans and livestock, and the frequency of migration. The frequency of migration protects livestock keepers and their animals from the accumulation of free-living stages of parasites, including most faecally transmitted protozoa and helminths, as well as from large numbers of nuisance flies (Macpherson, 1995). Migration, however, increases the risk of contamination with geographically limited or seasonally abundant diseases. Examples in Africa include *Trypanosoma spp*. and *Cowdria ruminantium*, which have a profound effect on migration patterns. Migration also increases the opportunity for interaction between domestic and wild animals, facilitating the transmission of several common diseases, including bacterial, viral, rickettsial and protozoan infections (Zannou et al., 2021a). Temperature and relative humidity play an important role in the distribution of parasitic species that have free-living forms or indirect life cycles, particularly those with invertebrate hosts.

Socio-cultural determinants and stakeholder practices of Epidemiological Surveillance Networks in cross-border transhumance areas (Burkina Faso - Benin)

3.1. Preparations for cross-border transhumance

At the administrative level, to obtain the International Transhumance Certificate (ITC), transhumant are required to vaccinate their animals against dreaded diseases such as contagious bovine pleuropneumonia, bovine pasteurellosis and symptomatic anthrax. It should be noted that transhumant select certain dairy cows and bulls to receive preventive treatment against trypanosomiasis, which is the dreaded disease in the study area (Zina, 2017).

Economically, the owners prepare a substantial budget to meet the various expenses during the transhumance. Breeders who do not have cash sell a few bulls on the various livestock markets to cover expenses.

On the cultural level, as the majority of transhumant cattle holders are Muslim, they proceed with the psychological and spiritual preparation of the cattle holders and the herd. Novice transhumant cattle holders are reminded of good manners and politeness to avoid problems during transhumance. Some consult marabouts to predict the state of the road. The marabouts write Koranic verses to make amulets for the protection of the shepherd and the herd against predators (lions) that are in the grazing areas. Most of these amulets are hung on the neck of a calf. The role of the amulets is to make the herd and the shepherd invisible to the lions (Zina, 2017).

3.2. Actors in animal disease surveillance networks

- Formal institutional actors

Veterinary services, in the field, are of two types: private and public. They are in charge of epidemiological surveillance and health care for the various herds present in their territory.

The Prefecture federates the actions of the veterinary services. It deals with the regulation of transhumance and grazing by issuing prefectural decrees applying ECOWAS decisions. In the surveillance of animal diseases, the prefect intervenes when there are suspected cases or confirmed outbreaks. In case of confirmed outbreaks, in collaboration with the local veterinary services, the prefect gives instructions to the forces of law and order to immobilise infected herds to prevent the spread.

The security forces (water and forestry agents and gendarmes) intervene on the instructions of the competent authorities (mayors or prefects) to circumscribe the suspected area and prevent the owners of suspected herds from fleeing (Zina, 2017).

- Informal institutional actors

The Fulani are perceived as 'non-natives' in both their home and host areas. The Rugga and the Garso are nowadays the official and central political institution for both sedentary and transhumant cattle holders, who represent them vis-à-vis the state and the communes. Indeed, the Rugga is the basic traditional institution of the pastoral community that is responsible for organising transhumance and managing the difficulties encountered by the cattle holders along their routes. He is assisted at the local level by the Garso, who act as relays and informers or scouts (Thomas Bierschenk and Reiner Forster, 2004).

The local customary administration is involved in disease surveillance through chiefs, chairmen and members of village development committees (VDCs). When these authorities receive information about suspected disease outbreaks, they intervene by immobilising the infected herd or prohibiting it from crossing territorial boundaries. The chief of the area affected by the suspected outbreak informs his population and neighbouring villages through a town crier to take precautions (Zina, 2017).

3.3. Local knowledge and representations of animal diseases

Farmers have developed a set of symptoms that allow them to organise their popular representations of animal diseases. These groups of symptoms enable them to establish diagnoses and initiate treatment, sometimes well before they have to seek veterinary help. The possibilities of therapeutic recourse include i) self-medication with medicinal plants and the occult sciences; ii) self-medication with veterinary products sold on the informal market and iii) veterinary posts. Also, some diseases and diseases symptoms are named in Fulfulde. For example, fever is referred to as 'Djuké', lumpy skin disease as 'Boorla' and foot and mouth disease as 'Safa'. Ticks in general are referred to as "Koti" with nuances concerning the genus. For example, "Koti Balaidji" means "black tick" for the genus Hyalomma and "Koti Burhédjii" means "red tick" for the genus Amblyomma (Zina, 2017).

3.4. The relationship between transhumant and host communes

One of the main relationships between transhumant cattle holders and the communes is the economic one. Markets and taxes are very important revenues for the receiving communes. For example, the livestock market in the commune of Matéri in northern Benin, which is mainly run by transhumant cattle holders, brings in up to 900 euros per month during the transhumance. The other relationships that exist between communes and pastoralists are sometimes social and conflictual. These conflicts most often involve pastoralists and indigenous people (Zina, 2017).

3.5. Relations between cattle holders

Apart from mutual accusations in the case of damage and theft of animals, social relations between transhumant herdsmen are better because they consider that they face the same difficulties. If a herd is followed by two herdsmen, the older one takes charge of driving the animals to the night pasture and rests during the day, while the younger one drives them during the day (Zina, 2017).

Overview of epidemiological concepts, methodologies and statistics used in the thesis

4.1. Multiple correspondence analysis (MCA)

The methods of the main components are used to summarize and visualize the information contained in multivariate data. Among these methods, there is Multiple Correspondence Analysis (MCA). MCA is a method of multidimensional statistical description of a qualitative data table. It allows i) graphical representations of the content of the data table: representation of "similarities" between individuals and between the modalities of the qualitative variables; ii) a recoding into digital data, on which other methods can then be applied (Greenacre and Blasius, 2006). In practice, the MCA is a Factor analysis (FA) applied to the complete disjunctive table, i.e. to the matrix of indicators of the modalities of the qualitative variables.

4.2. Systematic review and meta-analysis

A systematic review is a synthesis of the scientific literature in response to a specific question. It uses explicit methods for searching, selecting and analyzing data. A systematic review attempts to gather all empirical evidence that meets pre-specified eligibility criteria to answer a specific research question. It uses explicit and systematic methods that are selected to minimize bias, thereby providing more reliable results from which conclusions can be drawn and decisions made (Higgins, 2003). The main characteristics of a systematic review are:

- a clearly stated set of objectives with predefined eligibility criteria for studies ;

- an explicit and reproducible methodology;
- a systematic search that attempts to identify all studies that would meet the eligibility criteria
- an assessment of the validity of the results of the included studies, for example by assessing the risk of bias; and
- a systematic presentation and synthesis of the characteristics and results of the included studies (Devillé et al., 2002; Moher et al., 2015).

Statistical methods may or may not be used to synthesize the results of the studies. When such methods are used, it is called a meta-analysis. A meta-analysis is a systematic scientific method that combines the results of several independent studies on a given problem, according to a reproducible protocol. It allows a more accurate analysis of the data by increasing the number of cases studied and drawing an overall conclusion (Field and Gillett, 2010). By combining information from all relevant studies, meta-analyses can provide more precise estimates of the effects of the endpoints studied than those derived from individual studies included in a single review (Kelley, 2012). They also facilitate investigations of the consistency of evidence across studies and exploration of differences between studies.

A systematic review is therefore a true research method, and should not be confused with a general review in which the literature search is generally not exhaustive and which represents more the opinion of an expert or group of experts (Gopalakrishnan and Ganeshkumar, 2013).

4.3. Species distribution models (SDM)

Species distribution models (SDMs) are numerical tools that combine data on the occurrence or abundance of species with estimates of environmental parameters. They are used to generate ecological and evolutionary information and to predict the landscape distributions of species. These predictions of the distribution of different animal and plant species sometimes require extrapolation in space and time (Elith and Leathwick, 2009).

Species distribution modelling is at the core of basic and applied biogeographic research. In recent years, species distribution models are increasingly used in biogeography, conservation, biology, ecology, paleoecology, and wildlife management studies. Model adaptation is often based on pattern matching methods, where links between the geographical occurrence of a species and a set of predictor variables are investigated. This helps to validate and prove statements about the mechanisms governing species distributions. These models provide estimates of the ecological requirements of species, although the demonstration of causal relationships between species distributions and predictor variables is dependent on the adequacy of the predictors used in model development (Araújo and Guisan, 2006).

Species distribution modelling generally involves five main steps: conceptualisation; data preparation; model fitting; model implementation and prediction. These five steps are described below. The data needed for species distribution modelling depends on the objectives set at the outset, and the choice of model type depends on this. In general, three main objectives for species distribution modelling can be distinguished: (i) inference and explanation, (ii) mapping and interpolation, and (iii) prediction and transfer (**Figure 8**).

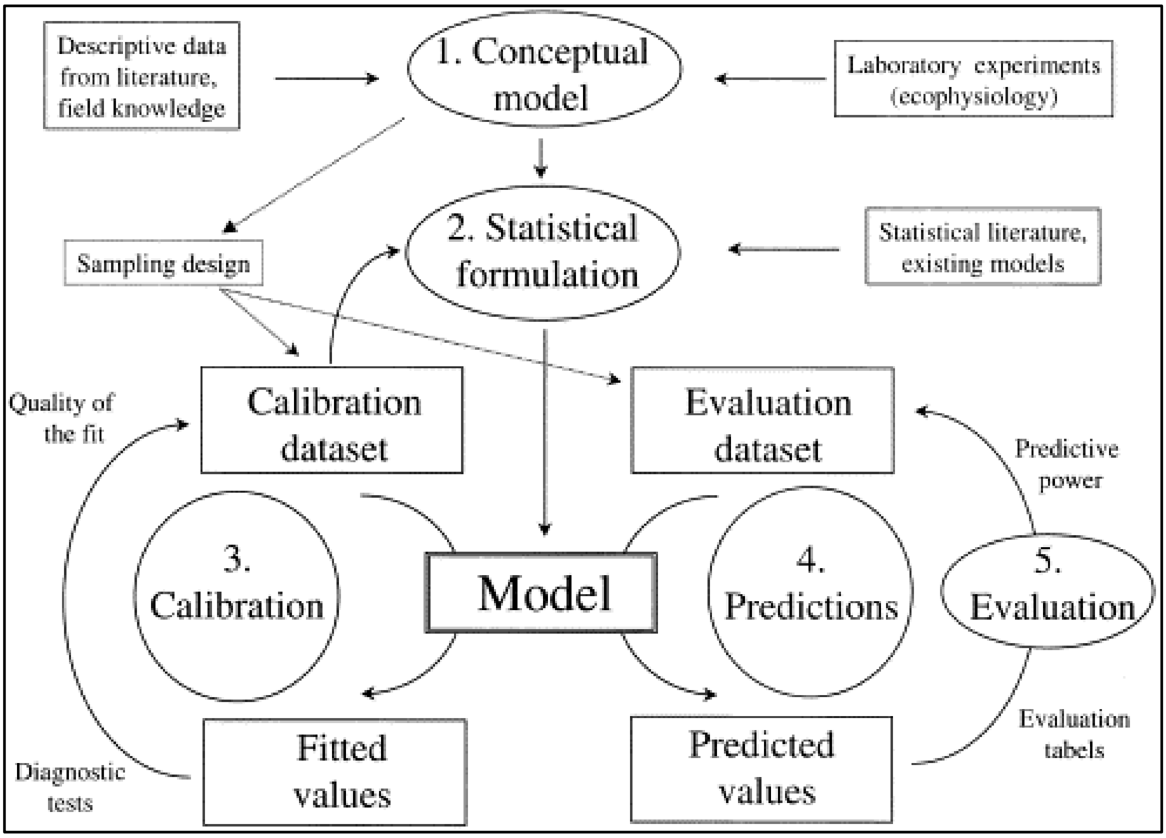


Figure 8: Overview of the successive steps (1–5) of the model building process, when two data sets – one for fitting and one for evaluating the model – are available. Model evaluation is either made: (a) on the calibration data set using bootstrap, cross-validation or Jack-knife techniques; (b) on the independent data set, by comparing predicted to observed values using preferentially a threshold-independent measure (such as the Receiver Operating Characteristic ROC-plot approach for presence: absence models) (Source: Guisan and Zimmermann, 2000)

- Conceptualisation

During the conceptualisation phase, the main objectives are defined along with the choice of the type of model(s) to be implemented. This stage is devoted to the conceptualisation of the study in the light of the detailed knowledge we have of the species to be modelled. An inventory is made of the available biodiversity data that can be used and of those that need to be sought. The eventual collection of data will require a well-defined and adapted sampling plan to cover the study area in a representative manner. It is also during this phase that the hypotheses put forward are carefully tested (Guisan et al., 2017). It will be necessary to identify and select the different predictors that best characterise the species under study. Environmental variables are divided into three types of predictors: resource variables, direct variables and indirect variables (Guisan and Zimmermann, 2000). Finally, the different modelling algorithms and the complexity of the model must be chosen according to the objectives and assumptions about the species' relationship with its environment.

- Data preparation

At this stage, real data on biodiversity and the environment are collected and subsequently processed. This process concerns all the data required for model adjustment, but also the data used to make transfers. Much attention should be paid to scale mismatch, i.e. when the spatial (or temporal) grain or range does not correspond between the biodiversity and the environmental data or within the environmental data. In such cases, decisions need to be made on appropriate scaling up and scaling down strategies. Environmental information collected at the required spatial resolution for the whole study area is best stored in a Geographic Information System (GIS). We distinguish four potential sources for collecting such environmental data, namely (i) field surveys or observational studies; (ii) printed or digitised maps; (iii) remotely sensed data (digital aerial photographs and satellite images) and (iv) maps obtained from GIS-based modelling procedures. These field data can be measurements made directly in the field (e.g. abiotic characteristics of a site) or a network of meteorological measurements to further interpolate climate maps. Spatial data on geology, soil units or hydrology are most often derived from existing printed or digitised maps. Maps of land cover, rock surfaces, snow cover, potential moisture or vegetation can be derived from aerial photographs from drones or satellite images.

The other very important concern is the form of absence information provided for the biodiversity data. Not all SDM applications use the same form of species presence information. It could be direct observations, GPS positions of data loggers or museum archives, among others. All the SDM algorithms need some form of absence or background data which they use in opposition to the presence data. As absence data is not always available, suitable background or pseudo-absence data must be selected. The best strategy will depend on the objectives, the research question, the data and the SDM algorithm (Guisan et al., 2017).

- Model fitting

Model fit is the measure of the ability of a model to generalise to data similar to that with which it was trained. A good model fit relates to a model that matches the output accurately when provided with unknown inputs. Fitting involves the adjustment of the model parameters to improve the accuracy of the model. The method involves performing an algorithm on data for which the variable of interest is known to generate a machine learning model. Then, the results of the model are checked against actual and observed values of the target variable to assess the accuracy. The following step is to adjust the standard parameters of the algorithm to reduce the level of uncertainty and make the model more precise in finding the relationship between the characteristics and the target variable. The process is replicated several times until the optimal parameters are found for the model to make predictions with high accuracy.

Model adjustment is the core of every SDM implementation. Many different algorithms are available. There is also the possibility to combine several algorithms into ensemble models or several candidate models with different sets of candidate predictors are averaged (Elith* et al., 2006; Hastie et al., 2009). These issues need to be addressed in the conceptualisation phase. There are important aspects to address in the model fitting stage. These include investigating multicollinearity in the environmental data, identifying the variables to be included in the model (without overfitting) and the process of selecting them. It will also be necessary at this stage to define the model parameters to be used. When several model algorithms or potential models are adjusted, what should be done to select the final model or to aggregate the results of the models? Should data non-independence (spatial or temporal autocorrelation, nested data) be tested or corrected? If the objective is to derive binary forecasts, what threshold should be used? More detailed information on these matters can be gleaned from (Franklin, 2010) and (Guisan et al., 2017).

Overfitting negatively impacts the performance of the model on new data. It occurs when a model learns the details and noise in the training data too efficiently. When random fluctuations or the noise in the training data are picked up and learned as concepts by the model, the model overfits. It will perform well on the training set, but very poorly on the test set. This negatively impacts the model's ability to generalize and make accurate predictions for new data.

Underfitting happens when the machine learning model cannot sufficiently model the training data nor generalize new data. An underfit machine learning model is not a suitable model; this will be obvious as it will have a poor performance on the training data (https://www.educative.io/edpresso/definition-model-fitting).

- Model assessment

Model assessment is an integral and essential part of the model development process. Evaluation allows us to find the optimal model that represents our data and to know how well the chosen model will perform in the future. Evaluating the performance of models with the data used for training is not an appropriate approach in data science as it can easily lead to over-optimistic and over-fitting models. Two methods of model evaluation exist in data science, the Hold-Out and the Cross-Validation. To prevent overfitting, both methods use a test set (not experienced by the model) to assess the performance of the model.

Hold-Out

This method is used when we have a large database. The data set is randomly divided into three subsets in this method:

- ✓ The training set is a subset of the dataset used to develop predictive models.

- ✓ The validation set is a subset of the data set used to evaluate the performance of the model built in the training stage. This provides a test platform for refining the model parameters and choosing the best model. All modelling algorithms do not need a validation set.
- ✓ The test set, or unseen examples, is a subset of the data set for assessing the likely future performance of a model. If a particular model fits the training set significantly better than the test set, it is probably an over-fit.

Cross-validation

This method is used when only a small database is available. In this case and to obtain an unbiased estimate of the model's performance, it is recommended to use k-fold cross-validation. In k-fold cross-validation, we divide the data into k subsets of equal size. We build models k times, each time excluding one of the subsets from the training and using it as a test set. If k is equal to the sample size, this is called leave-one-out.

- Predictions

After thoroughly fitting the SDMs, inspecting the behaviour of the model and the extrapolation, and evaluating the predictive performance, it is now the stage of making predictions in both space and time. It is important in this process to consider the quantification of uncertainty due to input data, algorithms, model complexity and boundary conditions (e.g. climate scenarios) (Araújo et al., 2019; Thuiller et al., 2019). It is also recommended to quantify the uncertainty due to new environments when transferring the model to a different geographical area or period (Zurell et al., 2012).

In our study of modelling the distribution of *Rhipicephalus (Boophilus) microplus* in West Africa, we used six types of models: Boosted Regression Tree (BRT), Generalized Additive Models (GAM), Generalized Linear Models (GLM), Maximum Entropy (MaxEnt), Random Forest (RF) and Support Vector Machine (SVM). We described these six models below.

4.2. Random Forest (RF)

Random Forest (RF) is a supervised learning algorithm that can operate efficiently on databases and provide estimates based on the importance of specific variables in classification (Wang et al., 2015). The "forest" constructed is a set of decision trees trained by the bagging method. The principle of the bagging method is a combination of learning models that increase the overall model output. Each tree is constructed independently from a random sample with bootstrapping of the data set. A randomly selected subset of predictors is used to divide each node (Kotsiantis, 2011). In the case of bagging, successive trees are not dependent on each other. A simple majority vote is used for the final prediction. (Liaw and Wiener, 2002).

4.3. Boosted Regression Tree (BRT)

Boosted regression tree (BRT) models use two techniques: bagging methods of decision tree algorithms and boosting methods. BRT methods randomly sample from the data for each new decision tree constructed. The selected samples are returned to the dataset and can be selected in the following trees. BRTs use the boosting method which weights the input data in the following trees. The weights increase the probability of selection in the new tree of data poorly modelled by the previous trees. By this continuous adjustment process the model tries to improve its accuracy. Boosted regression trees are quite robust, work well with missing data and need at least two predictors to work. (De'ath, 2007; Elith et al., 2008; Elith and Leathwick, 2017; Franklin, 2010).

4.4. Generalized Linear Models (GLM)

Generalized linear models is a class of models that share a common method for computing parameter estimates and the property of linearity. GLM includes linear regression models, analysis of variance models, logit and probit models, log-linear models and multinomial response models (McCullagh and Nelder, 1998). Generalised Linear Models (GLM) highlight the relationship between the response variable and a set of predictor variables by searching for the most suitable and parsimonious model (Guisan et al., 2002). They are often used to describe the relationship between species and their environment. GLMs offer a less restrictive form than conventional multiple regressions by providing error distributions for the dependent variable other than normal and non-constant variance functions (Thuiller et al., 2003).

4.5. Generalized Additive Models (GAM)

Generalized additive models (GAMs) are a broader generalization of generalized linear models (GLMs) that automatically identify appropriate polynomial transformations of predictors for better predictions (Guisan et al., 2002). GAMs are tuned like GLMs, except in cases where some predictors can be modelled non-parametrically in addition to the linear and polynomial terms of other predictors. The probability distribution of the response variable must always be specified, and in this case a GAM is said to be parametric. The selection of the appropriate level of the "smoother" of a predictor is a very important step in the application of GAMs. Using the concept of effective degrees of freedom would be the best way to specify the level of smoothness.(Elith* et al., 2006; Franklin, 2010; Guisan et al., 2002; Hastie et al., 2009).

4.6. Maximum Entropy (MaxEnt)

MaxEnt is a generic machine learning technique using a simple and precise mathematical formulation. It presents some features that make it well adapted to the modelling of species distribution. MaxEnt is a very popular species distribution modelling because of its high degree of accuracy and flexibility to species specific situations (Zeng et al., 2016).

The MaxEnt software relies on the maximum entropy approach to model niches and species distributions. Using a set of environmental grids and georeferenced localities of occurrence, the model expresses a probability distribution where each cell of the grid has a predicted fit of conditions for the species. Depending on specific assumptions about the input data and the biological sampling efforts that led to the recording of occurrences, the output can be interpreted as a predicted probability of occurrence or as a predicted local abundance (Elith et al., 2011; Phillips et al., 2017). We implemented this model using R packages rJava and dismo.

4.7. Support Vector Machine (SVM)

Support Vector Machine (SVM) is a family of machine learning algorithms that can be used to solve classification, regression and anomaly detection problems. They are known for their strong theoretical guarantees, their great flexibility as well as their simplicity of use even without much knowledge of data mining. Their purpose is to separate data into classes using a boundary that is as "simple" as possible so that the distance between the different groups of data and the boundary that separates them is maximum. This distance is also called the "margin" and SVMs are thus called "wide margin separators", with the "support vectors" being the data closest to the border. This notion of boundary assumes that the data are linearly separable, which is often not the case. To overcome this, SVMs often rely on the use of "kernels". These mathematical functions make it possible to separate the data by projecting them into a feature space (a vector space of higher dimension). The margin maximisation technique, on the other hand, guarantees greater robustness to noise and therefore a more generalisable model (Wang et al., 2004).

4.8. Ensemble modelling

Ensemble modelling is the process of running two or more related but different analytical models and then consolidating the results into a single score or variance to increase the accuracy of both predictive analysis and data mining applications. In predictive modelling and other types of data analysis, a unique model based on a sample of data may have significant bias, variability or inaccuracies that affect the reliability of its analytical results. The use of specific modelling techniques can have similar drawbacks. By combining different models or analysing multiple samples, scientists and other data analysts can reduce the effects of these limitations and provide better information to decision-makers. A common example of ensemble modelling is a random forest model. This approach to data mining relies on multiple decision trees, a type of analytical model designed to predict outcomes based on different variables and rules. A random forest model mixes decision trees that can analyse different data samples, evaluate different factors or weigh common variables differently. The results of the different decision trees are then converted into a simple average or aggregated by additional weighting (Kotu and Deshpande, 2019; Naimi and Araújo, 2016).

Ensemble modelling has gained popularity as more and more organisations have deployed the computing resources and advanced analysis software needed to run such models. Furthermore, the emergence of Hadoop and other big data technologies has driven organisations to store and analyse larger volumes of data, creating greater potential for running analytical models on different data samples.

Objectives of the thesis

Livestock farming accounts for a large share of the agricultural GDP of all ECOWAS countries (44% according to the ECOWAS Commission). According to the World Bank, cattle farming is generally practised extensively (70% to 90% pastoralism). This type of farming favours the exchange of vectors and pathogens on pastures and water points. In the 2000s we witnessed the introduction of the invasive tick *R. microplus* in West Africa through Côte d'Ivoire and Benin. Since then, this tick has continued to spread to other countries in the sub-region. The various actors in the epidemiological surveillance networks of West African countries do not always have a good knowledge of the different tick species that circulate there. They do not master the risk of the introduction of these ticks and their pathogens and their dispersion dynamics.

General objective

The general objective of this work is to contribute to reduce the impact of vector-borne diseases by improving the knowledge of the different factors that contribute to the dispersion of ticks and tick-borne diseases in the area.

Specific objectives

This thesis has been structured into four parts according to the specific objectives pursued

Part I: Assessing the level of knowledge of farmers regarding ticks and tick-borne diseases and the different practices they use to control these parasites (Study 1).

The first study aimed to investigate the perception of cattle holders about ticks and tick-borne diseases (TBD) in cattle, their practices in tick control and the social groups involved in cattle farming in Burkina Faso and Benin. This inventory will provide a clear overview of farmers' knowledge of the different tick species present in the study area. It will also allow us to assess their knowledge of tick-borne diseases. Finally, this inventory will allow us to identify the different methods of control used by these farmers against ticks and tick-borne diseases.

Part II: Characterizing the departure and arrival zones of transhumant cattle holders and the transhumance corridors (Study 2).

The second study aimed to highlight, firstly the corridors and grazing areas used by Burkina Faso transhumant cattle herds going to Benin, secondly the characteristics of departure and arrival areas of transhumance and thirdly, the risk score related to the introduction and spread of the invasive tick species, *R. microplus,* in free areas. It is important to identify the different transhumance corridors used by Burkina Faso's transhumant towards northern Benin and the different grazing areas to highlight the risk factors that could contribute to the spread of ticks and tick-borne diseases in the region.

Part III: Assessing the dispersion dynamics of *Rhipicephalus microplus* in West Africa (Studies 3 and 4).

The third study aimed to identify models developed by researchers to understand the dynamic of ticks and tick-borne diseases spread and to assess the performance of these various models with a meta-analysis.

The fourth study aimed to highlight the extent of the spread of *R. microplus* in West Africa today and to show at which level the West African environment is adapted to the habitat of *R. microplus* through habitat suitability models.

Part IV: Assessing the economic impact of ticks and tick-borne diseases in the study area (Study 5).

The fifth and last study aimed to evaluate the clinical and economic impact of ticks and tick-borne diseases in cattle herds and the benefits of controlling these parasites.

Experimental section

Study 1: First tick and tick damage perception survey among sedentary and transhumant pastoralists in Burkina Faso and Benin

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Preamble of study 1

This study responds to a concern to better know the actors involved in the livestock sub-sector. It was important to characterise the livestock actors in the area through their ethnicity, social groups, main activities, etc. This information is crucial for the development of acceptable animal disease control strategies by the animal health authorities. It was also necessary to assess the knowledge of these farmers about ticks and tick-borne diseases and their various practices for controlling these parasites. Using a questionnaire and statistical modelling, this study explored farmers' perceptions of ticks and tick-borne diseases in cattle, their tick control practices and the social groups involved in cattle farming in eastern Burkina Faso (46 random herds) and northern Benin (44 random herds).

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ORIGINAL ARTICLE

WILEY

First tick and tick damage perception survey among sedentary and transhumant pastoralists in Burkina Faso and Benin

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Abstract

Background: Transhumance, a main ancestral animal production strategy of the West African Countries (WAC), can favour the spread of vectors and vector-borne diseases within and/or across countries. Transhumance has been implicated in such spread as well as that of related tick-borne diseases (TBD).

Methods and principal findings: Using a questionnaire survey and statistical modelling, this study explores the perception of herders about ticks and TBD in cattle, their practices in tick control and the social groups involved in cattle farming in eastern Burkina Faso (46 random herds) and in the northern Benin (44 random herds). Results show that most of the herders (79%) are from the Fulani social group. The principal and secondary activities of herders are respectively cattle farming and agriculture. The mean age of pastoralists is between 40 and 50 years depending on the province of origin and 60% of the surveyed herds practice internal or transboundary transhumance. Herders have a clear knowledge of different genus of ticks except the genus *Rhipicephalus*. Their knowledge of TBD is very limited. These results also reveal that herders in Benin use less acaricides treatment calendar compared with those in Burkina Faso. Transhumant pastoralists (i.e. transhumant cattle farmers) plan more acaricide treatment and have more cows with lost teats (i.e. tick damage) than the sedentary ones. In addition, amitraz appears to be the main acaricide compound used by herders for tick control (68%) but its use is inappropriate and its source is frequently the unregulated market.

Conclusions and significance: All of these findings can induce acaricide resistance especially as the inefficacy of amitraz against *Rhipicephalus* (*Boophilus*) *microplus* has already been reported in previous studies. Such results would help to elaborate suitable strategies of control and prevention of ticks and TBD in Burkina Faso and Benin.

KEYWORDS

Benin, Burkina Faso, pastoralist, socio-epidemiological survey, tick-borne diseases, ticks, transboundary diseases, transhumance

1 | INTRODUCTION

Transhumance is a livestock production and management system, which refers to an ancestral practice of moving herds seasonally and according to specific paths, repeatedly every year (Abiola, 2005). It is an animal production system adapted to the context of grassland savannah and steppe zones (Wagenaar et al., 1986). This type of animal farming is usually practiced in the dry season in West Africa, from Sahelian countries to the coastal countries following rangelands (Fournier et al., 2014). It has historically enabled pastoralist communities to survive major weather crises in Africa (Bouslikhane, 2015). This practice often raises serious concerns, including social conflicts and animal health problems (Abiola, 2005). In West Africa, cross-border transhumance is a common animal sustainable production strategy. The major droughts of the 1970s and 1980s forced a mass movement of herders in the Sahel towards the south, with most converting into agro-pastoralists and some completely settling. However, it is not known how many have been able to return to their previous transhumance systems. In addition to preserving the sahelian livestock, transhumance contributes to regional integration and the supply of animal products to an increasingly large and urbanized population. It contributes to the production of more than 65% beef meat, 40% meat of small ruminants and 70% milk of the sub-region (FAO, 2012), which represents 661,750 tons of meat annually and 1,435,000 tons of milk.

The movement of animals in search of water, pasture or markets sometimes leads them to areas where they have increased risks of becoming infected by specific infectious diseases (e.g.): fields contaminated by anthrax during previous outbreaks, reservoirs of ticks for heartwater, tsetse areas for trypanosomiasis, swampy areas with an abundance of arthropods that carry arboviruses (Abiola, 2005). Thus, the transhumance system has changed the epidemiological map of cattle diseases in West and Central Africa with the appearance of some diseases in areas where they were previously absent. Livestock movements represent the third cause of the spatial dynamics changes of animal disease after climate change and market concentration (Perry et al., 2013). The transhumant herd (i.e. cattle herds raised by the transhumance system) can rapidly disseminate contagious diseases during its movements. For example, transhumance has been cited among the vehicles of the spreading of rinderpest in the past. This may impede the livestock health within some regions, or even a whole country. The problem becomes particularly serious in the case of cross-border transhumance (Lesse et al., 2016). Examples include , the appearance of the invasive tick, *Rhipicephalus* (*Boophilus*) *microplus*, with the related transmitted diseases (i.e. babesiosis and anaplasmosis) in the northern part of Côte d'Ivoire (Madder et al., 2007) and in Benin (Madder et al., 2012). Formerly, its introductory sites are located in the south of each of these countries (de Clercq et al., 2012). It has also invaded other West African bordering countries such as Burkina Faso, Mali, Nigeria and Togo (Adakal et al., 2013; Adedayo & Olukunle, 2018; Musa et al., 2014; Opara & Ezeh, 2011).

Considering the direct and indirect losses of livestock due to ticks in West Africa (Sutherst, 1987) and the practice of transhumance, which has become a way of life for some farmers (Cabot, 2017), it is necessary to understand the role of transhumance in the spread of ticks and associated pathogens in order to propose some improvements for an integrated pest management. However, this type of information is very rare.

Therefore, a first epidemiological survey was conducted in the eastern region of Burkina Faso and in northern Benin to investigate the putative role of the transhumance in the spread of ticks and tick-borne diseases (TBD) and practices of pastoralists that may have contributed to these.

The aim of this study is to investigate on the perception of herders about ticks and TBD in cattle, their practices in tick control and the social groups involved in cattle farming in Burkina Faso and Benin. The survey was carried out in dry season, just before herders start moving for transhumance from Burkina Faso to Benin.

2 | MATERIALS AND METHODS

2.1 | Study area and design

This survey was conducted in two West African bordering countries: Burkina Faso and Benin. The study area includes three provinces in the eastern region of Burkina Faso (Gourma, Kompienga and Tapoa), which represent the departure area and four departments in the north of Benin (Alibori, Atacora, Borgou and Donga), which represent the arrival area of the transhumant herds from Burkina Faso (Figure 1).

The climate of the eastern region of Burkina Faso is of south-Sudanese type, characterized by a rainy season of 5 months, from May to September, and 7 months of dry season, from October to April (Ibrahim et al., 2012). A shrubby savannah in the north and a wooded savannah in the south characterize the vegetation of the region. The eastern region belongs to the Sudanese phytogeography domain, with very variable precipitation both in number of rainy days and in quantity of water (between 900 and 1100 mm/year). Three types of vegetation occur in this region: the steppe, the savannah and the forests established of galleries (i.e. Pendjari). The region has an abundance of reserves of fauna and national parks covering the provinces of Gourma, Kompienga and Tapoa (Ministère de l'Economie et des Finances, 2009).

In the province of Kompienga, all of Pama's rivers are tributaries of Pendjari's river. Pendjari and its tributaries do not flow in the dry season. However, numerous puddles or permanent restraints are situated on the course of the river. An important artificial restraint (Kompienga) was realized on the river Ouali. The storage capacity is 2.5 billions of m^3. In the province of Tapoa, the river system gets organized with regard to Tapoa, which is the only permanent stream. There is also not a permanent water source to Kankandi (Ministère de l'Economie et des Finances, 2009).

In addition to these main areas, there are anthropogenic formations forged mainly by agro-pastoral activities. These formations are dominated by spared species spread by man (*Vitellaria paradoxa*, *Parkia biglobosa*, *Acacia albida*) in the management of agricultural spaces and species that have been planted as part of reforestation activities (e.g. *Eucalyptus camaldulensis*, *Mangifera indica*) (Portail sur le développement du Burkina Faso, 2008).

The northern part of Benin has a Sudanese-type climate with a rainy season of 5 months (May to September) and a dry season of 7–8 months (October to April). Rainfall is between 700 and 1,100 mm of water/year. The external temperatures are between 22°C and 37°C throughout the country with daily thermal amplitudes in the north (greater than 10°C) (Adam, 1993). Two river basins water the northern of Benin: the Pendjari river basin and the Niger river basin. The Pendjari river basin (length of 420 km in Benin) is composed of three main drainage axes. These three main areas of drainage are: the Kounne (550 km^2 for a length of 46 km and 200 m of vertical drop), the Tigou (317 km^2 for a length of 27 km and 300 m of vertical drop) and the Sarga (567 km^2 for a length of 48 km and 300 m of vertical drop) (Le Barbé, 1993).

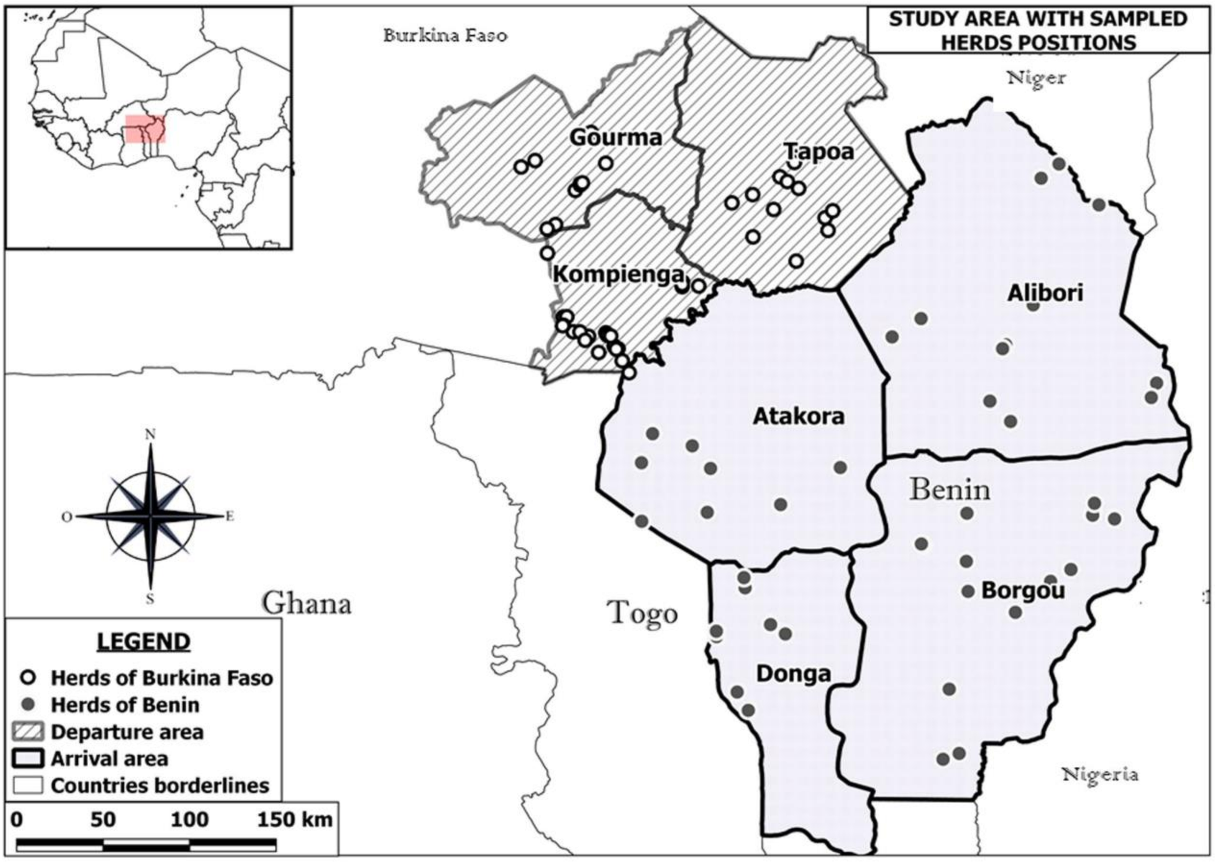

FIGURE 1 Study area with the geographical positions of the 90 sampled herds in Benin and Burkina Faso

Over 135 km, the Niger River represents the natural border for Benin and Niger. Its watershed in this region is close to 1 000 000 km^2. On this short route, the Niger has a straight-line oriented NW-SE and receives on the right bank the contributions of four tributaries, which are from west to east: Mekrou (10,500 km^2), Kompa Guru (1,980 km^2), Alibori (13,740 km^2) and Sota (13,360 km^2). Southeast of the Sota basin are the high basins of Nigerian which tributaries include Wara and Oli (Le Barbé, 1993; Olivry et al., 2005).

The north of Benin is characterized with its Sudan-Sahel type climate located between 10° N and 12° 30' N, it has shrubby and wooded savannahs; clear forests with *Anogeissus leiocarpa* (deep soils) or with *Isoberlinia doka* (siliceous soils); and forest galleries (Aregheore, 2009).

Pastoral exploitation is the work of sedentary and transhumant Fulani herders, who graze their flocks in the various plant formations of the Atacora mountain chain (Wala, 2010).

2.2 | Herds sampling and distribution

A total of 90 herds were selected from a pastoralists' list provided by the veterinary offices of each country. The selection was made by choosing randomly the name of a pastoralist in the list, calling him and having his agreement for the survey. When the picked pastoralist did not agree, another one was chosen randomly until we had the required number for each area. The size of the sampling was related to logistical constraints. The main criteria of inclusion of livestock keepers in the study included ownership of at least 50 cattle and whether or not they practiced transhumance. The minimum of 50 cattle per herd was set because transboundary transhumant herds often have a herd size of at least 50 animals. It was necessary to harmonize the herd size class among the transhumant and non-transhumant herds to make comparisons without bias. Furthermore, distance between herds in each province is at least 3 km. Also, effort was made to have herds distribution covering the whole study area within each province to ensure representability (Figure 1).

In the transhumance departure zone (east region of Burkina Faso), 46 herds were selected according to the density of the population, the extent of the area and the natural constraints: 16 herds in the province of Gourma, 15 in the province of Tapoa and 15 in the province of Kompienga. In the transhumance arrival area (north region of Benin), 44 sedentary cattle herds were selected and distributed applying the same criteria as in Burkina Faso: 8 were chosen in the department of Atacora, 14 in the department of Alibori, 8 in the department of Donga and 14 in the department of Borgou. The eastern region of Burkina Faso and the north of Benin hosted respectively 51% and 49% of the sampled herds.

2.3 | Collection of socio-epidemiological data

A questionnaire survey was administrated to pastoralists during biological sample (ticks and cattle blood) collection that was carried out in cattle herds for another purpose (acarological and parasitological survey). The questionnaire survey included questions about the type of husbandry, the herd size, the cattle breeds on the farm, the presence of transhumant cattle in the area of stay, the knowledge of the herder about ticks and TBD and the use of acaricides (Data S1). The knowledge of herders about ticks was evaluated by providing tick specimens (available ones) and pictures of ticks for identification. The herders were asked if they had already seen such species and what was the name of that species in the local language. The knowledge of herders about the ticks was assessed according to their aptitude to recognize easily the specimens or the picture, and giving their name in local language. The interviews were done one to one in French or local language with the help of an experimented interpreter if needed. The geographical coordinates of each site were recorded using a handheld Global Positioning System (GPS), for the generation of distribution maps using the Quantum Geographic Information System (QGIS) software (Quantum GIS Development Team, 2016). The field data collected were encoded in an MS Access database.

2.4 | Statistical analysis

Various models were used accordingly to find out if certain factors are associated with the variables of interest. The linear regression was used for continuous dependent variables, logistic regression for binary dependent variables and Poisson or negative binomial regression for count variables (Petrie & Watson, 2013) using STATA SE 14 (StataCorp, 2015).

The linear regression helped to find out the factors associated with the variations of the continuous dependent variables (e.g. herders age, experience in cattle farming, seniority in the surveyed herd). The purpose of such analysis was to appreciate the effect of the variation of the different independent variables (e.g. country, mode of farming) on these continuous variables.

The logistic regression helped to appreciate the effect of the variation of the independent variables (e.g. country (Benin or Burkina Faso), the mode of farming (transhumant or sedentary)) on the categorical-dependent variables such as acaricide used (e.g. amitraz, cypermethrin or deltamethrin), origin of acaricide (e.g. unregulate market, veterinary source), and presence of species of ticks. The Poisson regression helped to analyse the effect of independent variables on the countable dependent variables (e.g. herd size, number of goats, number of sheep, number of donkeys).

These various models were performed to allow us to notice if the variables (e.g. presence of ticks; season of abundance; acaricides used by breeders; origin of acaricides; and the use of treatment schedule) are influenced by country, farming method (sedentary or transhumant) and season.

Multiple correspondence analysis (MCA), a classical multivariate data analysis technique was used to group the herders based on socio-economic and epidemiological factors registered during the survey using the package 'FactoMineR' of R free software (Lê et al., 2008). MCA analysis was performed to: (a) provide a typology of the individuals from a multidimensional perspective (b) to assess the relationships between the variables and (c) to link the study herds and the variables in order to characterize the individuals using the variables. Initially intended for qualitative variables, the MCA may also deal with quantitative variables, if they are made qualitative.

Another way to study the similarities between individuals with respect to all the variables was to perform a hierarchical clustering, which was performed after the MCA. This analysis used the coordinates of the individuals on the principal components for the hierarchical classification by an hierarchical clustering on principal components (HCPC) (Husson, 2010). The principal component representation was also used to visualize the partition in a 3D-map (factor map) to better understand the data.

For the epidemiological group (concerning perception of herders on tick and tick-related damage) partition of 90 herders, the MCA was also used with 52 variables. The principal variables retained are 19 (e.g. presence of various species of ticks, season of abundance of ticks and tick-related damages on cattle) and the remaining are supplementary variables (Data S2 and S3). Regarding socio-economic group analysis, MCA was performed considering all herders described by 55 variables (Data S2 and S3).

3 | RESULTS

3.1 | Characteristics of herders

The questionnaire respondents were mainly the herd owners who belong to the Fulani social group. They represented more than 79% ($n = 71$) of all herders in both Benin and Burkina Faso. However, there were more Fulani herders in Burkina (85% of herders) than in Benin (73% of herders). Only three ethnic groups had been found in Burkina Faso herders, whereas Benin herders belong to eight different ethnic groups. The herders belonging to social groups of 'Gourmantché' and 'Mossi' are found only in Burkina Faso whereas the ethnic groups of 'Gando', 'Bariba', 'Dendi', 'Kountéba', 'Mokolé', 'Tanika' and 'Yorouba' are found only in Benin (Table 1).

TABLE 1 Ethnic group of surveyed herders

Ethnic group	Benin	Burkina Faso	Total	Percentage
Bariba	3	0	3	3%
Dendi	1	0	1	1%
Gourmantché	0	6	6	7%
Kountéba	1	0	1	1%
Mokolé	1	0	1	1%
Mossi	0	1	1	1%
Fulani	32	39	71	79%
Gando	4	0	4	4%
Tanika	1	0	1	1%
Yorouba	1	0	1	1%
Overall total	44	46	90	100%

The level of education of the herders was very low; 52% had no formal education, whereas 24% had attended Koranic schools. Only 10% of the herders had attained primary education, 9% had secondary or higher level of education and 5% were Fulfulde literate.

All the 36 interviewed transhumant cattle farmers in Burkina Faso were men. Those that come from the province of Kompienga belonged all to the Fulani social group, whereas in Tapoa they were 83% Fulani and 17% Gourmantché and in Gourma they were 90% Fulani and 10% Gourmantché. The principal activity of all of them was cattle farming and agriculture represents their secondary activity. The highest average experience in cattle farming was 39.7 years in Kompienga province, but the most experienced cattle farmer was from the Tapoa province with 70 years of activity. The transhumant cattle keepers of Kompienga were the least literate (90%), whereas those of Gourma were the least illiterate (38%) (Table 2).

This survey revealed that 40% of all the sampled herds in the study area practiced transboundary transhumance and 20% of herds practiced internal transhumance. The remaining 40% of herds represents a sedentary population. Internal transhumance is performed during all seasons and transboundary transhumance took place during the dry season (Figure 2). Farmers confirmed that their herds moved to uncultivated areas during the rainy season to allow farmers to cultivate crops and avoid conflicts between cattle keepers and farmers. Herds can come back to cropped areas during dry season, after farmers harvested crops, to graze on the crops wastes.

Negative binomial regression in Stata demonstrated that there were no significant ($p > 0.05$) differences between the numbers of herds, which practice transhumance in the two countries. Thus, the country of membership has no influence on this cattle farming technique.

3.2 | Socio-economic groups

The MCA revealed that the first 23 dimensions are needed to have 80% of the total variance. The first two dimensions only explain 14.7% of the total variance. The clustering (HCPC) results show that the social group and the principal activity led to the partitioning of the herders in different socio-economic groups (Data S4). The clustering analysis also revealed seven clusters among which we have two main ones with more than 80% of herders (Figure 3). The first cluster (cluster n°1) regrouped 43% of herders and was characterized essentially by the practice of transboundary transhumance and the origin from Burkina Faso. The second one (cluster n°2) regrouped 44% of herders and was characterized by the non-practice of transhumance and not giving food supplements to their cattle. In addition, the third, the fourth, the fifth and the sixth clusters have respectively only one member each. The seventh and last socio-economic group includes seven members. This cluster is characterized by 'Agriculture' as principal activity and 'Cattle breeding' as secondary activity.

TABLE 2 Comparison of the Burkina Faso transhumant (*N* = 36) profiles according to the province of origin

Parameter	Provinces: Gourma (N=10)	Provinces: Tapoa (N=12)	Provinces: Kompienga (N=14)	Overall Burkina Faso transhumant (N=36)
Social group	90% Fulani & 10% Gourmantché	83% Fulani & 17% Gourmantché	100% Fulani	92% Fulani and 8% Gourmantché
Age (year)	Mean: 40.4 (±8.3)	Mean: 49.5 (±15.9)	Mean: 47.1 (±9.8)	45.94 (±12.19)
Secondary activities	60% farmers & 40% traders	100% farmers	64% farmers & 36% traders	75% farmers and 25% traders
Cattle farming experience (years)	Mean: 32.5 (±9.3)	Mean: 35.7 (±13.4)	Mean: 39.7 (±11.3)	Mean: 35.9 (±12.93)
Level of education	38% No level 38% Koranic school 12% Fulfulde literate 12% Primary school	60% No level 20% Koranic school 10% Primary school 10% Secondary school and beyond	90% No level 10% Fulfulde literate	64% No level 22% Koranic school 6% Fulfulde literate 6% Primary school 3% Secondary school and beyond
Herder as manager	100%	83%	100%	94%

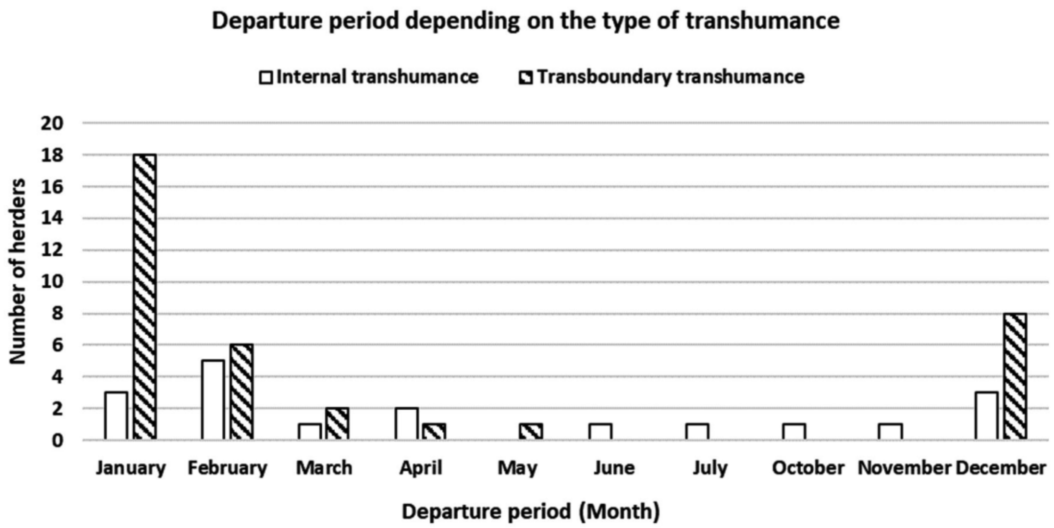

FIGURE 2 Departure period depending on the type of transhumance

3.3 | Ticks and tick-related damages on cattle perception groups

The results of the MCA and the HCPC are depicted in Data S5 and Figure 4. The presence of *Hyalomma* spp., *Amblyomma variegatum* and *Rhipicephalus* (*Boophilus*) spp. in the herds lead the clustering of the herders according to their perception of ticks and tick-related damages on cattle (Data S5). The MCA revealed that the first 12 dimensions were needed to account for up to 80% of the total variance. The first two dimensions explain only 22.68% of the total variance. Five epidemiological clusters were revealed by the HCPC (Figure 4). Two main clusters are highlighted (i.e. cluster n°2 and cluster n°4). The cluster n°2 including 39 herders is characterized by low implication of ticks in milk drop and dermatosis, whereas the cluster n°4 with 33 members is characterized by a high implication of ticks in milk drop and dermatosis. The cluster n°1 contains two members characterized by their ignorance of the seasonal abundance of *A. variegatum*, the absence of this tick in their herds, the use of cypermethrin as the main acaricide and the location of the herd in the department of Borgou in Benin. The cluster n°3 gathers eight members mainly characterized by their ignorance of the abundance season of the ticks belonging to the sub-genus *Boophilus* and the absence of those ticks in their herds. The cluster n°5 also groups eight members characterized by their ignorance of the seasonal abundance of the tick genus *Hyalomma* and the absence of those ticks.

In addition, the Figure 5 shows the abundance of different tick species in function of the season.

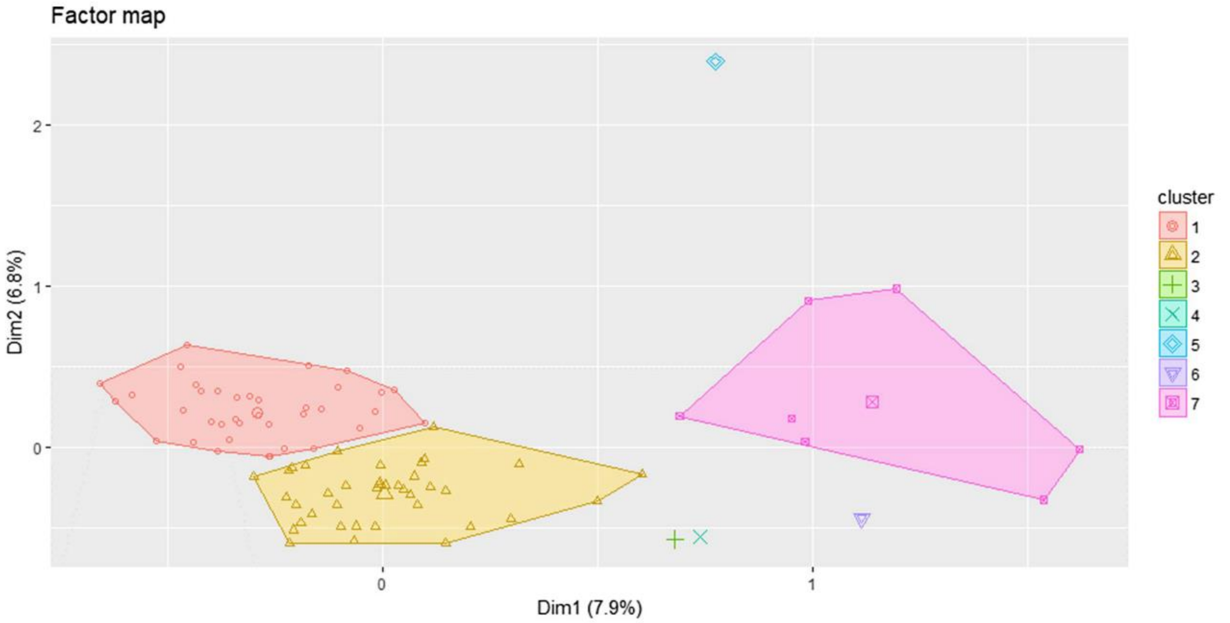

FIGURE 3 Socio-economic factor map of the herders

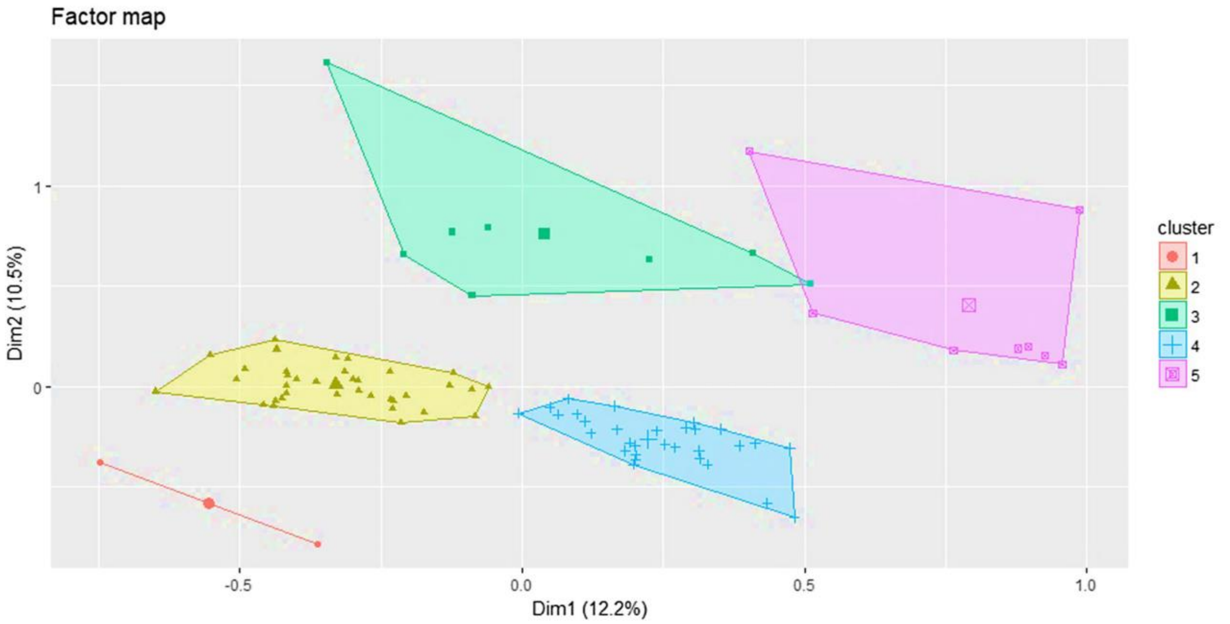

FIGURE 4 Ticks and tick-related damages perception factor map of the herders

In the control of ticks, herders mentioned that they used both conventional methods such as veterinarian products (acaricides) and unconventional methods such as manual removal and insecticidal sprays. Additionally, application methods of products may differ accordingly.

The majority of herders (97%) used acaricides to treat their cattle against tick infestations. The main active substance used by 68% of the herders is amitraz. The principal origin of the acaricides is the 'unregulated market' (51%) and 47% of herders are supplied by the veterinary services in both countries. Interestingly, there is no significant difference concerning the place of supply in acaricidal products according to the country ($p > 0.05$). The majority of herders do not follow the usual dose of this acaricide. The survey revealed that 84% of the herders overdosed amitraz when they used it and 5% of them underdosed it. A multinomial logistic regression model showed that there was no significant difference in the frequency of use of the various acaricides between the two countries ($p > 0.05$).

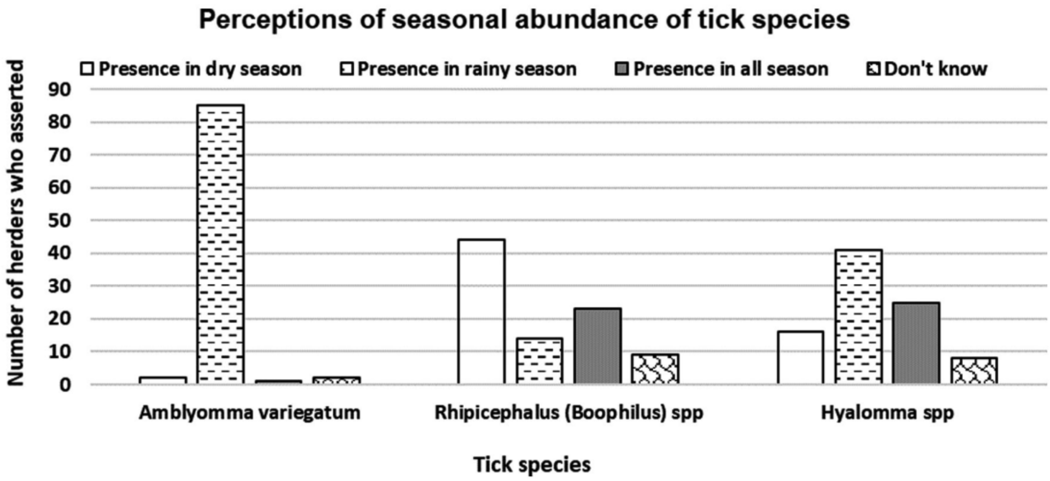

FIGURE 5 Perceptions of seasonal abundance of tick species

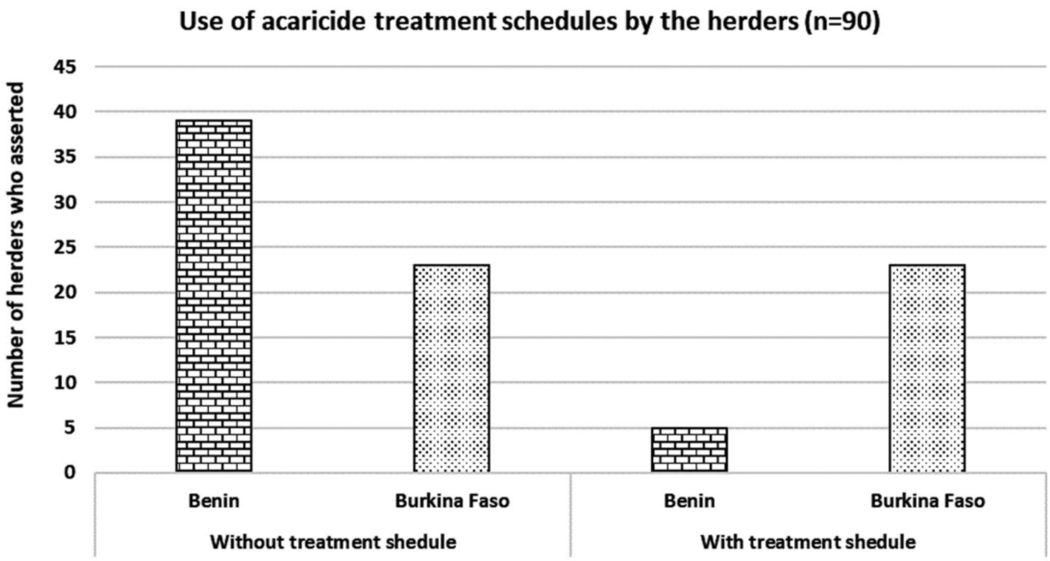

FIGURE 6 Use of acaricide treatment schedules by the herders ($n = 90$)

During this survey, information were collected on five main methods of tick control. The most frequently reported method was swabbing (56%). This method is used to apply the main acaricide which contains amitraz. They also use manual spraying (23%), pour-on (16%), manual removal (6%) and insecticidal sprays (1%).

Results also indicated that cattle herders in Benin planned acaricide treatment less frequently compared to those in Burkina Faso (Figure 6). A logistic regression model showed that Benin breeders used almost eight times less acaricide schedules (Odds ratio = 7.8; $p < 0.05$). In both countries the herders who practice transhumance used significantly almost three times more acaricide treatment schedules compared to those who are sedentary (Odds ratio = 3.22; $p < 0.05$).

3.4 | Perception of herders on tick-related damages on cattle

Dermatosis is the most frequently cited damage caused by ticks (i.e. 96% of the cattle herders reported it). In Burkina Faso, all herders reported this disease as the major consequence of the presence of ticks on the cattle, whereas in Benin, 91% of them asserted it. Lameness (2%) is the less reported consequence of tick's presence on cattle. In Burkina Faso, 4% of herders declared ticks cause lameness but in Benin, no cattle keeper mentioned it as a consequence of ticks presence on their cattle (Table 3).

Injuries (57%), milk reduction (48%) and mortality (47%) are the other important consequences of the presence of ticks on cattle according to the cattle keepers. Herders also reported TBD (18%),

TABLE 3 Tick-related damages on cattle

Departments	Injuries	Teats lost	Dermatosis	Milk reduction	Mortality	Abortion	Weight loss	Lameness	Tick-borne diseases	Myiasis
Alibori	8	10	10	6	7	0	5	0	1	1
Atacora	7	7	8	4	5	2	1	0	3	0
Borgou	9	14	14	6	6	0	0	0	5	0
Donga	6	8	8	7	2	3	3	0	3	0
Benin (Herders)	30	39	40	23	20	5	9	0	12	1
Benin percentage (%)	**68**	**89**	**91**	**52**	**45**	**11**	**20**	**0**	**27**	**2**
Gourma	6	15	16	6	9	1	1	2	0	0
Kompienga	9	11	15	9	8	1	3	0	0	0
Tapoa	6	15	15	5	5	2	0	0	4	4
Burkina Faso (Herders)	21	41	46	20	22	4	4	2	4	4
Burkina percentage (%)	**46**	**89**	**100**	**43**	**48**	**9**	**9**	**4**	**9**	**9**
Overall total	51	80	86	43	42	9	13	2	16	5
Percentage (%)	**57**	**89**	**96**	**48**	**47**	**10**	**14**	**2**	**18**	**6**

The bold values are the percentage of the herders who asserted that the corresponding tick-related damages are recorded in their herds. The percentages are calculated by each country (Northern Benin and Eastern Burkina Faso) and in all the study region (Overall values).

weight loss (14%), abortion (10%) and myiasis (6%) as damages caused by ticks.

Teats loss is one of the most tick-related damages on cattle reported by 89% of herders. A Poisson regression model with the incidence rate ratio (IRR) option allowed us to notice that there were significantly 1.35 times less cows which lost teats because of ticks in Benin compared to those in Burkina Faso (IRR = 1.35; $p < 0.05$). In addition according to the statements of herders in the both countries, transhumant herds presented 1.40 times rate more cows which have lost teats because of ticks compared to the non-transhumant herds (IRR = 1.40; $p < 0.05$).

Hyalomma spp. were most cited as responsible for teat losses of cows in Burkina Faso, whereas *A. variegatum* was most cited in Benin but there was no significant difference (multinomial logistic regression) with regard to the species of tick responsible for the teats' losses of cows.

4 | DISCUSSION

4.1 | Social groups

Several social groups were present within the study area, but the Fulani group were more dominant, and mainly engaged in livestock keeping. This corroborates the findings in the study of Basset *et al* (Bassett & Turner, 2007). The majority of herders (78%) were from this social group as also demonstrated in other previous studies (Adehan et al., 2018; Alkoiret, 2009). The Fulani also known as Fulbe, constitutes one of the largest and most widely spread social groups in Sub-Saharan Africa. They are living in some 20 African countries from Senegal to Sudan and bearing at least 13 names in West Africa alone (Iro, 1994). They are known for their pastoral traditions, although in the course of their long migration from the Senegal Basin eastwards after the 10th century, some of them had given up pastoralism and the nomadic way of life and shifted to agriculture or various urban sources of livelihood (Virtanen, 2015). Cattle farming is ancestral, cultural and sociological in this social group. This activity is exclusively dedicated to men. Women are associated to the management of milk, one of the cattle farming products (Ayoade et al., 2009; Micere Njuki et al., 2016; Yisehak, 2008). Transhumance is the main farming mode practiced by Fulani herders (Ayantunde et al., 2014; Bassett & Turner, 2007; FAO, 2012). The history identifies the Fulani as people who use mobility as production and consumption strategy. Movements in search of water, markets, pasturage, salt licks and the highly priced crop residues account for the spread of the Fulani in Sub-Saharan Africa. A good knowledge on the social groups that manage the cattle farming is an important asset useful for veterinary services for disease control and elaborate adapted awareness messages.

4.2 | Main activity and the level of education of the herders

The principal activity of the herders is cattle farming (91%) and they start this activity at a very young age. Similar finding was observed in Nigeria, where Fulani own over 90% of the livestock population, which accounts for one-third of agricultural GDP and 3.2% of the entire GDP of the country (Iro, 1994). This activity is passed on from father to son. The son starts leading cattle to grazing at around 7 or 8 years old (Ouoba, 2018). He does not get the opportunity to attend primary school. His principal activity until he gets married is to lead cattle to pasture. When he reaches the age to get married, his father will give him a part of the family herd to provide for his wife and children. It will be the same thing with his son. However, some of herders attend to Koranic School (24% of them according to this study). A few of them attained primary education (9%) and secondary or beyond (10%). The literacy rate of adults over 15 years of age was around 34.5% in Burkina Faso in 2014 (Institut national de la statistique and et de la démographie (INSD) Burkina Faso, 2015) and 38,4% in Benin in 2015 (Ministère du Plan et du Développement du Bénin, 2018). The literacy rate of cattle farmers from the present study is lower than the overall rate in their respective countries. The elaboration and implementation of various diseases control strategies should consider this situation.

4.3 | Practice of transhumance

Globally, 60% of the herders involved in this study practice transhumance. According to the World Bank, pastoralism represents an important part of the entire stock-raising sector in West Africa, where it covers between 70 and 90 per cent of cattle raising and 30–40 per cent of small ruminants (SWAC/OECD, 2007; World Bank, 2013).

Internal transhumance is practiced during all seasons. The herders (20%), in partnership with farmers, stay in the farms during the dry season when their bovines eat crop residues and fertilize the farms with their faeces. It is a win–win partnership between farmers and cattle keepers. When the rain starts, they move towards the uncropped areas to graze. These movements are local in the same country. The transboundary transhumance takes place in the dry season. In some areas such as Sahelian countries, harvested residues cannot feed all the livestock. Hence, a relatively big proportion of the livestock (40%) have to move towards less dry countries to find water and grass. Agro-pastoral livestock farming is prevalent throughout West Africa. Animals move within Sahelian countries, from Sahelian countries to coastal countries and within coastal countries (SWAC/OECD, 2014).

Otherwise, animals' mobility (e.g. transhumance) is cause of disease spread. This cattle farming strategy has the double effect of bringing pathogens or vectors to the arrival area or exposing healthy animals to new diseases by leading them to contaminated places (Kardjadj et al., 2019). For instance, the north of Benin is known to be infested by the invasive tick species *R. microplus* that is not yet found in the eastern Region of Burkina Faso. These frequent movements of cattle between the two countries can lead to the contamination of the free areas. The veterinary authorities should increase herder's awareness of this issue.

4.4 | Knowledge of herders on cattle tick seasonality

The surveyed herders assert that ticks are more abundant in the rainy season than the dry season as many authors have already shown (Biguezoton, 2016; Fantahun, 2012; Farougou, 2006, 2007; Keesing et al., 2018; Mattioli et al., 1997; Mulilo, 1985). This pattern is most characteristic for two or three-host tick species (*Amblyomma* spp. *Hyalomma* spp. and *Rhipicephalus* spp.) (Biguezoton et al., 2016). However, ticks belonging to the genus *Rhipicephalus* (*Boophilus*), mainly one-host tick species, are reported to be more present in the dry season, compared to rainy season (Adehan et al., 2018; Biguezoton et al., 2016). In fact, one-host tick species adult stage is observed mainly during dry season in contrast to two-or three-host tick species for which dry season mainly correspond to nymph stage. During rainy season when adult stage of two- and three-host tick species occurs, *Rhipicephalus* (*Boophilus*) adult ticks are also present but with less abundance than in dry season. Herders could not perceive such differences. However, possible confusion of the engorged nymph of *A. variegatum* with engorged female of *Rhipicephalus* (*Boophilus*) spp. could be raised from perception of herders on ticks.

The other ticks of the genus *Rhipicephalus* spp. (not *Boophilus*) are not well known by herders. This genus is rare among cattle herds, so cattle keepers are not familiar with them. The only one species we collected in our study area is *Rhipicephalus sanguineus*, a species usually found on dogs and herders who know it clearly called it 'Dog's tick' in the local language.

4.5 | Tick control

In general, this study shows that herders do not comply with withdrawal periods for milk and meat. One explanation of the apparent absence of intoxication will be that the main acaricide used is amitraz, which has no residues in milk and meat (De Meneghi et al., 2016). Furthermore, herders avoid applying the acaricide directly on cow's udders and teats to avoid mechanic contamination of milk during cow's milking. This mode of treatment highly decreases the risk of milk contamination by those acaricides. A study should be carried out to determine the eventual contamination of milk by these acaricides according to their real mode of application.

Assessment of the origin of the acaricides showed that 51% came from unregulated markets where the sellers do not comply with the storage conditions (temperature, lighting and humidity) prescribed by the manufacturers. Such practice can affect the quality of the products and favour the emergence of resistance of ticks to these acaricides. The origin and quality (real nature and dosage of the active substance) of these products sold on the unregulated market is unknown. This is a great challenge for the veterinary authorities in charge of veterinary drug control to break up the supply chain of these products. The West African Economic and Monetary Union (UEMOA) policies on veterinary drugs control require a community Marketing Authorization (MA) for all veterinary drugs before their introduction in any country of the union since 2006. Unfortunately, majority of the acaricides used by cattle keepers are from the black market without Marketing Authorization. Authorities should better regulate the sector to allow effective control of ticks with registered acaricides of good quality. Cattle keepers need good quality acaricides at affordable prices to abate the invasive resistant ticks in their herds. *R. microplus* is known to be an invasive tick species spreading in West Africa since 2000 and is resistant to most of the usual acaricide applied by West African herders. *R. microplus* had shown its resistance to Amitraz and Alpha-cypermethrin (Adehan et al., 2016; Muyobela et al., 2015). The non-compliance with the prescribed dosage of acaricides can also affect their efficacy on ticks. Our survey revealed that 84% of the herders overdosed the most commonly used acaricide “amitraz” when they use it and 5% of them underdosed it. Furthermore, herders in Benin used less acaricide treatment schedules than those from Burkina. The sedentary herders used less acaricide treatment schedules compared to their transhumant counterpart. This behaviour of herders can favour the emergence of ticks’ resistance to acaricides and complicate tick control. Veterinary services should develop simple and clear protocols for acaricidal treatments with precise timetables. Then, training and awareness-raising sessions for cattle farmers on the importance of adherence to these procedures should be organized on a periodic basis until these measures are fully adopted.

4.6 | Tick related damages on cattle

Ticks are responsible for many damages on cattle. For instance, 69% of the surveyed herds had cow that had lost teats because of ticks. The first consequences of this situation will be the reduction of milk production of these cows and the increase in the mortality of calves because of malnutrition. According to this survey, the species of ticks cited mostly by herders as responsible for teats losses are respectively *Hyalomma* spp. (53%) and *A. variegatum* (36%). However, the proportions change according to countries. In Benin, herders asserted that *A. variegatum* (28%) and *Hyalomma* spp. (25%) are the ticks mainly responsible for injuries and teats lost. This is not different from previous results in the region (Adehan et al., 2018; Biguezoton et al., 2016; Farougou, 2007). On the contrary, Burkina Faso herders assert that *Hyalomma* spp. (48%) is the first tick responsible for injuries and teats lost, followed by *A. variegatum* with 22%. There was no significant difference concerning the species of tick responsible for the teats’ losses of cows. According to the previous abundance studies implemented in this region, the *Hyalomma* genus is more abundant in the eastern of Burkina Faso than *Amblyomma* genus and vice versa in the northern of Benin (Biguezoton et al., 2016; Farougou, 2006, 2007). This observation corroborated the perception of cattle herders about the ticks responsible for cow's teats losses. These two genera reported by herders as responsible for skin damages on cattle are all long hypostome ticks. Therefore, the structure and the size of the hypostome participate to the level of skin traumatism of the tick's bites. Furthermore, many studies have revealed that the predilection sites of *Hyalomma* and *Amblyomma* species on cattle bodies are the perineum region, udder/scrotum and under tail were its hiding sites (Alemu & Chanie, 2012; Meskela & Gashaw, 2017; Ndhlovu et al., 2009; Rehman et al., 2017).

According to some herders, these ticks cause injuries on cow's teats and these injuries attract flies. The presence of flies and ticks maintains wounds that become infected and do not heal quickly. Sometimes flies lay their eggs inside these injured tissues and the larvae develop as part of their life cycle inside the wounds and cause the decay of teats.

Our results also show that herds in Burkina Faso comprise significantly more cows with teats lost than those from Benin. Transhumant herds comprise more cows that lost teats compared to sedentary herds. To avoid milk contamination with acaricides, herders do not apply the product on cow teats. Ticks are removed manually on teats. During transhumance, this method is difficult to apply because animals are too excited and the contention is complicated. Therefore, this cattle management strategy (i.e. transhumance) increases the damage caused by ticks in the herds.

Another finding of this survey is that cattle keepers of the area have little awareness and knowledge of TBD. Only 18% of them asserted that ticks could transmit diseases to their host cattle. Some of TBD and trypanosomiasis have similar symptoms. Most of herders often use drugs against trypanosomiasis. As trypanosomiasis is a frequent disease they face in herds in this part of Burkina and Benin, it is easy for them to mistaken trypanosomiasis for TBD. Moreover, some products use to control trypanosomiasis are also effective against some TBD.

4.7 | Ticks and tick-related damages on cattle perception groups

Epidemiological clusters 2 and 4 indicate an almost even split in the perception of the importance of ticks for milk drop and dermatosis, suggesting the herders have no consensus. It also means a large portion of herders' opinions is incorrect. If the cause is not correctly associated with the condition, control strategies will not adequately address the issue.

Epidemiological clusters 1, 3 and 5 indicate that some tick species, unknown from the herder, can be not perceived as a problem and will therefore not be controlled effectively. This is because they are unfamiliar with these tick species, which were not present in their areas before, and/or they have not been receiving any information about them either from other herders or from information sources. If these tick species are present but not recognized by uninformed transhumant herders, this can lead to tick range expansion and possible associated acaricide resistance.

If the information is not shared uniformly between herders, the knowledge clumps among certain people, probably related to geographic distance. This results into divergent perceptions and strategies for animal management and disease control. These divergent strategies will cause gaps in animal and disease management practices, which can induce the spread of ticks and especially, in case of transhumant herders.

Indeed, in case of irregular release of information by word-of-mouth, the information tends to remain localized. In order to prevent further knowledge and practice gaps, it is therefore crucial to recommend proper and uniformed channels of information to the herders. In addition, a special attention should be given to the seasonal activities of the tick species and the seasonal treatments by acaricides.

5 | CONCLUSION

This study enabled a better understanding of the perception of herders about ticks and tick-related damages on cattle. Cattle keepers demonstrated a high level of awareness on the seasonal tick abundance and their main visible effects on cattle such as dermatosis, wounds and teat losses. Tick-borne diseases did not appear to be well known by breeders. Therefore, sensitization campaigns are needed especially on the various diseases transmitted by ticks and the available suitable treatments. This is very important because there are some zoonoses transmitted by ticks that can represent a real hazard to the cattle herders. The survey also permitted us to appreciate the way the herders managed and controlled tick infestations in their herds. The principal active substance in the acaricides currently used to control the tick infestations in the cattle herds in the study area is amitraz. The majority of the herders do not follow the dosage of acaricides used. Unfortunately, more than 50% of the acaricides used are provided by the unregulated market, where quality is not guaranteed. This highlights a serious problem, given that the source and quality of veterinary drugs are contributing factors that induce the development of acaricide resistance. This study shows also that transhumance is contributing factor to cow's teats losses. Furthermore, the frequent stay of transhumant herds from Burkina Faso in the north of Benin could result in the spread of *R. microplus* in the eastern region of Burkina Faso where this species has not yet been found.

ETHICS STATEMENT

The activities of the research project 'Support to epidemio-surveillance networks for animal diseases and associated sociological aspects in West Africa (Acronym: TransTicks)' have received the favourable opinion of the Ethics Committee of the International Centre for Research and Development on Livestock in Subhumid Zones (CIRDES) (Ref. 001-02/2017/CE-CIRDES) under the strict respect of the protocol submitted to the members of the Committee and their unannounced control.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTION

Olivier Zannou: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Validation; Writing-original draft. **Achille Ouedraogo:** Formal analysis; Investigation; Validation; Writing-review & editing. **Abel Biguezoton:** Conceptualization; Funding acquisition; Project administration; Resources; Writing-review & editing. **Patrick Yao:** Conceptualization; Funding acquisition; Investigation; Project administration; Writing-review & editing. **Emmanuel Abatih:** Methodology; Writing-review & editing. **Souaibou Farougou:** Conceptualization; Supervision; Writing-review & editing. **Laetitia Lempereur:** Conceptualization; Funding acquisition; Investigation; Project administration; Supervision; Validation; Writing-review & editing. **Claude Saegerman:** Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing-review & editing.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1002/vms3.414.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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Study 2: First digital characterization of the transhumance corridors through Benin used by cattle herds from Burkina Faso and associated risk scoring regarding the invasion of *Rhipicephalus (Boophilus) microplus*

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Preamble of study 2

The main livestock strategy in West Africa is pastoralism, including transhumance, the seasonal migration of livestock with pastoralists. This ancient and adaptive strategy aims to optimise livestock access to water and pasture. However, it can favour the cross-border spread of pathogens and vectors. The objective of this study was to identify, firstly, the grazing corridors and areas used by transhumant herds from Burkina Faso to Benin; secondly, the characteristics of transhumance departure and arrival areas; and thirdly, to develop a risk score for the introduction and spread of the invasive tick, *Rhipicephalus microplus*, in free-ranging areas. For this purpose, GPS devices were given to 27 cattle holders to follow a full season of transhumance between eastern Burkina Faso and northern Benin.

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First digital characterization of the transhumance corridors through Benin used by cattle herds from Burkina Faso and associated risk scoring regarding the invasion of *Rhipicephalus* (*Boophilus*) *microplus*

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Abstract

Background: Livestock plays a key role in the macro-economy of West Africa and provides livelihoods for millions of people. The main cattle rearing strategy in West Africa is pastoralism, including transhumance, that is a seasonal migration of cattle with their herders. This adaptive strategy aims to optimize livestock access to water and pastures. However, it can favour pathogens and vectors transboundary spread. The aim of this study was to highlight firstly, the corridors and grazing areas used by Burkina Faso transhumant cattle herds going to Benin; secondly, the characteristics of departure and arrival areas of transhumance; and thirdly, the risk score related to introduction and spread of the invasive tick species, *Rhipicephalus* (*Boophilus*) *microplus*, in free areas.

Methods and principal findings: Therefore, GPS devices were given to 27 herders to monitor a full transhumance season between East Burkina Faso and North Benin. The analysis of 14,966 spots generated by the GPS devices revealed four main corridors and five main grazing areas used by cattle herds during transhumance. Statistical analysis of normalized difference vegetation index (NDVI), rainfall and temperature data, highlighted significant differences between departure and arrival areas. NDVI and rainfall are significantly higher in Benin than Burkina Faso, whereas temperature is significantly lower. Additionally, using biotic and abiotic parameters, a risk scoring was developed to predict the presence of *Rhipicephalus* (*Boophilus*) *microplus* at municipality level.

Conclusions and significance: The better vegetation, temperature and rainfall conditions during the dry seasons in Benin attract cattle herds from Burkina Faso. The invasiveness and adaptability of *Rhipicephalus* (*Boophilus*) *microplus* added to the frequent stays of transhumant herds in infested areas suggest its potential introduction and establishment in free areas soon. Moreover, frequent intrusions of the transhumant cattle in the wildlife reserves are another risk of vectors and pathogen exchange between domestic and wild animals.

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Benin, Burkina Faso, cattle, *Rhipicephalus (Boophilus) microplus*, ticks, transhumance

1 | INTRODUCTION

Livestock plays a key role in the macro-economy of the Economic Community of West African States (ECOWAS) and contributes to 44% of the regional agricultural gross domestic products (GDPs). This subsector provides livelihood opportunities for millions of people who are involved in various production, processing, marketing and livestock service activities (ECOWAS Commission, 2010). The main strategy in cattle rearing in West African countries is pastoralism. Grazing seems to be the main method of its sustainable development in fragile and irregular natural vegetation in sub-Saharan countries (SSC). This form of stockbreeding adapts both flexibly and rapidly to the wide seasonal and inter-annual variations in plant biomass and water resources (Touré et al., 2012). Transhumance is a cyclical migration of pastoralists with their herds. In SSC, the transhumance is an adaptive strategy that aims to improve livestock access to water and quality grazing land to sustain annual production. Transhumance accounts for 70–90% of cattle and 30–40% of small ruminants breeding in West Africa. It contributes to the production of 65% of beef, 40% of small ruminant meat and 70% of milk production. This form of livestock farming provides employment for about 80 million people and represents a source of income for local governments (SWAC/OECD, 2007; World Bank, 2013). Practically, at the end of the rainy season, livestock farmers leave their homeland for areas better suited to cover the nutritional needs of their livestock. The same family may split up into several transhumance routes depending on, for example, its assets, composition of the family, the use or not of paid workers and the herd size (Touré et al., 2012).

During the transhumance, pastoralists choose itineraries that allow them to reach the target area as soon as possible under good feeding and watering conditions for their cattle. Therefore, transhumance is constituted by a range of steps based on information (grazing land, water, crop residues, livestock markets and security) gathered from informants and depending on the farmer's personal experiences. Information and communication technologies (mobile phones, radio) have fundamentally changed the practices of today's pastoralists, empowering them to evaluate at a distance the resources available in the hosting areas, the terms of trade and the cross-border gateways. This itinerary choice depends also on the information provided by livestock networks on livestock safety and health status. Itineraries may change during the trip depending on the updated information.

Pastoralists move their livestock to avoid drought, disease or conflict. Some climate models predict that precipitation will be increasingly erratic and unpredictable during the next few decades (Ingram et al., 2002). In this context, herd mobility will be essential to help farmers adapt to changes in the climate.

South–north movements are most frequent during the rainy season, with livestock leaving their home areas in the most southern regions and extending to non-cropped pasturelands in the north to take advantage of the higher quality forage available there. Another advantage of these south–north migrations during the rainy season is that livestock are removed from the agricultural areas of the south and conflicts between herders and crop farmers are avoided. Livestock return in south with the senescence of pastures and the drying up of surface water points. The timing, direction and extent of these movements are influenced by the biogeography of vegetation phenology, particularly latitudinal gradients during the greening period and the onset of senescence at the onset and end of the monsoon rainy season (Butt et al., 2011).

Herds on transhumance may face many animal health risks when they arrive in new areas with various disease vectors and when they encounter other herds with a different or unknown health status. Grazing areas, vaccination parks, transhumance corridors, livestock watering points and livestock markets are the principal places where animals of different health's status meet and where pathogens and vectors are exchanged. However, very few studies addressed the transhumance routes and its determinants.

The objectives of this study were first to precisely identify the corridors used by Burkina Faso transhumant cattle herds going into Benin, the timing of this transhumance and finally the characteristics of the arrival areas of these transhumant herds. Given that *Rhipicephalus* (*Boophilus*) *microplus*, an invasive tick, is not yet recorded in the eastern part of Burkina Faso but well in the north of Benin, this study will also help to determine the parts of the study area, which are suitable for this tick species development and invasion. The choice of this tick species as a model in our analyses is not only based on its invasive characteristic. It is also resistant to local usual acaricide products and involved in the transmission of various tick-borne diseases. The most known animal diseases transmitted by *Rhipicephalus* (*Boophilus*) *microplus* are anaplasmosis and babesiosis, thus emphasizing its veterinary and economic importance.

2 | MATERIALS AND METHODS

2.1 | Study area

The study area comprises the eastern region of Burkina Faso and the north of Benin. It is located between 8° and 13°N latitude and 1°E and 4°W longitude. The climate in these two regions is almost similar to few particularities. The eastern region of Burkina Faso is characterized by south Soudan climate with five months of rainy season (May to September) and seven months of dry season (October to April) (AQUASTAT/FAO, 2015). The north of Benin is characterized by a Sudan-Sahel type climate located between 10°N and 12°30′N with a rainy season of 5 months (May to September) and a dry season of 7–8 months (October to April).

It is noteworthy to underline that the localities considered within each country do not have the same administrative level. In Burkina Faso, transhumant herds were sampled from three provinces (i.e. Gourma, Kompienga and Tapoa), whereas in Benin four departments (i.e. Alibori, Atacora, Borgou and Donga) were studied as arrival points. For the analyses in this study, these seven localities were regarded as ‘provinces’.

2.2 | Characterization of the vegetation

In order to determine the state of the vegetation during the transhumance period, we calculated its stress using the normalized difference vegetation index (NDVI) based on the raster images downloaded on the website of Landsat (https://landsat.gsfc.nasa.gov/landsat-8/) and according to the formula below (Rouse et al., 1973; Tucker, 1979). These data were used to map the vegetation stress with QGIS software (Quantum GIS Development Team, 2016) in the study area. This index varies from −1 for less vegetative areas to 1 for more vegetative areas (Pettorelli et al., 2005). The NDVI is one of the most successful of many attempts to simply and quickly identify vegetated areas and their 'condition'. It remains the most well-known and used index to detect live green plant canopies in multispectral remote sensing data (Alonso-Carné et al., 2016; Butt et al., 2011; Hogrefe et al., 2017).

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{R}}{\mathrm{NIR} + \mathrm{R}} \quad (1)$$

with NDVI = normalized difference vegetation index; NIR = near infrared; R = red.

Normalized difference vegetation index (NDVI) data for the various locations in our study area were downloaded from the NASA moderate resolution imaging spectroradiometer (MODIS) website (https://modis.gsfc.nasa.gov/data/dataprod/) for a 10-year retrospective period (2009–2018) including thus our field work period (2016–2017). The data used here are precisely that of the MODIS vegetation index MOD13Q1 v006. This MODIS vegetation index product makes spatiotemporal time-series comparisons of global vegetation conditions. These data can be used to monitor the photosynthetic activity of vegetation through the detection and interpretation of phenologic changes. Maps describing spatial and temporal variations in vegetation activity are generated at 16-day and monthly intervals for accurate periodic monitoring of terrestrial vegetation (Didan, 2015). The 10-year NDVI mean data were compared according to the departure and arrival locations of the transhumant herds and according to whether or not they were infested by *Rhipicephalus* (*Boophilus*) *microplus*.

2.3 | Characterization of the climate

To analyse the climate patterns with accurate data (rainfall, temperature and moisture), we retrospectively collected data for the last 20 years from the local climate stations of the study area. Ten-year (2009–2018) land surface temperature and emissivity (LST&E) data were also downloaded from the NASA moderate resolution imaging spectroradiometer (MODIS) website (https://modis.gsfc.nasa.gov/data/dataprod/). The product used here is the MOD11A2 v006, which provides an average of 8 days LST&E pixel with a spatial resolution of 1 kilometre. The 8-day composition period was chosen because twice this period is the exact repetition period of the ground track of the terra and aqua platforms. The day and night surface temperature bands are supplemented by quality control assessments, observation times, zenith angles and clear sky cover, as well as emissivity bands for the associated land cover types (Wan et al., 2015). These data were compared to detect the suitability of these areas to tick species development and establishment.

2.4 | Herds tracking with Global Positioning System tags

To precisely determine the different spaces covered by herds during transhumance, twenty-seven herdsmen conducting cattle herds from Burkina Faso to Benin were given global positioning system (GPS) tags SPOT Gen3 (SPOT LLC). These GPS tags send signals every hour, and those signals were visualized as spots through an account created on the website of Findmespot (https://africa.findmespot.com/en/https://africa.findmespot.com/en/). This allowed us to follow the selected herds in real time and to know their position when the GPS tags worked normally. When there is dysfunction with the GPS tags, we noticed it on the website and instructions were given to the herdsmen responsible to solve the problem. This tracking helped to determine (a) the real itinerary of every surveyed cattle herd and the transhumance corridors used; (b) the entry point to the arrival country; (c) the duration of the transhumance season; (d) the stay areas in the arrival country; (e) and the grazing areas during their stay in the arrival country. These transhumance parameters (i.e. corridors, main entry point in Benin and grazing areas during the dry season) were highlighted on heat maps of all spots generated by the SPOT gen GPS devices using QGIS software (Quantum GIS Development Team, 2016).

2.5 | Evaluation of the risk of the presence of *Rhipicephalus* (*Boophilus*) *microplus* in the different municipalities of the study area

The main farming system practiced in West African countries is free ranging. This farming system is based on quest of pasture to feed livestock and water points for watering animals. Livestock vaccination campaigns are organized every year against the main diseases (i.e. contagious bovine pleuropneumonia and bovine pasteurellosis) for which vaccines are available. Livestock markets are set in every locality to facilitate trade of animals and animal products. These various meeting points are risk areas for many vectors and diseases transmission between animals (Kao, 2002, 2006; Kao et al., 2007; Ortiz-Pelaez et al., 2006; Shirley & Rushton, 2005).

A census of these different areas has been done through the geolocation with GPS devices and information given by offices in charge of animal health in the two countries. The statistics of these risk areas crossed with the biotic and abiotic factors of the tick *Rhipicephalus* (*Boophilus*) *microplus* (e.g. NDVI, cattle density and climate data) allowed generating an infestation risk score for this tick species. A model was developed based on eight variables (Table 1) which can influence the presence or absence of *Rhipicephalus* (*Boophilus*) *microplus* in the area. A score was attributed to each variable by the authors according to its importance in the introduction and development of the tick in an area (maximum score of 100). The biotic and abiotic factors (rainfall, temperature, vegetation index and cattle density) had the highest score because of their importance in the life cycle of ticks. These four variables that have a key role in the life of the ticks received 80% of the global score of the risk. The other variables (livestock market, water point, transhumance corridor and transhumance grazing area), which are involved in the introduction and the spread of ticks, had lower scores (Tables 1 and 2). The importance of each variable has been documented by some publications that have highlighted their role in the biology or spreading of the tick. These different publications are referenced in Table 2. The scoring grid (Table 2) attributed to each variable is the result of the authors' proposals according to the importance and optimal value of this variable for the tick. These applied scores have been subject to a validation and amendment process by a panel of four experts (two acarologists, one parasitologist and one epidemiologist) consulted for this purpose. In each municipality, every variable receives a score according to its value in this locality. The score is the highest when the value of the variable is optimum and lowest when the value is worst. The risk score of each municipality was calculated by summing all the scores of the different variables of that specific area. The results were mapped with QGIS.

2.6 | Acarological survey used for validation of the model

An acarological survey was carried out simultaneously with the present study (Ouedraogo A.S., 2020, personal communication). The results of this survey are ongoing of publication with parasitologists of the consortium as lead. The *Rhipicephalus (Boophilus) microplus* occurrence data used to validate the risk model resulted from morphological and molecular identifications of ticks sampled in the same study area.

TABLE 1 List of variables used for the presence risk model of *Rhipicephalus* (*Boophilus*) *microplus*. (NASA: National Aeronautics and Space Administration; MODIS: Moderate Resolution Imaging Spectroradiometer; DGSV: Direction Générale des Services Vétérinaires; DE: Direction de l'Elevage)

Variable names	Variable categories	Data sources	Weight justification	Justification references
Rainfall	Abiotic	Météo Bénin & https://www.infoclimat.fr/climato	Abiotic factors, essential for the presence and the development of the tick. They heavily influence the distribution of the tick	Estrada-Peña et al. (2006)
Temperature	Abiotic	NASA/MODIS https://modis.gsfc.nasa.gov/data/dataprod/		Estrada-Peña et al. (2006), Estrada-Peña and Venzal (2006)
Vegetation Index	Abiotic	NASA/MODIS https://modis.gsfc.nasa.gov/ data/dataprod/		Estrada-Peña et al. (2006), Estrada-Peña and Venzal (2006)
Cattle density	Biotic	DGSV (Burkina Faso) & DE (Benin)	Biotic factor, also needed in the development of the life cycle of the tick	Baneth (2014) and McCoy et al. (2013)
Livestock market	Biotic	DGSV (Burkina Faso) & DE (Benin)	Cattle is the favourite host for *Rhipicephalus (Boophilus) microplus*	Ma et al. (2016)
Water point	Biotic	DGSV (Burkina Faso) & DE (Benin)	These variables represent areas of meeting of hosts and spread of the parasites and pathogens	
Transhumance corridor	Biotic	Transhumance monitoring (this study)		
Transhumance grazing area	Biotic	Transhumance monitoring (this study)		

TABLE 2 Variables and corresponding scores used in the risk model for *Rhipicephalus (Boophilus) microplus*

Variables (unit)	Variable (value range)	Score attributed	Justification references
Vegetation Index (index)	Null [0]	0	Estrada-Peña et al. (2006), Estrada-Peña and Venzal (2006)
	Low [0.10–0.40]	6	
	Medium [0.41–0.50]	12	
	High [0.51–1]: 20	20	
Temperature mean (°C)	Low [20–29.4]	20	Estrada-Peña et al. (2006), Estrada-Peña and Venzal (2006)
	Medium [29.5–30.4]	12	
	High [30.5–45]	6	
	Other	0	
Rainfall mean (mm)	Null [0]	0	Estrada-Peña et al. (2006)
	Low [0–1,000]	6	
	Medium [1,000–1,100]	12	
	High [1,100–∞]	20	
Cattle density (cattle/km^2)	Low [0–20]	6	Baneth (2014), McCoy et al. (2013)
	Medium [21–40]	12	
	High [41–60]	20	
Water point (number)	Null (0)	0	Perry et al. (2013)
	Low [1–6]	2	
	Medium [7–12]	4	
	High [13–21]	6	
Transhumant grazing area (number)	Absent	0	Perry et al. (2013)
	Small	2	
	Medium	4	
	Large	6	
Transhumance corridor (number)	Absent	0	Perry et al. (2013)
	Present	4	
Livestock market (number)	Absent [0]	0	Perry et al. (2013)
	Very low [1]	1	
	Low [2]	2	
	Medium [3]	3	
	High [4]	4	

2.7 | Sensitivity analysis of the predictors used in the risk model

A sensitivity analysis was added to check whether all the predictors (eight variables) used to evaluate the risk of presence of *Rhipicephalus* (*Boophilus*) *microplus* in the municipalities of the study area are useful. The first step consists of ranking all the 44 municipalities considering their global risk score with all the eight variables. At the second step, one-by-one predictors were suppressed and the risk score was ranked each time considering all the municipalities. The third (and last) step was counting how many changes occurred in the municipalities ranking, using a diagram. We only count changes in rank that represent at least 10% of the total number of municipalities (10% of 44 = 4). For each variable, we look at how many municipalities were affected by a change in superior or equal to 4 ranks (Petit et al., 2020; Saegerman et al., 2020). This allow to evidence the variables that have the most influence on the ranking of the municipalities and consequently in the evaluation of the risk of the presence of *Rhipicephalus* (*Boophilus*) *microplus*.

A sensitivity analysis was also carried out by comparing the rankings of municipalities in the model with weighted criteria and the model without weighting.

2.8 | Statistical analysis

Analysis of variance (ANOVA) was used to determine whether the means of NDVI, rainfall and temperature (10-year retrospective data) are the same in the departure and arrival areas or in the areas where *Rhipicephalus* (*Boophilus*) *microplus* was found or not. A negative binomial regression analysis was performed with Stata/SE 14.2 (StataCorp) to understand the variation of the risk between the two countries and also between areas where *Rhipicephalus* (*Boophilus*) *microplus* was found or not. The aim was to check the variation of the risk score (dependent variable) according to the various countries and areas where the tick was found (independent variables).

To test the predictive performance of our model in terms of the presence of *Rhipicephalus (Boophilus) microplus*, we used the area under the curve of the receiver operating characteristic (AUC-ROC) plot and the scale established by Swets (1988). The risk score prediction of the presence of the invasive tick by municipalities was compared to data of tick sampling which occurred during the studied transhumance campaign within the concerned herds.

3 | RESULTS

3.1 | Characterization of the vegetation

The satellite images downloaded on NASA website help to map the vegetation of the study area. The vegetation in the arrival area in Benin is greener and healthier than the departure area (Figure 1) during the transhumance period. A ten-year mean value of NDVI also showed that during all the years the vegetation is always better in northern Benin than in eastern Burkina Faso (Figure 2). An analysis of variance (ANOVA) showed that the vegetation index (NDVI) of the north of Benin was higher than that of the eastern region of Burkina Faso ($p < .001$). An analysis of variance (ANOVA) indicated that there was also an important difference between the NDVI of some of the departments located in the study area (Figure 3). This statistical analysis revealed that Atacora, the main arrival area of the transhumant in Benin, has a better NDVI than the three other departments of Burkina Faso ($p < .001$). The NDVI map also indicated that wildlife reserves areas are greener than other parts of the study area (Figure 1). During the period of transhumance, cattle herds spent their stay in Benin in the greenest places of the moment. Those that do not transhumant graze near the wildlife reserve areas. The vegetation is still green and better around the parks even in the dry season. Some of the transhumant cattle herds passed over the ban, visited the wildlife reserve area and spent some days in the park of Pendjari in Benin (Figure 1).

An ANOVA of the vegetation index revealed that there was a statistically significant difference ($p < .001$) between areas where *Rhipicephalus (Boophilus) microplus* is found and where it is not yet found.

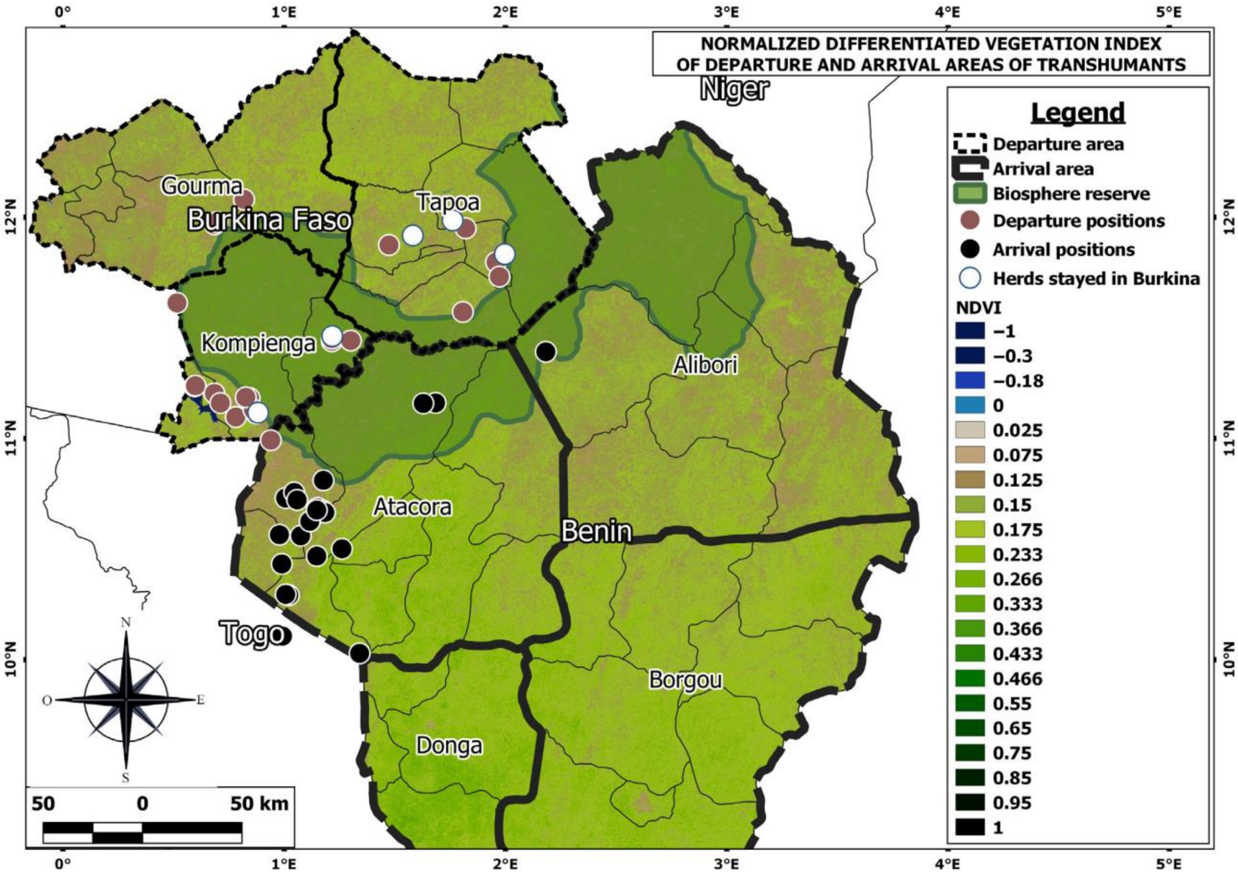


FIGURE 1 Normalized difference vegetation index of the study area

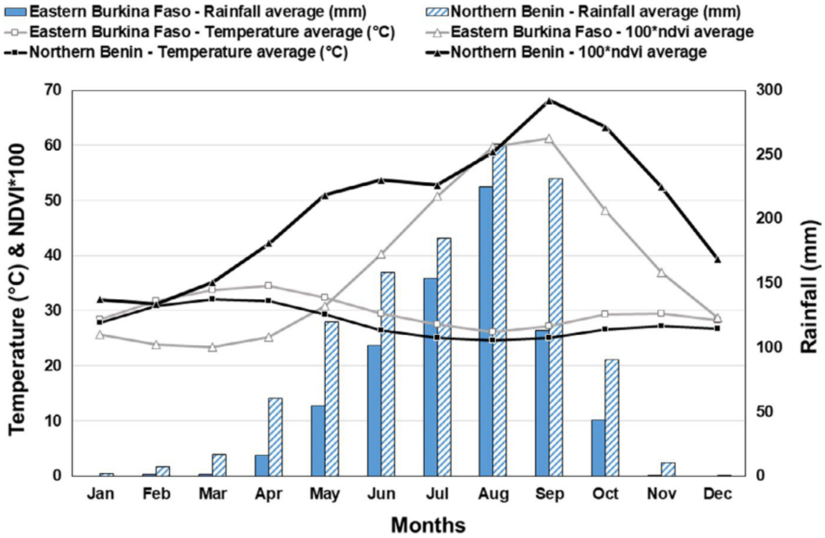


FIGURE 2 Comparative monthly evolution of rainfall, temperature and normalized difference vegetation index (NDVI) between the departure and arrival areas [Colour figure can be viewed at wileyonlinelibrary.com]

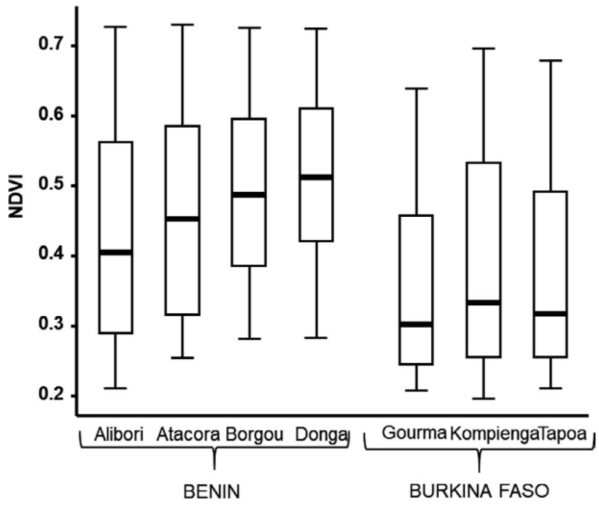


FIGURE 3 Distribution of comparative normalized difference vegetation index (NDVI) across the provinces of the study area (Alibori, Atacora, Borgou and Donga are Benin provinces and Gourma, Kompienga and Tapoa are Burkina provinces). Legend: The dashed line represents the median value of NDVI; the solid lines below and above each rectangle represent, respectively, the first and the third quartiles; and adjacent lines to the whiskers represent the limits of the 95% confidence interval

3.2 | Characterization of the climate

ANOVA test revealed that there is a sizeable difference ($p < .001$) between the rainfall of eastern region of Burkina Faso (10-year annual rainfall average: 713 ± 115 mm) and the north of Benin (10 years annual rainfall average: 1,130 ± 101 mm) (Figure 2). The two areas have almost the same rainy season duration (from May to September). However, the north part of Benin is more watered than the eastern part of the Burkina Faso (difference of + 417 mm between the two regions). The areas where *Rhipicephalus (Boophilus) microplus* has been found (Northern Benin) appear to be more watered than those (eastern region of Burkina Faso) where it is not yet found based on the current study.

Regarding temperature, statistical analysis (ANOVA test) results revealed that eastern region of Burkina Faso (annual mean: 29.8 ± 2.7°C) is ($p < .001$) hotter (+2.03°C) than the north of Benin (annual mean: 27.8 ± 2.6°C). The ANOVA test also indicated that the areas where *Rhipicephalus (Boophilus) microplus* has been sampled are colder (−2.03°C) than the areas where it has not been encountered ($p < .001$). Additionally, there is a strong positive correlation between NDVI and rainfall (Pearson's correlation coefficient, $r = .8$), a strong negative correlation between the NDVI and the temperature ($r = -.77$) and a negative correlation between rainfall and temperature ($r = -.65$).

3.3 | Herds tracking with global positioning system tags

The 27 global positioning system (GPS) tags SPOT Gen 3 have emitted 14,966 spots during the transhumance season. Around 70% of these spots have been emitted between 06:00 am and 07:00 pm (Figure 4). This time slot of the day matched with the period when the cattle herds were on pasture for grazing. At night, the GPS tags are kept in houses or under shelters where the transmission with satellites is very bad, so few spots were recorded during this period.

The monitoring of transhumance for one season with GPS tags helped to know the real corridors used by the selected herds. Four corridors and three entry points were identified (Figure 5). The herds coming from Gourma used only one corridor, which passed through Kompienga to join Atacora in Benin. The entry point used by these herds is Porga, the main one also used by some herds from Kompienga. The transhumant herds coming from Tapoa used two corridors. The first and main one joins the corridor of Gourma and

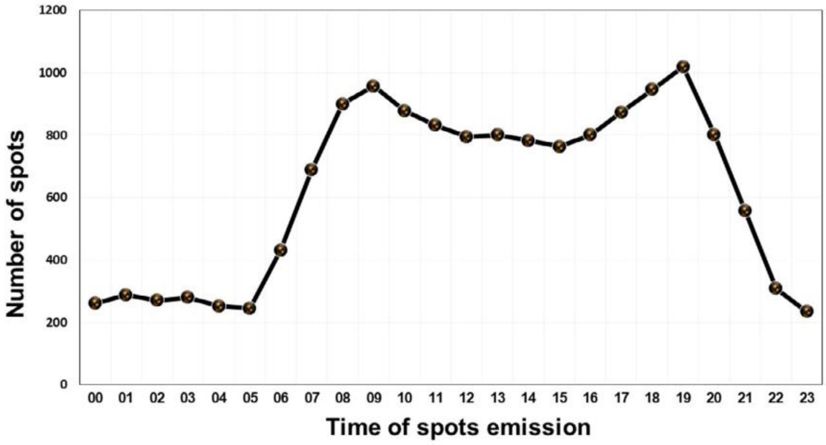


FIGURE 4 Spot distribution according to the time of transmission, expressed in hours. Legend: Grazing period in daytime, between 06 and 19 (hr); rest period in the park at night, between 20 and 05 (hr). [Colour figure can be viewed at wileyonlinelibrary.com]

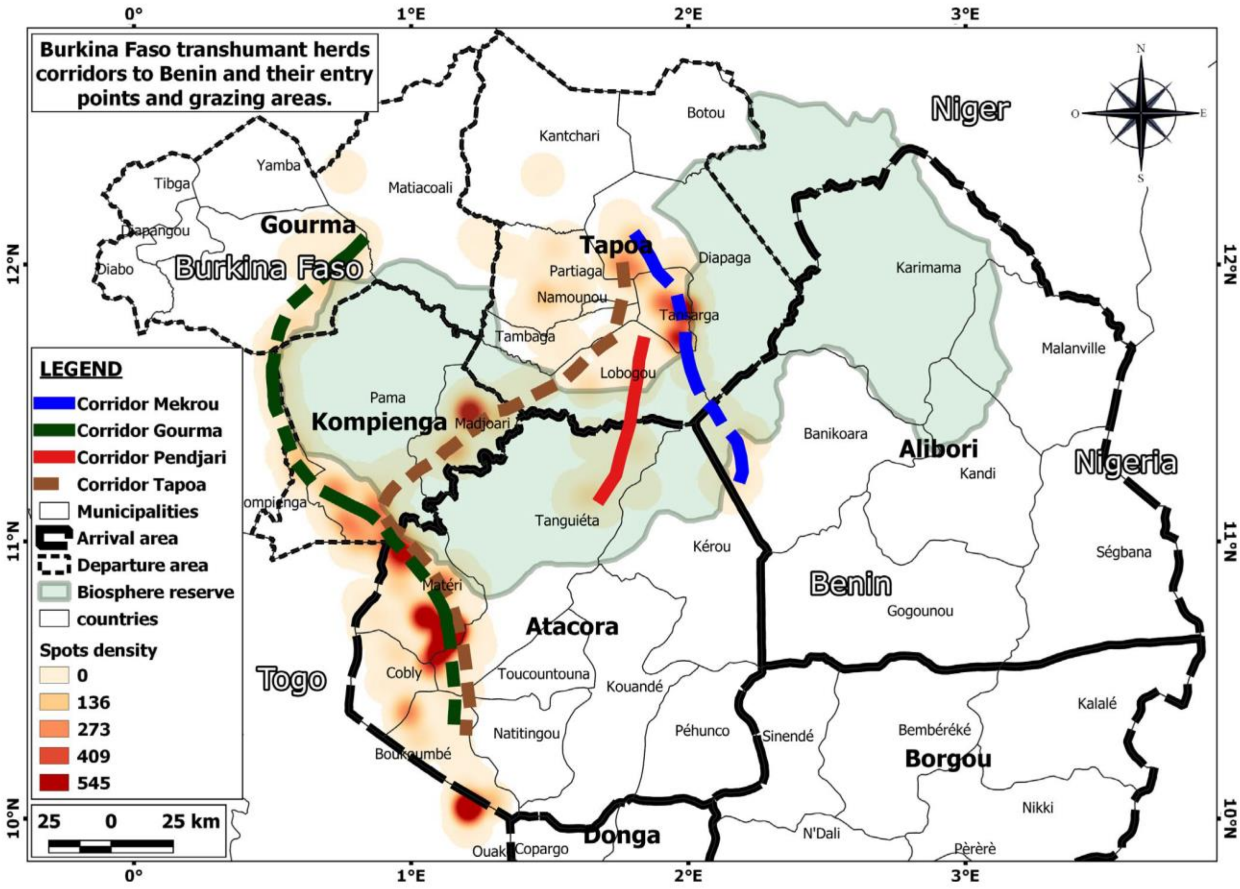


FIGURE 5 Transhumance corridors, grazing areas and entry points of Burkina Faso transhumant herds through Benin

the second one joins Alibori in Benin *via* Banikoara, the second entry point (Figure 5). Some herds from Kompienga also used the first corridor of Tapoa. The fourth and last corridor is the one through which some herds illegally enter the Pendjari Park where there are wild animals. The Pendjari Biosphere Reserve (PBR) is situated in the Atacora Department, in the north-western part of Benin (10°30′ to 11°30 N; 0°50′ to 2°00′E).

3.4 | Prediction of the risk of the presence of *Rhipicephalus (Boophilus) microplus* in the different municipalities of the study area

The kernel density estimate of the risk score indicated a discriminatory power due to the bimodal distribution (Figure 6). The result of the risk score evaluation is mapped and represented in Figure 7. These results showed that the north of Benin is more suitable to the ticks than the eastern region of Burkina Faso. Furthermore, a negative binomial regression analysis revealed that the scores associated with the presence of *Rhipicephalus (Boophilus) microplus* ($p < .001$) were higher in the northern part of Benin (mean score of Benin is 62.70%) compared with the eastern part of Burkina Faso (mean score of Burkina Faso is 33.76%). Results also indicated that the scores in areas where the tick was found were ($p < .001$) higher (mean score difference is +23.33%) than those it was not yet found.

The heat map shows the grazing areas (i.e. places with high value of spot density corresponding to more red coloured areas) of the cattle herds during transhumance. There were five main grazing areas (three in Benin and two in Burkina Faso) (Figure 5). This heat map also confirms that some herds had a stay in the park of Pendjari where we have wild animals.

The statistical analysis of the risk scores across the provinces showed wide variations and important differences between some of them. The province with the lowest risk score is the province of Gourma in Burkina Faso, and the highest risk was noticed in the province of Atacora in Benin.

The evaluation of the performance of our model in predicting the presence of *Rhipicephalus (Boophilus) microplus* using the area under the ROC curve revealed that the AUC was 0.81 with a standard error of 0.07 (Figure 8). According to the classification established by Swets (1988), such model is qualified as a 'useful' model.

3.5 | Sensitivity analysis about the impact of predictors on the municipalities risk score ranking and the associated weighting

The sensitivity analysis results showed that all our predictors are important in the *Rhipicephalus (Boophilus) microplus* presence risk

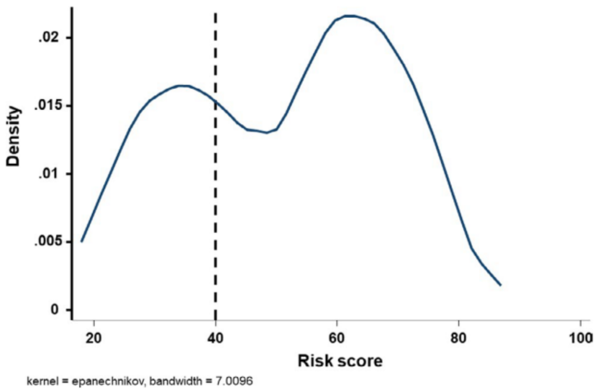


FIGURE 6 Kernel density estimate of the risk score produced to predict the presence of *Rhipicephalus (Boophilus) microplus*. Legend: Vertical line corresponds to the best cut-off to divide the distribution in two different subpopulations according to the ROC curve presented in the Figure 8. [Colour figure can be viewed at wileyonlinelibrary.com]

scoring of the municipalities. The removal of each predictor (variable) induced important changes in the ranking. The threshold has been set at least on four unit difference in ranking of the municipalities. Three predictors which have a strong effect on the sensitivity (Figure 9a) generate at least twelve municipalities ranking changes. These predictors are as follows: 'Cattle density' ($n = 14$), 'Rainfall mean' ($n = 13$) and 'Temperature mean' ($n = 12$). 'Cattle density' was the predictor that induced the most changes in the ranking of the risk score of the municipality, that is 14 municipalities ranking changed. Meanwhile, 'Livestock markets' generate the least changes: 01 municipality ranking changed. The other predictor changes in municipality ranking are in decreasing order: 'Transhumance corridor' (05 municipality ranking changes); 'Water point' (04 municipality ranking changes); 'Transhumant grazing area' (04 municipality ranking changes); 'Vegetation Index' (03 municipality ranking changes); and 'Livestock market' (01 municipality ranking changes).

The sensitivity analysis according to weight of the predictors shows a great variation in the ranks of many municipalities between the weighted and unweighted models. The comparison of the weighted and the unweighted models revealed that 25 municipalities ranking change with at least four units (Figure 9b).

4 | DISCUSSION

4.1 | Vegetation and climate divergences between eastern Burkina Faso and north of Benin: main drivers of the transhumance

Globally, the north of Benin has significantly a better NDVI, a greater rainfall and is less warm than the eastern region of Burkina Faso. Additionally, there is a positive correlation between the NDVI and the rainfall and a negative correlation between temperature and NDVI and also between temperature and rainfall. Higher rainfall generates a better vegetation index (NDVI) and low temperature. Indeed, ticks biology needs good vegetation, humidity and appropriate temperature. It is well known that abiotic factors, including climatic factors, ecological factors and vegetation cover, govern the presence and development of ticks in an environment (Dantas-Torres, 2015). Variations in these abiotic factors can lead to modifications in the distribution of ticks species (Léger et al., 2013).

Vegetation plays a key role in the development of ticks because they can spend 80%–90% of their life out of the host as questing larvae in nature (Leal et al., 2018). They need during these periods an adequate vegetation coverage that will generate at the same time a good humidity and temperature essential for their development (Pfäffle et al., 2013). Vegetation is also important to the tick for host questing. Ticks use vegetation to stay alert waiting for the host to pass by. Depending on the size of the hosts available in their living environment, ticks need vegetation of high or small size accordingly to increase the probability of catching these hosts (Ginsberg et al., 2014). The availability of vegetation is also an opportunity for ticks to have host that need vegetation (e.g. ruminants). Therefore,

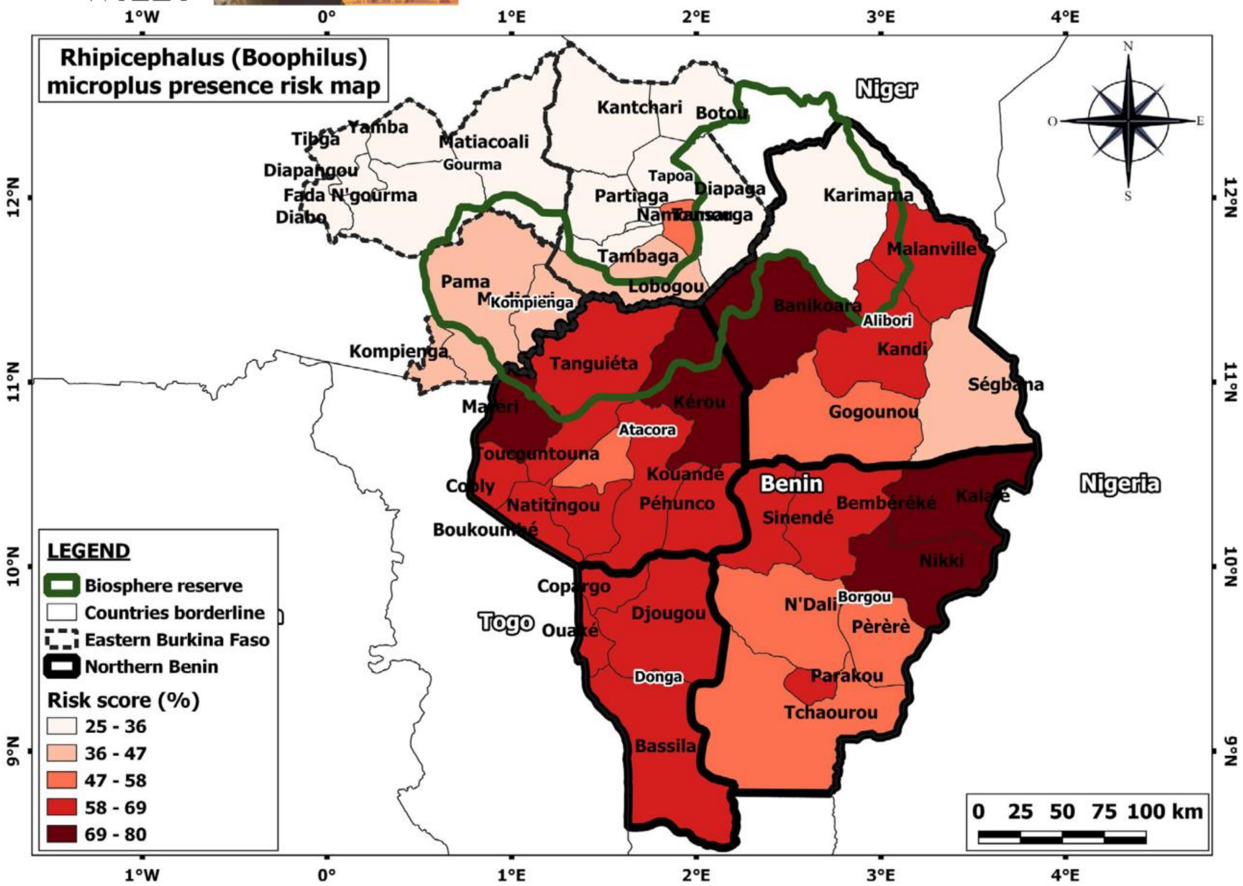


FIGURE 7 Distribution of risk scores for the occurrence and establishment of *Rhipicephalus (Boophilus) microplus* in the various study regions

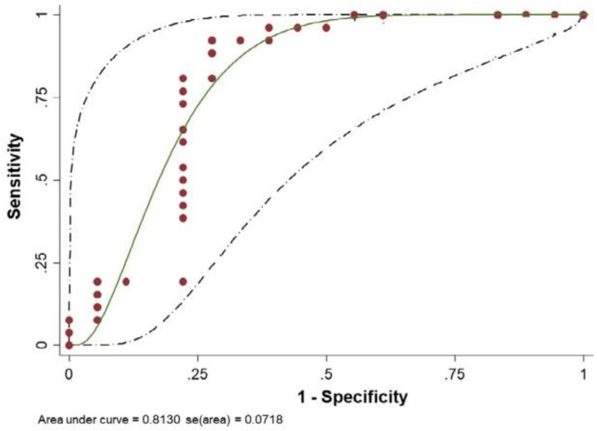


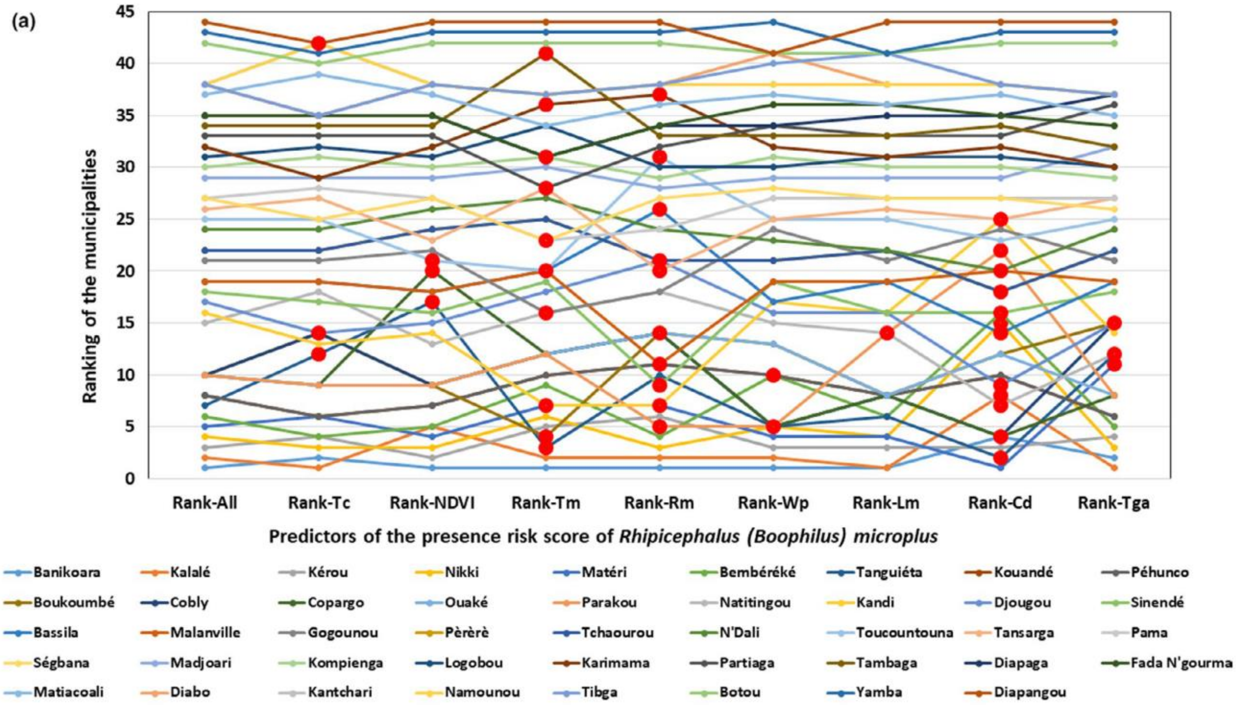
FIGURE 8 Area under the curve (AUC) of a receiver operating characteristic (ROC) plot with 95% confidence interval (broken line) for the risk scoring system of prediction of the presence of *Rhipicephalus (Boophilus) microplus* [Colour figure can be viewed at wileyonlinelibrary.com]

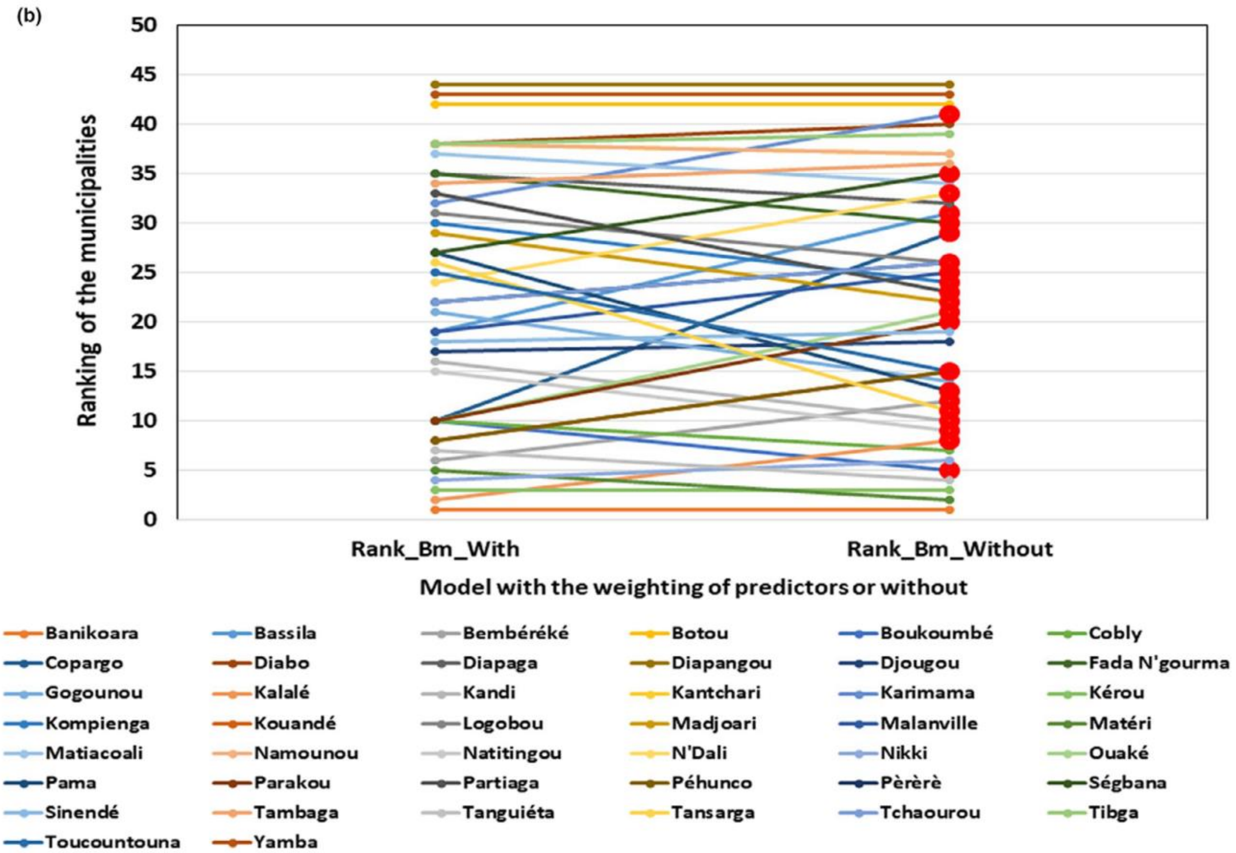
area with better NDVI represents better areas for both ticks and their host and their relationship.

The risk of presence of tick species in green and wet places is higher than in the dry and hot ones. During the dry season, the density of cattle increases on the few places where there is grass and water. Many herds with various health statuses come from different places. This situation increases the risk of infection/infestation and raising of epidemic diseases (e.g. foot-and-mouth disease).

Burkina Faso is globally hotter and drier than Benin. The downloaded climate data have shown it clearly (Figure 2). These climate patterns seem to be more suitable for *Rhipicephalus (Boophilus) microplus* in Benin than Burkina Faso. Climatic risk factors (rainfall and temperature) are more favourable to cattle of Burkina Faso than those of Benin for the infestation by ticks. *Rhipicephalus (Boophilus) microplus* seems to have a preference to areas that are not too hot like the Sahel region in Burkina Faso. In fact, statistical analyses of its

FIGURE 9 Sensitivity analysis according to the predictors of the risk of presence of *Rhipicephalus* (*Boophilus*) *microplus*. (a) The diagram shows the modifications of the rank induced by the removal of a given predictor of the presence risk score. (b) The diagram shows the modifications of the rank induced by the weighting of the predictors or not. Legend: Rank All, all the eight predictors included; Rank-Tc, rank all minus transhumance corridor; NDVI, normalized difference vegetation index; Tm, temperature mean; Rm, rainfall mean; Wp, water point; Lm, livestock markets; Cd, cattle density; Tga, transhumant grazing area; red circles represent the cut-off of more than three rank between different step. Removal of the predictor Cd (Cattle density) highlights the importance of this predictor leading to the highest cut-off number.


(a)
Ranking of the municipalities
Rank-All
Rank-Tc
Rank-NDVI
Rank-Tm
Rank-Rm
Rank-Wp
Rank-Lm
Rank-Cd
Rank-Tga
Predictors of the presence risk score of Rhipicephalus (Boophilus) microplus
Banikoara
Kalalé
Kérou
Nikki
Matéri
Bembéréké
Tanguiéta
Kouandé
Péhunco
Boukoumbé
Cobly
Copargo
Ouaké
Parakou
Natitingou
Kandi
Djougou
Sinendé
Bassila
Malanville
Gogounou
Pèrèrè
Tchaourou
N'Dali
Toucountouna
Tansarga
Pama
Ségbana
Madjoari
Kompienga
Logobou
Karimama
Partiaga
Tambaga
Diapaga
Fada N'gourma
Matiacoali
Diabo
Kantchari
Namounou
Tibga
Botou
Yamba
Diapangou


(b)
Ranking of the municipalities
Rank_Bm_With
Rank_Bm_Without
Model with the weighting of predictors or without
Banikoara
Bassila
Bembéréké
Botou
Boukoumbé
Cobly
Copargo
Diabo
Diapaga
Diapangou
Djougou
Fada N'gourma
Gogounou
Kalalé
Kandi
Kantchari
Karimama
Kérou
Kompienga
Kouandé
Logobou
Madjoari
Malanville
Matéri
Matiacoali
Namounou
Natitingou
N'Dali
Nikki
Ouaké
Pama
Parakou
Partiaga
Péhunco
Pèrèrè
Ségbana
Sinendé
Tambaga
Tanguiéta
Tansarga
Tchaourou
Tibga
Toucountouna
Yamba

presence and temperature data showed that its presence areas are not as hot as those of absent areas.

4.2 | Period and location of grazing during transhumance: Are protected areas at risk?

Most of the spots of the global positioning system (GPS) tag were emitted in the daytime from 06:00 am to 07:00 pm. This time slot corresponds to the time spent by the herds on pasture, and this correlates with the statements of the majority of herders in the survey that followed this work. However, some herders asserted that sometime they could go on pasture at night, whereas it is forbidden. The 30% of spots we had at night time may be a result on these forbidden practices.

The Pendjari Biosphere Reserve (PBR) is located in north-western Benin (10°30′ to 11°30′ N; 0°50′ to 2°00′ E) in the Department of Atacora. It was designated as a hunting reserve in 1954 and transformed into a national park in 1961. Today, it is divided into a protected core area (Pendjari National Park, PNP: 2,660 km^2) and a buffer and hunting zone to the west and south (1,870 km^2). This biosphere is one of the best managed protected areas in Benin. It is also one of the richest and most diverse wildlife reserves in West Africa (Nago et al., 2006; Oumorou et al., 2011). Whereas the PNP has a special status (protected area) and its access is forbidden to domestic animals, we noticed that this ban is not respected by some local and transhumant herds. Such protected areas are very attractive to transhumant herds because there they can find water and pasture during the dry seasons (Séidou et al., 2017). The droughts of 1973 and 1984 and the pressure of the tsetse fly obliged the transhumants of the Sahel (Niger and Burkina Faso) to descend into the protected areas of northern Benin. This was the beginning of incursions into these protected areas (Boutrais et al., 2008; Escadafal et al., 2012; Kagone et al., 2006). Interestingly, a census conducted in 2000 reveals twenty species of wild animals, comprising most of the larger mammals of West Africa, in particular bovids (Sinsin et al., 2002), for example buffaloes. These wild animals can easily share vectors and pathogens with transhumant cattle, which spent time in the park during the dry season questing water and pasture. This represents a real health risk for wildlife. If we consider the importance of the protected species for this park and the wildlife, it is important to control the sanitary situation of these wild animals by avoiding frequent contact with domestic ones. Wild animals also are often reservoirs for zoonotic pathogens which can be transmitted to humans *via* domestic animals. Whereas *Rhipicephalus (Boophilus) microplus* is described as a specific tick for cattle (cattle fever tick), it can use other mammals (e.g. deer, wild carnivores and oryx) as alternate host (Busch et al., 2014; De Meeûs et al., 2010; Labruna et al., 2005; Tonetti et al., 2009). An introduction of *Rhipicephalus (Boophilus) microplus* in the park will cause a real threat to the protected species that can host this vector and its transmitted diseases (George, 1990). Its introduction in wildlife will also complicate its control. Buffaloes are reservoirs for the foot-and-mouth disease virus. The frequent relationship of cattle and wild bovids could undermine ongoing efforts to control and/or eradicate this disease (in domestic animals) in West Africa.

4.3 | Prediction of the risk of the presence of *Rhipicephalus (Boophilus) microplus* in the different municipalities of the study area

A scoring system was developed using biotic and abiotic variables to predict the presence of *Rhipicephalus (Boophilus) microplus* at municipality level. The choice of variables was motivated either by their importance in the biology of the tick (temperature, rainfall, vegetation index, cattle density) or by their role in the introduction and spread of the tick in an environment (livestock market, transhumance corridor, grazing area and water points). The score of 20% was dedicated to each of the four variables (rainfall, temperature, vegetation index and cattle density) because they are vital factors for the tick life. The tick cannot live without one of these factors (Baneth, 2014; Estrada-Peña et al., 2006; Estrada-Peña & Venzal, 2006; McCoy et al., 2013). The introduction and the spreading of the tick will be possible through the four other factors (livestock market, water point, transhumance corridor and transhumance grazing area). They are highly implicated in changes in spatial dynamics of animal diseases (Perry et al., 2013). These variables that are not crucial for the tick life are rated lower than the first four ones. The importance of these variables lies in their involvement in the infestation of new animals and environments. Using this scoring system, the predictability of the model for the presence of *Rhipicephalus (Boophilus) microplus* was estimated as useful according to John A. Swets (Swets, 1988) scale. These value means that our model can predict the presence of *Rhipicephalus (Boophilus) microplus* with an accuracy of 81%.

Benin presents more suitable conditions to *Rhipicephalus (Boophilus) microplus* than Burkina Faso. This tick prefers wet and cold places than dry and hot ones (Estrada-Peña & Venzal, 2006). The risk of its presence in the eastern region of Burkina Faso as shown by current results is not null (Figure 7). The periodic movements of cattle through the eastern part of Burkina Faso and the north of Benin enhance the risk of introduction of *Rhipicephalus (Boophilus) microplus* in this part of Burkina Faso. Such situation has yet been observed in western-south Burkina Faso where transhumant herds to Côte d'Ivoire lead on the introduction and establishment of the invasive tick species (Adakal et al., 2013; Biguezoton et al., 2016).

The risk is higher in some municipalities of Benin, bordering Burkina Faso, in contrast to some municipalities in central northern Benin. This difference is due to some abiotic factors such as vegetation index, rainfall and temperature, which are better in the first areas and make there the environment more suitable for ticks. The same thing has been noticed with the municipalities of Burkina located near the border with Benin. These municipalities appear to be more suitable to the tick than others. The municipalities of Benin and Burkina Faso around the borderline belong to complex WAP (W-Arly-Pendjari). It is a transnational property shared by the Republic of Niger, Burkina Faso and the Republic of Benin in West Africa. Furthermore, this complex is at the heart of the largest protected area block in the West African Savannah/Woodland Biogeographic Province. It comprises the largest and most important continuum of terrestrial, semi-aquatic and aquatic ecosystems in the West African savannah belt (Schmidt et al., 2016). The controlled management of this area prevents anthropic action and allows the conservation of several animal and plant species. Moreover, there is a permanent river (Pendjari) along the borderline between Burkina Faso and Benin and a mountain range (Atacora mountain range) in the eastern north of Benin that makes its climate different from the rest of northern Benin.

Furthermore, the frequent introduction of transhumant cattle in the park of Pendjari, as it was revealed by the GPS trackers, will create damages later. The park showed a suitable habitat for *Rhipicephalus (Boophilus) microplus* through our risk map (Figure 7) and many wild animal species, which could be alternative host to this tick, are present. An introduction of *Rhipicephalus (Boophilus) microplus* even if it is known to be cattle tick (specific to cattle) in wildlife seems to be possible and will complicate its control or/and eradication.

Among the wild mammals listed in the Pendjari National Park, there is the African Buffalo (*Syncerus caffer*). This animal is known to be a reservoir host to many pathogens responsible of economically important livestock disease. Several livestock tick-borne diseases (theileriosis, heartwater, babesiosis and anaplasmosis) have been cited among these diseases (Eygelaar et al., 2015). Therefore, contact with domestic animals can severely affect their health and thus their production.

The model used here for risk analysis could be improved later by incorporating additional variables such as tick species interaction and the vaccination parks. These data were not available for all the parts of our study area when this paper was written. Since the presence and abundance of native tick species can increase the presence and the abundance of the invasive tick (Biguezoton et al., 2016), such parameter should be considered too. Regarding parks, they represent as grazing areas and markets, some meeting points for many herds and can favour sharing of pathogens and parasites. Even if animals do not meet on these areas, they can infest the areas during their short stay and other animals could be contaminated later when they visit.

The model should be implemented in larger areas than our study area and be further externally validated by *Rhipicephalus (Boophilus) microplus* presence/absence data of these areas.

The sensitivity analysis of the importance of each predictor in the model highlights the prominent role of 'Cattle density', 'Rainfall mean' and 'Temperature mean'. These three variables generate the ranking changes in at least twelve municipalities when they are removed from the model. This prominence would be attributed to the weight of these predictors in the model, but NDVI, which had the same weight, did not have such impact on the sensitivity. Furthermore, all the predictors used in the model are relevant because their removal induced the ranking change in at least one municipality.

The sensitivity analysis according to the weight of predictors reveals great variation between weighted and unweighted models. The weighting of the criteria has a major effect on the ranking of municipalities. It is very important to make a reasoned case for this weighting.

5 | CONCLUSION

Globally Benin has better vegetation index, temperature and rainfall compared with Burkina Faso even during the dry season. These are certainly the main reasons driving the movement of cattle from Burkina Faso to Benin in the dry season. Burkina Faso transhumant cattle herds use four transhumance corridors during their displacement into Benin. These corridors pass through various areas with different pathogens and vector risks. The eastern region of Burkina Faso is not yet known to be infested by *Rhipicephalus (Boophilus) microplus*. However, the probability of infestation of animals in this part of Burkina Faso by the invasive tick is not null. Considering its progression in the north of Benin, various cattle movements between the two countries and the suitability of some localities in Burkina Faso bordering Benin, such an event will certainly occur.

Besides, the frequent intrusion of domestic cattle in the wildlife reserves also presents a high risk of introduction of the invasive tick species in wildlife, ensuring pathogen sharing. In fact, sharing grazing areas with wild animals means the sharing of pathogens and vectors with these animals. This represents a risky behaviour that will complicate plans to control certain infectious, parasitic and vector-borne diseases. Some of the wild animals that live in this reserve such as African Buffaloes are known to be reservoir hosts to many pathogens. Thus, herdsmen should avoid contact of their cattle or environment sharing with these animals. A screening of the ticks infesting the potential *Rhipicephalus (Boophilus) microplus* host in this reserve is needed.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

ETHICAL APPROVAL

The activities of the research project 'Support to epidemio-surveillance networks for animal diseases and associated sociological aspects in West Africa (Acronym: TransTicks)' have received the favourable opinion of the Ethics Committee of the International Centre for Research and Development on Livestock in Subhumid Zones (CIRDES) (Ref. 001-02/2017/CE-CIRDES) under the strict respect of the protocol submitted to the members of the Committee and their unannounced control.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Study 3: Models for studying the distribution of ticks and tick-borne diseases in animal health: a systematic review with a focus on Africa

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Preamble to Study 3

To understand the process of introduction and spread of ticks and tick-borne diseases in different areas, and to predict their occurrence, scientists have developed different models. One of the first activities of this thesis was to review the state of the art of the different models used to study the dynamics of tick and tick-borne disease dispersal in the world over the last 20 years (2010-2020) with a focus on Africa. This study aimed to identify the different models developed by researchers to understand the dynamics of the spread of ticks and tick-borne diseases. A literature search based on the PRISMA protocol was implemented in two online databases (Scopus and PubMed). The selected articles were classified according to country, type of model and purpose of modelling. The sensitivity, specificity and accuracy of the available data of these models were investigated using meta-analysis approaches.

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Systematic Review

Models for Studying the Distribution of Ticks and Tick-Borne Diseases in Animals: A Systematic Review and a Meta-Analysis with a Focus on Africa

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Abstract: Ticks and tick-borne diseases (TTBD) are constraints to the development of livestock and induce potential human health problems. The worldwide distribution of ticks is not homogenous. Some places are ecologically suitable for ticks but they are not introduced in these areas yet. The absence or low density of hosts is a factor affecting the dissemination of the parasite. To understand the process of introduction and spread of TTBD in different areas, and forecast their presence, scientists developed different models (e.g., predictive models and explicative models). This study aimed to identify models developed by researchers to analyze the TTBD distribution and to assess the performance of these various models with a meta-analysis. A literature search was implemented with PRISMA protocol in two online databases (Scopus and PubMed). The selected articles were classified according to country, type of models and the objective of the modeling. Sensitivity, specificity and accuracy available data of these models were used to evaluate their performance using a meta-analysis. One hundred studies were identified in which seven tick genera were modeled, with *Ixodes* the most frequently modeled. Additionally, 13 genera of tick-borne pathogens were also modeled, with *Borrelia* the most frequently modeled. Twenty-three different models were identified and the most frequently used are the generalized linear model representing 26.67% and the maximum entropy model representing 24.17%. A focus on TTBD modeling in Africa showed that, respectively, genus *Rhipicephalus* and *Theileria parva* were the most modeled. A meta-analysis on the quality of 20 models revealed that maximum entropy, linear discriminant analysis, and the ecological niche factor analysis models had, respectively, the highest sensitivity, specificity, and area under the curve effect size among all the selected models. Modeling TTBD is highly relevant for predicting their distribution and preventing their adverse effect on animal and human health and the economy. Related results of such analyses are useful to build prevention and/or control programs by veterinary and public health authorities.

Keywords: systematic review; meta-analysis; modeling; ticks; tick-borne diseases; Africa

1. Introduction

Ticks are of veterinary, medical and economic importance because of their involvement in the transmission of various pathogens to animals and humans. Ticks carry a wider variety of pathogenic micro-organisms than any other arthropod. They are among the most important vectors of diseases affecting animals and humans [1].

Tick-borne diseases (TBD, e.g., theileriosis, babesiosis, anaplasmosis, cowdriosis, lumping skin disease) and tick-associated diseases (e.g., dermatophilosis) represent the main health and management problems of livestock in many developing countries. For example, in Tanzania, TBD have led to significant economic losses in cattle farming. Kivaria et al. in 2006 estimated the economic losses due to TBD in Tanzania at USD 364 million. This loss included cattle deaths estimated at 1.3 million head of cattle or 7.34% of the herd [2].

The most important Ixodidae tick species hampering livestock improvement in West Africa belong to the genera of *Hyalomma* spp., *Rhipicephalus (Boophilus)* spp., *Rhipicephalus* spp. and *Amblyomma* spp. [3]. Among these species, *Rhipicephalus microplus* was the most studied during the last two decades following its introduction in Côte d'Ivoire [4] and Republic of Benin [5] in 2002–2004. The other tick species most studied in West Africa is *Amblyomma variegatum* with its transmitted pathogens, especially *Ehrlichia ruminantium*.

The challenging epidemiology of TBD is closely linked to and dependent on environmental factors that impact host accessibility, vector richness and pathogen acquisition [6].

The rapid spread of ticks and TBD suggests the necessity of implementing prompt and efficient preventive and/or curative programs. Developing relevant control programs for tick spread and the various TBD requires a deep understanding of the epidemiology of these ticks and TBD through accurate epidemiological models.

A model is always a simplification of a complex system to improve understanding. There are several types of models, ranging from simple deterministic mathematical models to complex, spatially explicit stochastic simulation models. The approach and design used may vary depending on the degree of understanding of the epidemiology of a particular disease, the quantity and quality of the data available and the experience of the modelers [7]. Modeling is a very valuable decision-making tool for the development of animal disease management policies. It is currently a widely used tool to enhance the effectiveness of disease surveillance activities and to facilitate their evaluation [8]. The choice of model type depends on the objectives of the modeler or the study. In the field of animal health, models can be used in a variety of ways. Models can be used for retrospective analysis, contingency planning, resource planning, training, surveillance targeting and real-time decision support [9]. Taylor [9] has described six types of models according to the objectives of animal health: risk, analytical, disease, population, economic and specialized models. Some of these types of models have already been used or not used to study ticks and tick-borne diseases in the veterinary field. As ticks are living organisms with particular environmental requirements depending on their species, understanding their global distribution often requires the use of species distribution models [10,11]. These species distribution models can be used to assess the suitability of different habitats for certain species and to make decisions about the control of these ticks and the pathogens they transmit [12,13].

This review aimed to collect, evaluate and synthesize the existing knowledge on modeling of the distribution or the spread of ticks and TBD in animal health during the last 20 years. The meta-analysis was implemented based on the values of sensitivity, specificity and the accuracy of the models to assess their performance.

In the literature, we did not find works that were interested in a systematic review of models used to study the distribution of ticks and tick pathogens. The studies that have conducted systematic reviews of work on ticks and TBD are recent. Generally, they focus on the distribution of single tick species or pathogens [14], on risk factors for TBD, on the economic impact of ticks and their pathogens on livestock [15]. A synthesis of the modeling of tick and pathogen distribution was necessary to highlight the different tools available in the field with an emphasis on their performance, hence the relevance and originality of our study.

2. Results

The keywords and Boolean operators used in the request in the two online databases selected 3009 articles, 2054 from PubMed and 918 from Scopus. Other sources (i.e., articles found in the references of the other ones) allowed us to collect an additional 37 articles. The Preferred Reporting Items for Reviews and Meta-Analysis (PRISMA) process in our study helped to, finally, select 100 articles. The PRISMA process results are depicted in Figure 1.

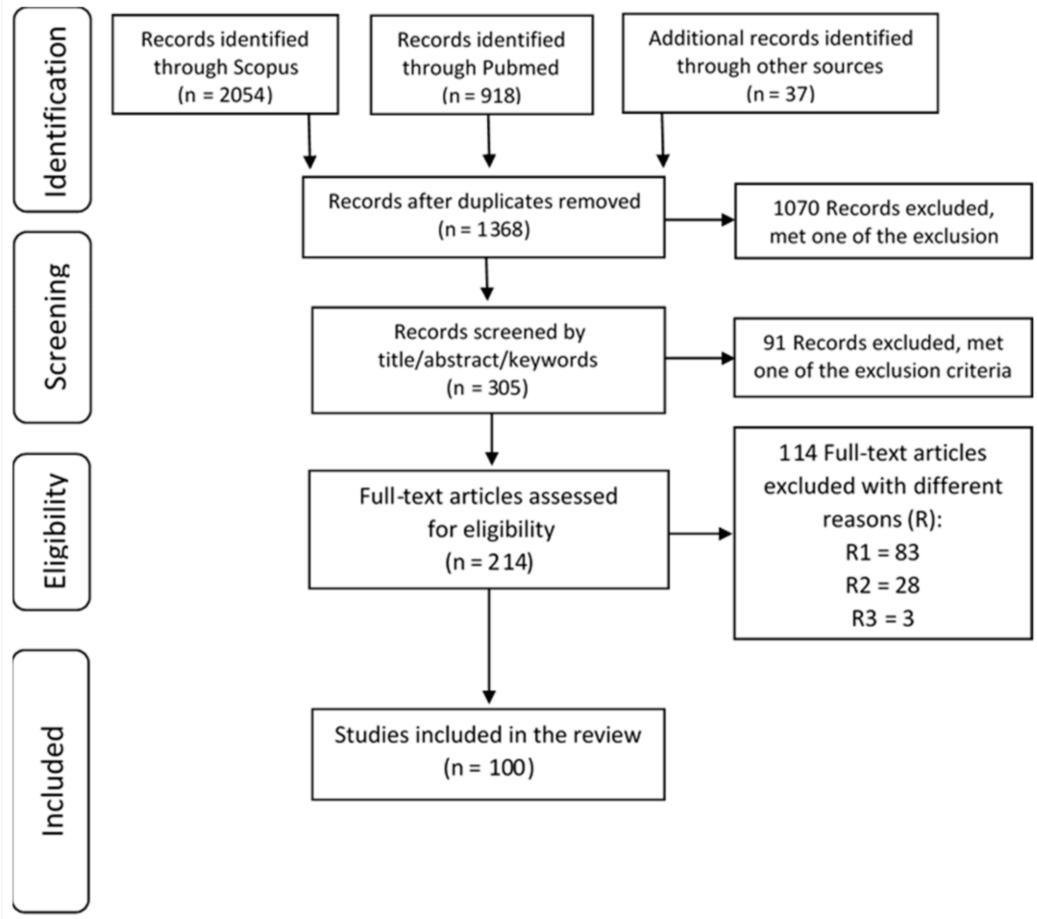


Figure 1. The Preferred Reporting Items for Reviews and Meta-Analysis (PRISMA) Flow Diagram. R1: Records without a clearly stated model; R2: Records with model explanations without field application; R3: Records with a compilation of case studies.

2.1. General Description of the Included Studies

This study selected 100 papers about 23 different models. The most used being the generalized linear model (GLM) with a frequency of 26.67%. The second most frequently used model was the MaxEnt model with a frequency of 24.17% (Table 1 and Figure 2).

Table 1. Categories and objectives of main modeling techniques collected in this review.

Category	Model	Objective
Regression models	Generalized linear models (GLM)	Investigate the levels of tick aggregation at different spatial ranges, determine and disaggregate the drivers of tick density and probability of presence, and provide robust estimates of tick densities between landscape segments. Study the effect of environmental conditions on the prevalence of different stages of ticks and in the epidemiology of the tick-borne disease (TBD).
Species distribution modeling	Maximum entropy (MaxEnt)	Explore the limits of the potential distribution by extrapolating the environmental requirements of ticks. Analyze the possible spatial range of tick species, to explore how climate changes can shape the distribution of these species.
	Classification and regression tree (CART)	Review data on tick distribution and prevalence of TBD for a national TBD management approach using the current ecological and epidemiological information on ticks and the related diseases they transmit.
	Species distribution modeling (SDM)	Discuss and illustrate the precise boundaries of the present range of ticks based on computational map modeling and demonstrate the way in which local populations of these ticks differ in abundance towards the boundaries of the range.
	Ecological niche factor analysis (ENFA)	Measuring the extent to which the requirements of a given species deviate from average conditions and the extent to which the species is selective over the range of environmental conditions available in a country. Develop a rigorous definition of the climatic niche of a set of relevant tick species in a geographical area.

The included papers in the analysis of this systematic review were grouped into four different categories: (1) articles modeling tick distribution or spread, (2) articles modeling TBD distribution or spread, (3) models with a sensitivity/specificity analysis and an accuracy analysis, (4) models without any sensitivity/specificity analysis or accuracy calculation. These categories are not mutually exclusive as some papers may model both the distribution of ticks and the pathogens transmitted by these ticks. These papers may analyze performance for some models and not for others. They will therefore be classified in several categories depending on the models.

The number of publications that focused on modeling ticks and TBD increased over time, which could reflect increased scientific attention or interest (Figure 3). America (43%) and Europe (38%) are areas more concerned by this modeling but Africa (14%) has also an interest in this research subject (Figure 4). Asia and Oceania are the less concerned by TTBD modeling with, respectively, 6% and 2% of the selected publications. Considering our study period (2001–2020), the first modeling of ticks and TBD in Africa took place in the first half of our study period, i.e., in 2003. The most recent tick modeling study over our study period was done in 2019. Oceania appeared as a continent less concerned by TTBD modeling. At the country level, the United State of America (USA) was the area the more concerned with modeling ticks and their transmitted pathogens. Globally, the majority of the studies took place in developed countries.

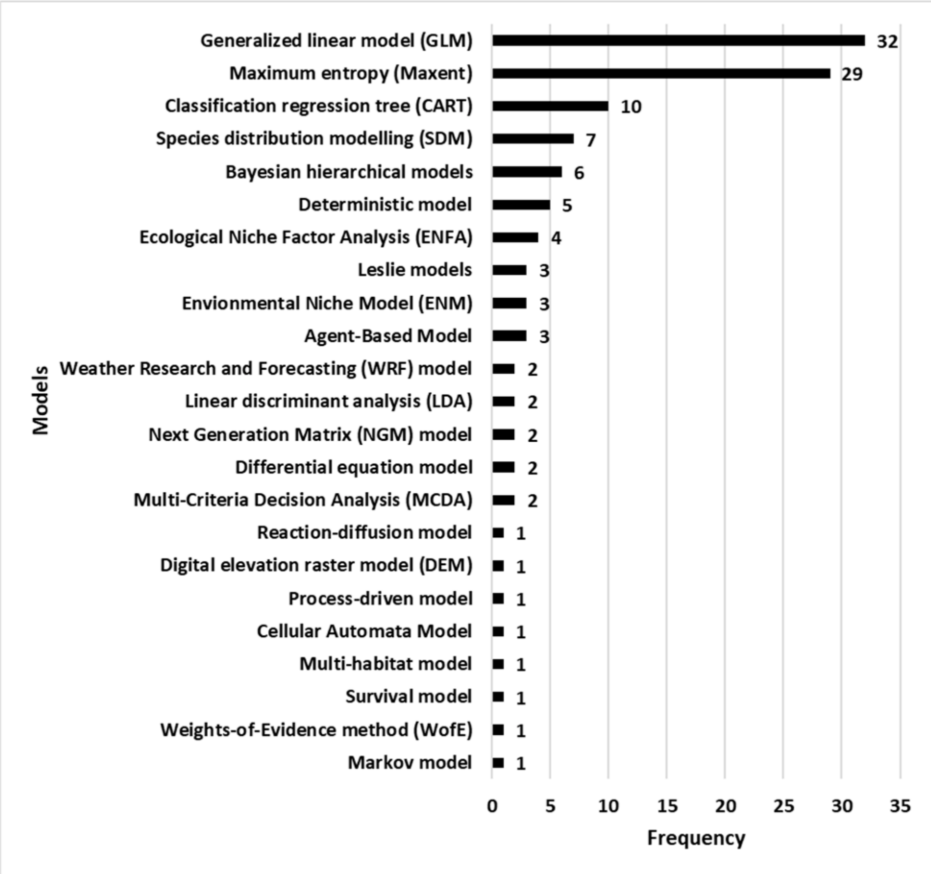


Figure 2. Frequency of models used in the selected publications (decreasing order).

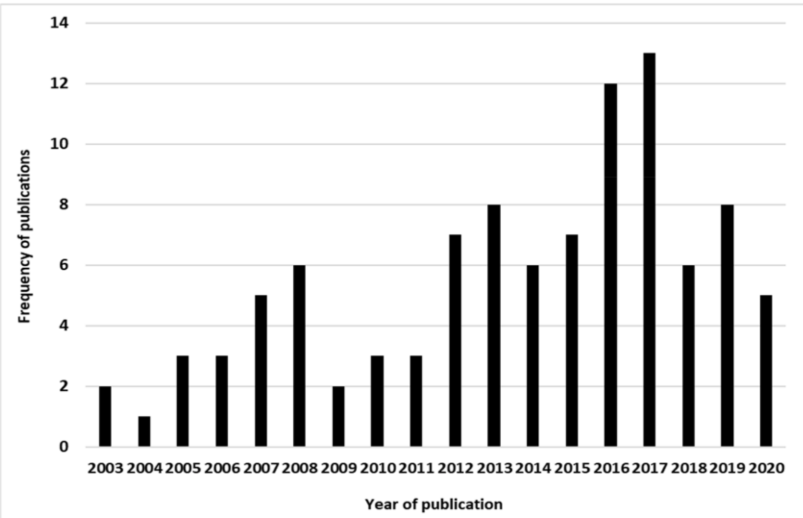


Figure 3. Publication trend on modeling ticks and tick-borne diseases during the last 20 years.

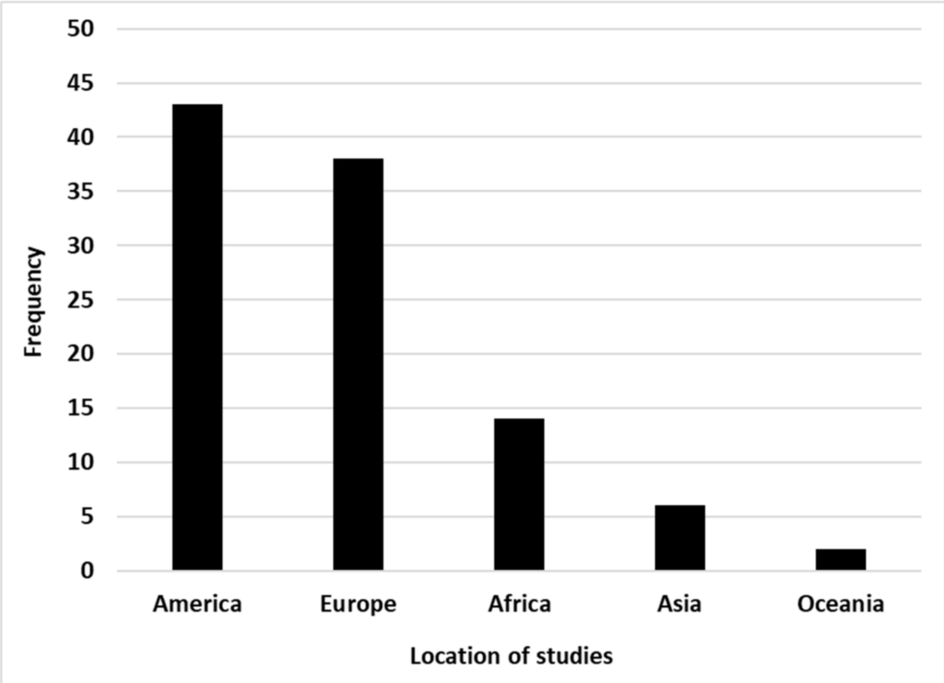


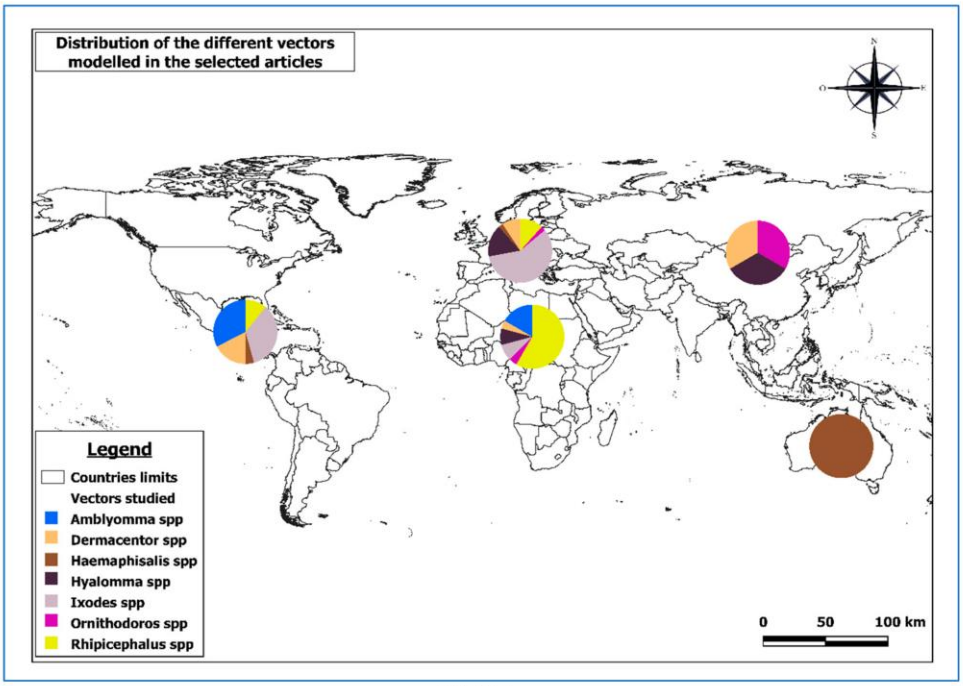
Figure 4. Geographic distribution of the selected publications on ticks and tick-borne diseases modeling.

2.2. Modeling Ticks Distribution or Habitats

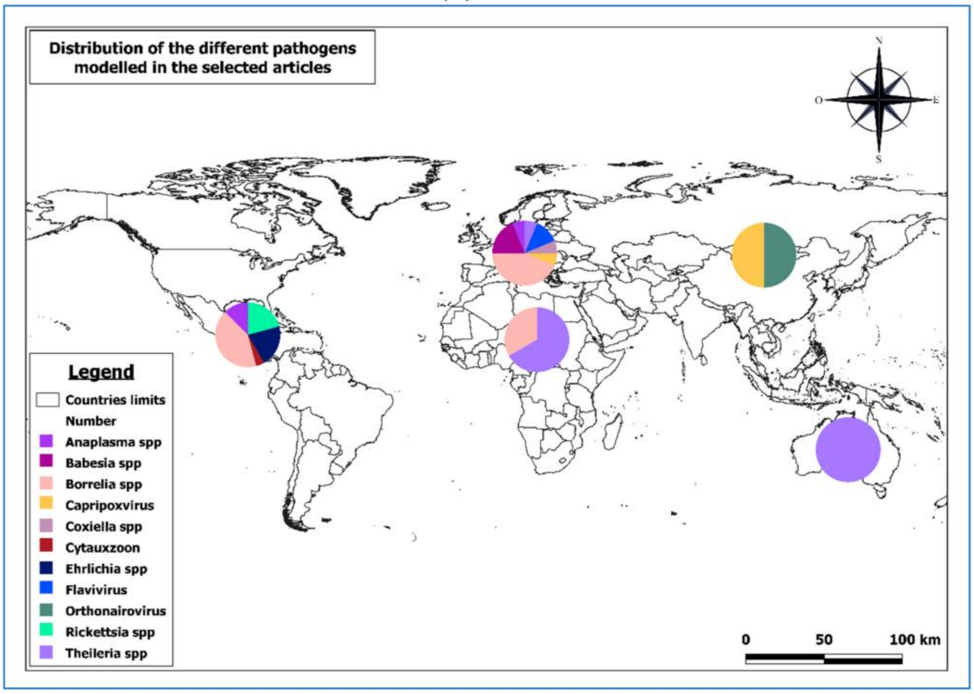
Seven genera of ticks have been modeled in 86 papers (Table 2 and Figure 5A). The most frequently modeled tick genus is *Ixodes* spp. (41 papers) and modeling areas are essentially in Europe (25 papers) and America (16 papers). The least modeled genus is *Ornithodoros* spp. (1 paper).

Table 2. Ticks modeled by the selected publications.

Ticks Studied	Country or Continent of Interest	References
Amblyomma spp.	Africa, Brazil, Central and Southern America and USA.	[16–34]
Dermacentor spp.	Europe, Czech Republic, Mediterranean region, Panama and USA.	[16,17,34–44]
Haemaphysalis spp.	Europe, New Zealand and USA.	[38,44–47]
Hyalomma spp.	Europe, Mediterranean region, Romania, South Africa, Spain and Western Palearctic.	[18,39,44,48–52]
Ixodes spp.	Belgium, Canada, Europe, France, Germany, Iceland, Ireland, Italy, Netherlands, Norway, Panama, Scotland, Slovakia, Spain, UK, USA and Western Palearctic.	[17,22,36,38,44,51,53–88]
Ornithodoros spp.	Africa, Asia and Europe.	[12]
Rhipicephalus spp.	Africa, America, Republic of Benin, Djibouti, Eritrea, Ethiopia, Europe, France, Mediterranean region, Panama, Romania, Somalia, South Africa, Tanzania, USA, Zimbabwe.	[16–18,22,26,27,36,39,44,50,89–100]



(**A**) Ticks



(**B**) Tick-borne pathogens

Figure 5. Geographical distribution of the different studies according to the object ((**A**) ticks and (**B**) tick-borne pathogens) of the models.

The most prevalent tick genus in terms of distribution patterns in Africa was *Rhipicephalus* spp. With 58% followed by *Amblyomma* spp. With 17%. The least prevalent genus in modeling distribution was *Haemaphysalis* spp.

On the American continent, the most prevalent tick genera in modeling were *Ixodes* spp. With 35% followed closely by *Amblyomma* spp. (33%). The least prevalent genera in distribution modeling were *Hyalomma* spp. And *Ornithodoros* spp.

In Asia, only the genera *Dermacentor* spp., *Hyalomma* spp. And *Ornithodoros* spp. Were modeled with a prevalence of 33% each.

In Europe, it was like in America with the genus *Ixodes* spp. (58%) followed by the genus *Hyalomma* spp. With 16%. The least prevalent genus in terms of modeling the distribution in Europe was *Amblyomma* spp.

In Oceania, only the genus *Haemaphysalis* spp. Has been modeled (Figure 5B).

Overall, these results showed that North America and Europe are more adapted to tick species of the genus *Ixodes* spp., notably *I. scapularis* and *I. pacificus* for North America and *I. icinus* for Europe. Africa is much more suitable for tick species of the genus *Rhipicephalus* spp. Ticks of the genus *Amblyomma* spp. do not seem to be widespread in Europe, unlike in America and Africa, where they seemed to be quite present.

2.3. Spatio-Temporal Modeling of Tick-Borne Diseases

Eleven genera of pathogens transmitted by ticks have been modeled, representing 39 papers (Table 3 and Figure 5B). The most modeled pathogen is *Borrelia* spp. (18 papers) and the modeling areas are essentially in America (10 papers) and Europe (7 papers). A similar distribution was observed for the genus *Ixodes* spp. This similarity is mainly due to the fact that *Ixodes* tick (*Ixodes ricinus* and *Ixodes scapularis*) is known to transmit *Borrelia* spp. as well. The most modeled pathogen genus in Africa is *Theileria* spp. transmitted essentially by the ticks of the genus *Rhipicephalus* spp.

Table 3. Pathogens modeled according to this systematic review (alphabetic order).

Pathogen	Country or Continent of Interest	References
Anaplasma spp.	USA	[62,101,102]
Babesia spp.	Europe	[72,84,103]
Borrelia spp.	Canada, Italy, Scotland, Slovakia, Spain, USA and Western Palearctic	[55,56,60,62,65,73,80,81,83,85, 88,104,105]
Capripoxvirus	Asia and Europe	[106]
Coxiella spp.	Spain	[107]
Cytauxzoon spp.	USA	[108]
Ehrlichia spp.	Australia and USA	[24,32,102,105,109]
Flavivirus	Europe, Italy and Scotland	[57,110]
Orthonairovirus	Iran, Turkey	[111]
Rickettsia spp.	Brazil, Panama and USA	[16,22,29,35,43]
Theileria spp.	Africa, Djibouti, Eritrea, Ethiopia, Greece, New Zealand and Somalia	[45,46,95,97,103]

2.4. Models with Estimation of Sensitivity, Specificity or Accuracy Values

Some of the selected publications have evaluated the predictive performance of their models by calculating sensitivity, specificity and/or the accuracy. Models that have a high sensitivity and specificity are supposed to well predict the presence (sensitivity) and the absence (specificity) of either the ticks or the associated pathogens. The study showed 39 papers with the value of the accuracy of the model given by the area under the curve

(AUC) of a receiver operating characteristic (ROC) plot as the measure of prediction success, i.e., accuracy (Figure 6; Appendix C). Only nine papers provided values of sensitivity and/or specificity of the model (Table 4).

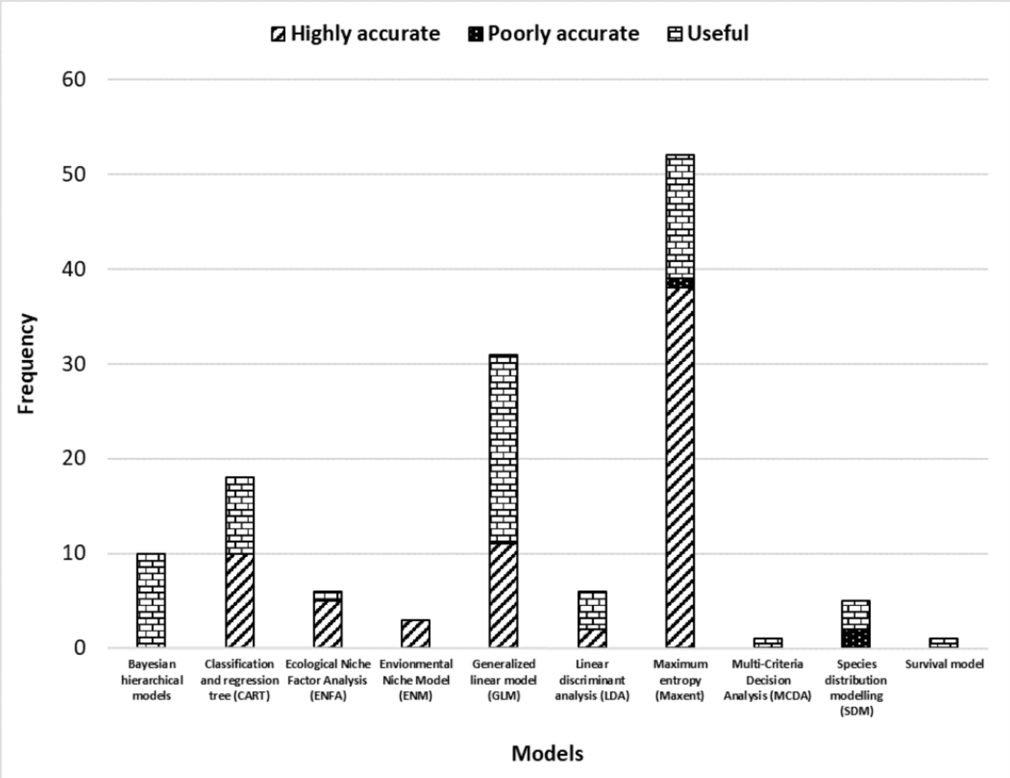


Figure 6. Classification of the models based on the area under the curve (AUC) of a receiver operating characteristic (ROC) plot as the measure of prediction success using the scale established by J.A. Swets in 1988.

Table 4. Models with only sensitivity and/or specificity values.

Type of Model	References	Sensitivity (%)	Specificity (%)	Youden Index
Classification and regression tree (CART)	[71]	75	78	0.53
Classification and regression tree (CART)	[91]	89	96	0.86
Classification and regression tree (CART)	[33]	87	-	ND
Generalized linear model (GLM)	[53]	100	80	0.80
Generalized linear model (GLM)	[59]	91.3	96.4	0.87
Generalized linear model (GLM)	[63]	89	82	0.71
Generalized linear model (GLM)	[91]	90	95	0.85
Generalized linear model (GLM)	[33]	88.5	-	ND
Linear discriminant analysis (LDA)	[91]	85	98	0.84
Maximum entropy (MaxEnt)	[16]	95.76	76	0.72
Maximum entropy (MaxEnt)	[71]	79	78	0.57
Maximum entropy (MaxEnt)	[64]	79.5	-	ND
Maximum entropy (MaxEnt)	[33]	84	-	ND
Bayesian hierarchical models	[102]	>90	<60	ND

The Youden index represents the sum of the sensitivity and the specificity (expressed between 0 and 1) minus 1; ND: not determined.

Most of the models that tested the predictive performance were classified as at least "useful" (AUC $\geq$ 0.7). Indeed, it is supposed that the models that are not useful are not published or the value of sensitivity is not clearly stated. The most commonly used model is the GLM but the best model according to the robustness analysis is the MaxEnt model. The MaxEnt model was classified on its robustness as (in a decreasing order) highly accurate (in 73.08% of cases), useful (in 25% of cases), and poorly accurate (in 1.92% of cases). While the GLM model was classified on its prediction accuracy as (in a decreasing order) useful (in 64.52% of cases) and highly accurate (in 35.48% of cases) (Figure 6). The papers that use the MaxEnt model stated the accuracy at 75.86% while those that use the GLM stated the accuracy at 37.5%.

2.5. Models without Any Estimation of Sensitivity, Specificity and Accuracy Values

The majority of the selected models included in 48 different papers did not mention any sensitivity, specificity or accuracy calculation to show the performance of their models or the authors do not clearly state this analysis (Table 5).

Table 5. Models without any sensitivity, specificity or accuracy analysis and their related papers.

Model	Reference
Agent-based model	[23,73,85]
Bayesian hierarchical models	[32,101,105,106,112]
Cellular automata model	[66]
Classification and regression tree (CART)	[26,87,96]
Deterministic model	[48,54,72,90]
Differential equation model	[24,56]
Digital elevation raster model (DEM)	[78]
Ecological niche factor analysis (ENFA)	[18,26,39,96]
Environmental niche model (ENM)	[93,106]
Epidemiological model	[113]
Generalized linear model (GLM)	[19,22,25,27,31,34,57,61,62,68,69,78–80,100,104,111]
Leslie models	[114–116]
Markov model	[110]
Maximum entropy (MaxEnt)	[20,28,37,44,45,47,50,58,65,92]
Multi-criteria decision analysis (MCDA)	[74]
Multi-habitat model	[67]
Next generation matrix (NGM) model	[55,60]
Process-driven model	[52]
Reaction-diffusion model	[29]
Species distribution modeling (SDM)	[42,51,78,97,98]
Weather research and forecasting (WRF) model	[36,89]
Weights-of-evidence method (WofE)	[26]

2.6. Focus on Modeling Ticks and Tick-Borne Pathogens in Africa

Six genera of ticks (*Amblyomma* spp., *Dermacentor* spp., *Hyalomma* spp., *Ixodes* spp., *Ornithodoros* spp. and *Rhipicephalus* spp.) and two genera of pathogen transmitted by ticks (*Borrelia* spp. and *Theileria* spp.) have been modeled in Africa (Figure 7 and Table 6). The most modeled tick species in selected studies in Africa is *Rhipicephalus appendiculatus* also called "Brown ear tick" or "African tick". The invasive tick *Rhipicephalus (Boophilus) microplus*, has been modeled in Tanzania in Eastern Africa (2008), in Republic of Benin in Western Africa (2013 and 2015), in a more general study in Africa (2009) and recently in Zimbabwe (2018). The models that were used are presented in Table 6.

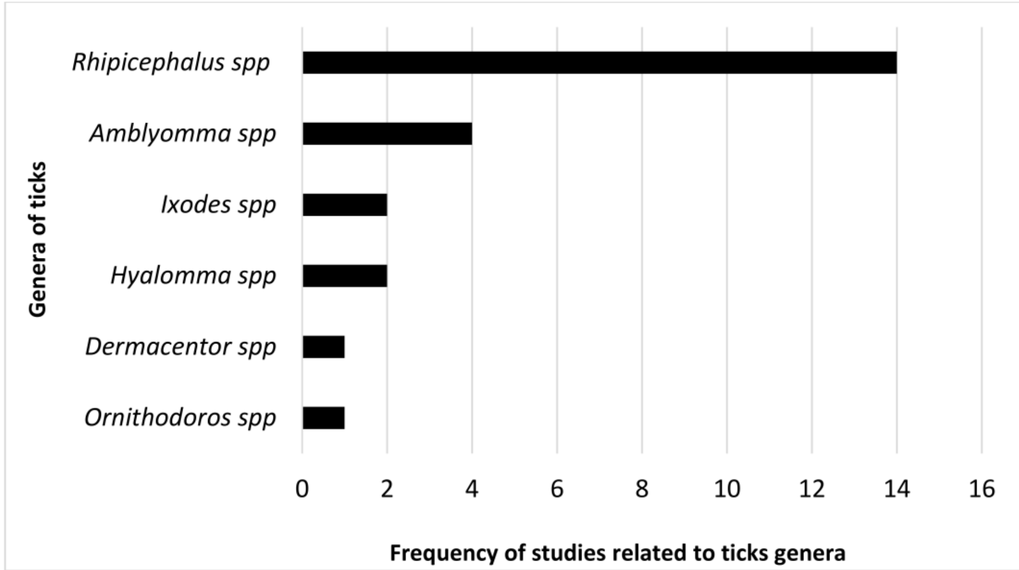


Figure 7. Genera of ticks modeled in Africa based on this systematic review.

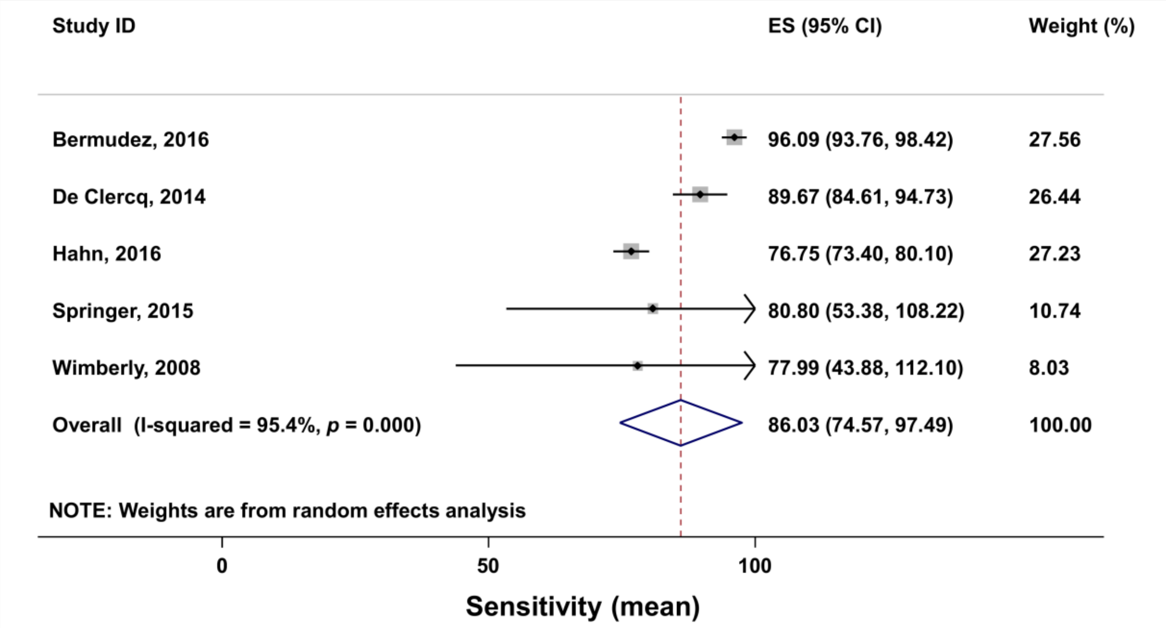
Table 6. Modeling *Rhipicephalus* (*Boophilus*) *microplus* in Africa between 2001 and 2020.

Year	Country	Models	References
2008	Tanzania	Ecological niche factor analysis (ENFA) Classification and regression tree (CART)	[96]
2009	Africa	Logistic regression	[100]
2013	Republic of Benin	Maximum entropy (MaxEnt)	[92]
2015	Republic of Benin	Generalized linear model (GLM) Linear discriminant analysis (LDA) Classification regression tree (CART)	[91]
2018	Zimbabwe	Generalized linear model (GLM)	[99]

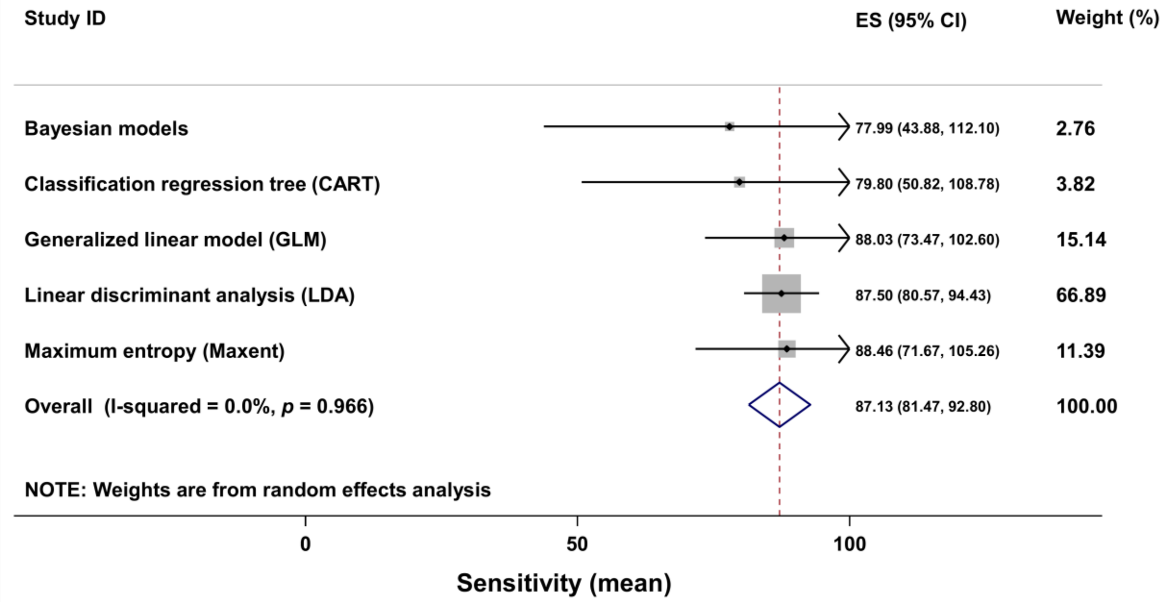
2.7. Meta-Analysis of the Models' Accuracy

This meta-analysis was possible with 20 of the 100 worldwide selected articles. The meta-analysis with sensitivity data was done with five studies. The forest plot shows that the sensitivities have different effect sizes in the various studies (Figure 8a). All effect sizes (ES) were positive and significant because none of their confidence intervals include zero. The study with the highest weight in this meta-analysis is that of Bermudez [16]. The one with the lowest weight is the study of Wimberly [102]. This meta-analysis revealed a very high degree of heterogeneity in the sensitivities ES (heterogeneity chi-squared = 87.20 (d.f. = 4) $p < 0.001$; I-squared (variation in ES attributable to heterogeneity) = 95.4%; test of ES = 0, z = 14.71, $p < 0.001$). This information suggests that there are some subgroups of sensitivities (i.e., type of models) in these studies. A meta-analysis by type of models was needed to check it. The meta-analysis considering the type of models as subpopulations showed a homogeneity (heterogeneity chi-squared = 0.57 (d.f. = 4) $p = 0.966$; I-squared (variation in ES attributable to heterogeneity) = 0.0%; test of ES = 0, z = 30.13, $p < 0.001$) with the sensitivity data (Figure 8b). The funnel plot (Figure 8c) confirmed this homogeneity. This funnel plot showed a symmetrical shape that means an absence of publication bias in the studies. It also showed that among the five models studied in this meta-analysis there was one that was very precise with a small standard deviation and located at the top of the funnel on the graph. Three models are very close to the average, proof of their very good precision

(Figure 8c). There are three models (MaxEnt, GLM and LDA) in which sensitivity effect sizes are greater than the pooled effect size of the meta-analysis (Figure 8b). The MaxEnt model has the highest sensitivity effect size (i.e., 88.46).

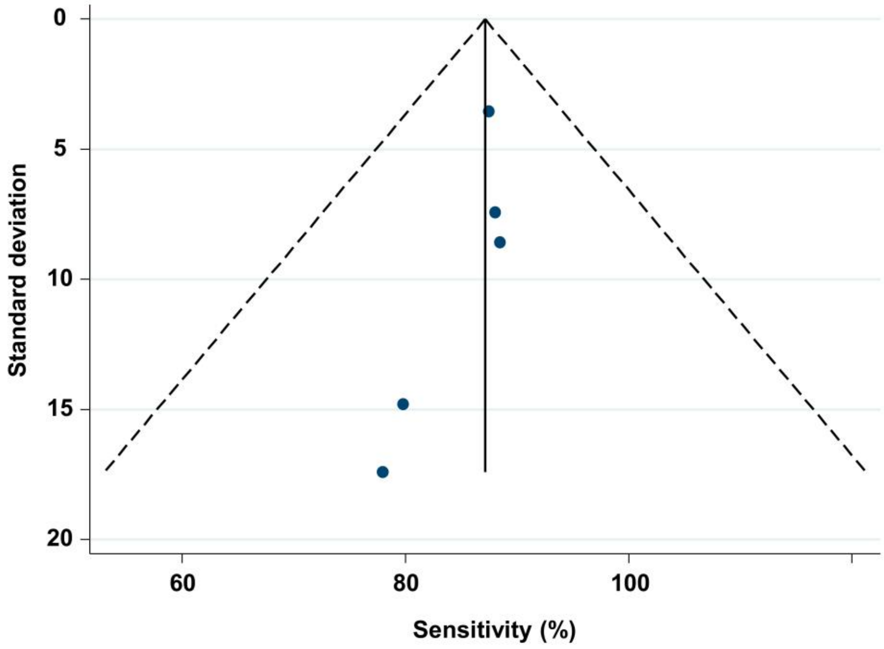


(**A**) Models sensitivity forest plot by study



(**B**) Models sensitivity forest plot by model type

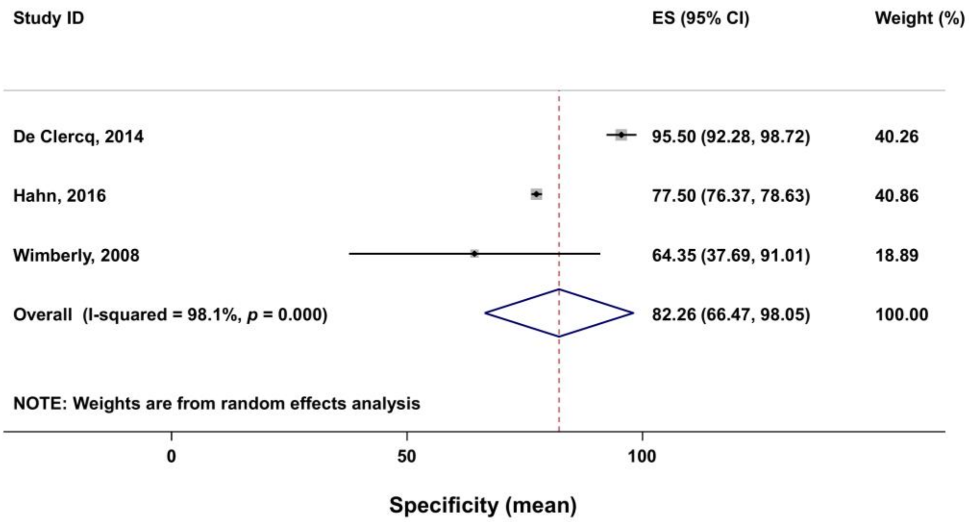
Figure 8. *Cont.*



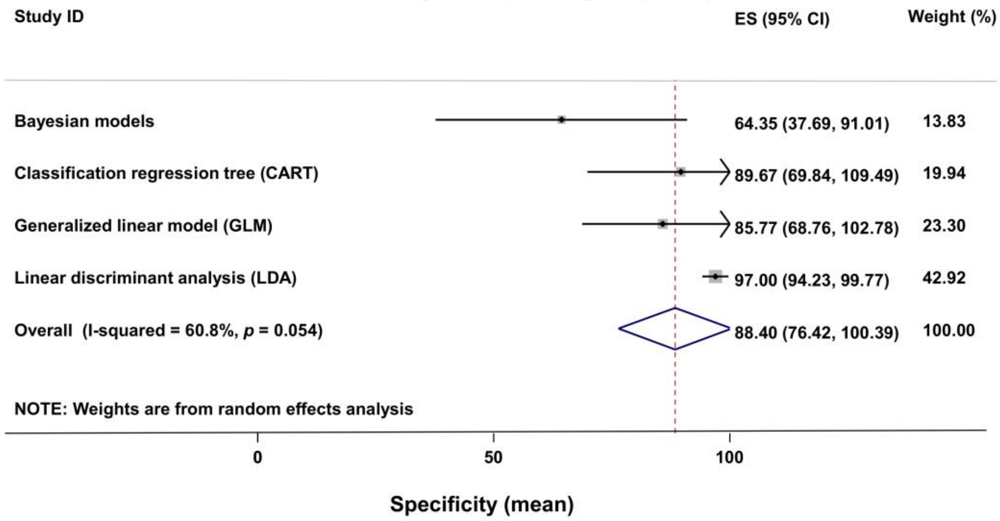
(**C**) Funnel plot with pseudo 95% confidence limits for the sensitivity

Figure 8. Forest plots (**A**,**B**) and funnel plot (**C**) of the sensitivity of models using meta-analysis. Forest plot legend: ES (effect size); CI (confidence interval); names on the left (first author of primary studies); solid line (sensitivity mean); grey square size (weight of each study); horizontal lines (95 confidence intervals); vertical line (line of no effect); diamond (overall sensitivity effect); vertical dash line (combined sensitivity effect); tips of diamond (95% confidence intervals).

The meta-analysis of specificity data was done with three studies. The forest plot of this meta-analysis (Figure 9A) also showed a high heterogeneity (heterogeneity chi-squared = 108.05 (d.f. = 2), $p < 0.001$; I-squared (variation in ES attributable to heterogeneity) = 98.1%; test of ES = 0, z = 10.21, $p < 0.001$). The analysis done considering the type of model as subgroups and plotted on Figure 9B showed a moderate heterogeneity in the specificity effect size (heterogeneity chi-squared = 7.66 (d.f. = 3), $p = 0.054$; I-squared (variation in ES attributable to heterogeneity) = 0.0%, test of ES = 0, z = 14.46, $p < 0.001$). Among the four model groups, the linear discriminant analysis (LDA) and the CART models specificity effect size are greater than the pooled one (Figure 9B). The LDA had the greatest specificity effect size (i.e., 97) and the Bayesian models had the lowest specificity (i.e., 64.35).



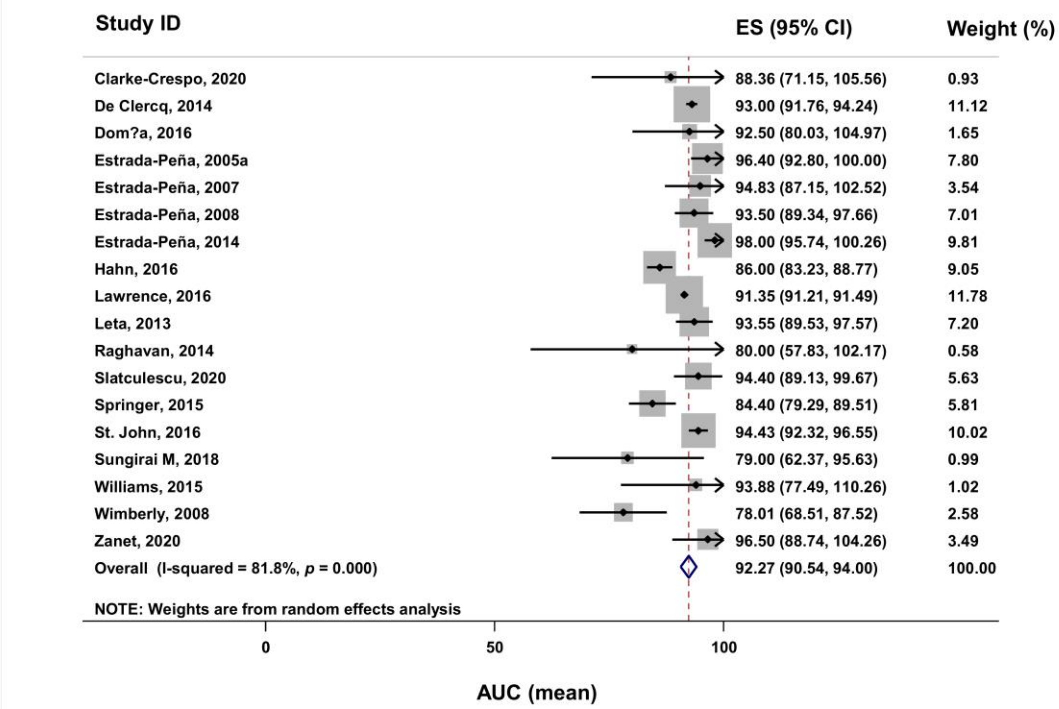
(**A**) Models specificity forest plot by study



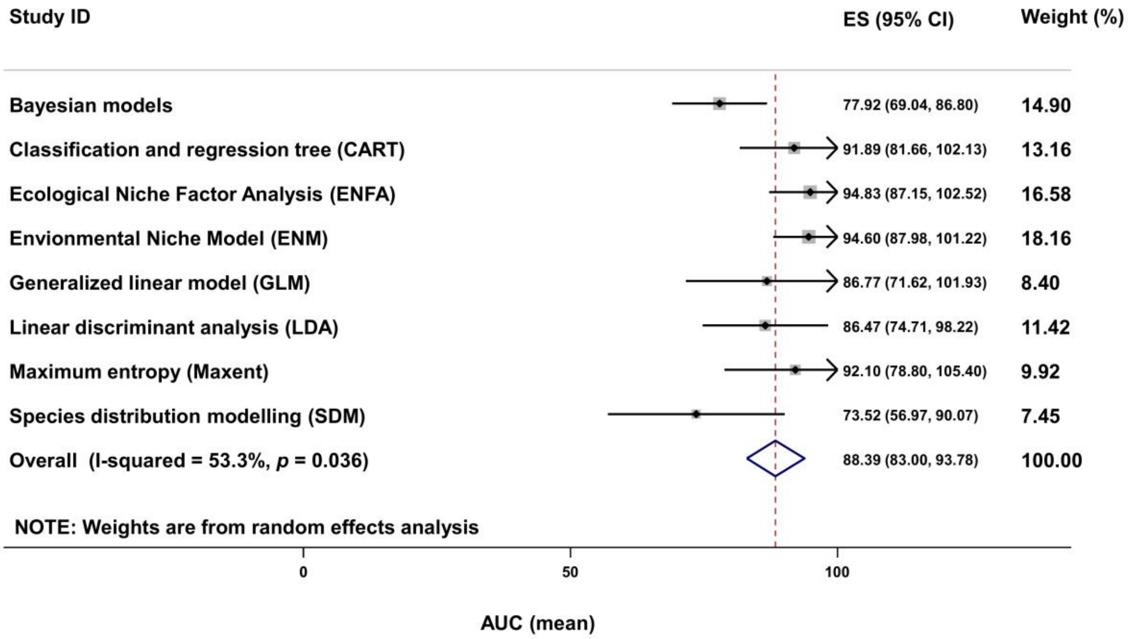
(**B**) Models specificity forest plot by model type

Figure 9. Forest plots (**A**,**B**) of the specificity of models using meta-analysis. Forest plot legend: ES (effect Size); CI (confidence interval); names on the left (first author of primary studies); solid dot (specificity mean); grey square size (weight of each study); horizontal lines (95 confidence intervals); vertical line (line of no effect); diamond (overall specificity effect); vertical dash line (combined specificity effect); tips of diamond (95% confidence intervals).

The AUC data meta-analysis was possible with 18 studies. There is a high heterogeneity (Figure 10A) in the effect size of the AUC data (heterogeneity chi-squared = 93.42 (d.f. = 17), $p < 0.001$; I-squared (variation in ES attributable to heterogeneity) = 81.8%; test of ES = 0, z = 104.62, $p < 0.001$). The analysis with the groups of models revealed a moderate heterogeneity (heterogeneity chi-squared = 14.98 (d.f. = 7), $p = 0.036$; I-squared (variation in ES attributable to heterogeneity) = 53.3%; test of ES = 0, z = 32.13, $p < 0.001$). There are four models (ENFA, ENM, MaxEnt and CART) in which effect sizes are greater than the pooled one (Figure 10B). The model with the highest AUC effect size was the ecological niche factor analysis (ENFA).



(**A**) Models AUC forest plot by study



(**B**) Models AUC forest plot by model type

Figure 10. Forest plot (**A**,**B**) of the AUC of models using meta-analysis. Forest plot legend: ES (effect size); CI (confidence interval); AUC (area under the curve); names on the left (first author of primary studies or model's name); solid dot (AUC mean); grey square size (weight of each study); horizontal lines (95 confidence intervals); vertical line (line of no effect); diamond (overall AUC effect); vertical dash line (combined AUC effect); tips of diamond (95% confidence intervals).

The large heterogeneity shown in the meta-analysis results of the sensitivity, the specificity and the AUC of the models at the study level shows the large uncertainty in the spatial distribution of ticks and TBD. This uncertainty was reduced considerably when the meta-analysis is done according to the types of models. The analysis is, therefore, better when done according to homogeneous groups of models.

3. Discussion

This study is the first systematic review of tick and tick-borne disease distribution models in animals with an assessment of the performance of these models through a meta-analysis. This study is also original in that it has a small focus on Africa following a global review of tick and tick-borne disease distribution modeling worldwide.

3.1. Models Used in the Selected Papers

The three models mostly used are the generalized linear model (GLM) with a frequency of 26.67%, the MaxEnt model with a frequency of 24.17% and the classification and regression tree (CART) with a frequency of 8.33%.

The GLM is a mathematical extension of the linear model that does not force data into unnatural scales and thereby allows for non-linearity and non-constant variance structures in the data. The data can be assumed to come from several groups of probability distributions, such as normal, binomial, Poisson, negative binomial or gamma, many of which better match the non-normal error patterns of many environmental data. This makes the GLM more accommodating and adaptable to the analysis of ecological linkages, that can be misrepresented by conventional Gaussian probability distributions [117]. In many standard statistical techniques, the absence/presence occurrence data are required for predictive modeling of species environmental requirements and geographic distributions. The use of spatial variables such as geographic coordinates is evident in machine learning models such as MaxEnt. However, these spatial data should be given special attention when used in regression models such as GLMs in species distribution modeling. The selection of predictors should also be given special attention to avoid collinearity, which should be seriously investigated. Predictors that show strong collinearities should be removed from the final model. Several processes exist for the analysis of collinearities. One of them is the variance inflation factor (VIF).

The MaxEnt method is a recent species geographic distribution modeling approach, which requires only presence data. High predictive accuracy is achieved with this model in addition to some interesting characteristics. The performance of the MaxEnt model is influenced by a limited set of factors [118]. It is a method of machine learning for general use. MaxEnt uses a straightforward and precise mathematical approach with certain aspects that make it well adapted to the modeling of species distribution [119]. A tick species absence in a geographic area is difficult to assert and needs very long and important investigations. The use of the MaxEnt model does not need great computer skills. That is certainly why many authors prefer to use this model. The MaxEnt model has a native probabilistic meaning, providing a gentle gradient from the most suitable to the least suitable conditions. The model may be conveniently explained by specialists, a characteristic of high functional relevance [120]. Some weaknesses have been identified with this model. These weaknesses concern the model transferability, the model evaluation and its selection. With the MaxEnt model, it is difficult to transfer results from one sampled area to another non-sampled area. This transferability could be a major problem since environmental variables vary by species. It is therefore important to do a good sampling in time and space (i.e., invasive species such as *Boophilus microplus*) to build good predictive models. It is therefore important to be careful about sampling bias [121]. When a model is built, this model is not necessarily informative. One of the biggest challenges MaxEnt faces is related to the evaluation of the model and the subsequent choice of model. Various approaches (i.e., AUC, Kappa, and Jackknife statistics) have been used to assess the importance of the models developed, although it is not clear which one is the most appropriate and whether they can help in the choice of the model [121]. The process of evaluation of models is very useful to know when a model can well predict the distribution of species. On the other hand, the evaluation process is not very useful to select the best model. The selection process is often based on one of these two approaches: the AUC approach and the Jackknife test. The AUC approach used by Hoenes and Baldwin [122,123] is based on the AUC score of listed models built from the most general to the parsimonious one. The best model selected is the one with the least variables with the best AUC score. The other selection approach is the Jackknife test of variable importance. This test is used to appreciate the strengths of each predictor variable of the model [124]. The principle of the Jackknife test is to remove one by one the predictor variable and appreciate the decrease in training gain when omitted. If the omission of a variable did not have a significant decrease on the average training gain it is removed from the model.

The third most frequently used model, the CART (classification and regression tree) model, also has strengths and weaknesses. The CART model is suitable for exploring data sets and can readily recognize linkages between factors. In contrast to logistic regression methods, CART has no requirement to specify the function used to analyze the covariates. These advantages are particularly valuable in dealing with the data non-uniformity (data from different sources) commonly associated with field data sets. The CART model is, however, vulnerable to incomplete data, which can be a problem when dealing with projectively sampled datasets [125]. There are some algorithms (the K-nearest neighbor algorithm, the E.M algorithm, the C4.5 algorithm and the CN2 algorithm) that can deal with the influence of missing data on the accuracy of a machine learning prediction [126].

Two types of models, depending on the variability and the uncertainty of data, are distinguished. Models that assign the mean, or the most probable value to all factors and models, which assign the mean or the most expected outcome of likely events, are called, deterministic models. They generate a unique outcome or response for each group of entry values [9]. Deterministic models are used in the following papers (e.g., [127,128]). Models that include variation and the effect of randomness in the approach are referred to as stochastic. Since the values of the model parameters are subject to variation and the arrival of probable events is random, stochastic models should be executed in a serial manner and generate a set of results from the same input case [9]. Stochastic models are used in the following papers (e.g., [119,129]). In addition, the treatment of time and space in the model can also lead to the definition of its type. The choice of a model depends on many parameters such as the object of modeling, the area where the model is supposed to be implemented, the data available, and the resources dedicated to the collection of data. All these parameters should be taken into account in the choice of the optimal and adapted model.

3.2. Performance of Models

The most accurate model was the MaxEnt model, which can accurately predict species environmental requirements and geographic distribution [119]. The most frequently used model, the generalized linear models (GLM) seems to be less suitable for modeling species distribution compared to the MaxEnt model. Other models such as classification and regression tree (CART), ecological niche factor analysis (ENFA) and environmental niche model (ENM), developed in some publications, also have at least an acceptable level of accuracy. Information on the performance of models is not always available in all studies on modeling the distribution of ticks and TBDs. The readers need to know about the quality of models developed in various studies. The authors should make this information available in their papers. Information on the performance parameters of the models is crucial in choosing the right model and assessing the quality of the message they provide. This information is essential to give relevance to the decisions of authorities in charge of managing ticks and TBD problems.

3.3. Evolution in Time of the Number of the Ticks and Tick-Borne Disease Modeling Studies

This systematic review highlights the increasing interest of scientists in the modeling of species environmental requirements and their geographic distribution (Figures 3 and 4). It has also confirmed the continuous interest of governments, farmers and other stakeholders who provide funding for the development of such models. Ticks and TBD have both medical and economic importance, and this can be noticed through the huge economic losses caused to breeders and the various diseases that can transmit from animals to humans. A better understanding of these environmental requirements and geographic distribution can lead to better management of their control and/or eradication. Climate change as a driver also favors changes in the behavior of these parasites (ectoparasites and hemoparasites). Therefore, the various models help to know the adaptability of ticks to climate changes and forecast their distribution according to this adaptability to further changes.

3.4. Geographical Distribution of the Ticks and Tick-Borne Disease Modeling Studies

The large majority of the studies were conducted in developed countries (America and Europe). These results highlight the fact that ticks and TBD get more attention from scientists and funders in developed countries than developing ones. Currently, international organizations sponsor most research programs in developing countries and many projects are implemented using different north–south partnerships. However, the abundance and burden of ticks and TBD are more important in developing countries and the subsistence of the local population is more dependent on its livestock [130]. Moreover, transhumance is a traditional practice, which has an impact on the spread of ticks and TBD [131,132]. Due to these reasons, the governments of developing countries should pay more attention to the funding of scientific national or regional institutions to conduct more research on ticks and TBD modeling as a decision tool for management purposes. In addition, associated socio-anthropology studies are needed to understand the perception of local populations concerning ticks and TBD.

Most studies do not mention the exact geographical location of the collection points of the analyzed samples on which they have based their models [85,116]. In the majority of cases, the localities (city, country, and region) were mentioned, without specifying the geographical coordinates of the collection points [53,101,105,112]. This situation has made it difficult to map the distribution of the various species studied. The availability of these data would have made it possible to carry out a meta-analysis much more oriented towards the presence and absence of ticks and tick-borne diseases than towards the performance of the models.

3.5. Ticks and Pathogens Modeled

Ixodes spp. (*Ixodes scapularis*, *Ixodes pacificus* and *Ixodes ricinus*) and *Borrelia* spp. (*Borrelia burgdorferi* sensu lato) are, respectively, the ticks and the pathogens most frequently modeled in the selected articles. *Ixodes scapularis* and *Ixodes pacificus* are the primary vectors of *Borrelia burgdorferi* s.l. responsible for Lyme disease, one of the most prevalent TBD in the United States [71]. The tick *Ixodes ricinus* is responsible of the transmission of the pathogens that cause tick-borne encephalitis (TBE) and Lyme disease [133–135] in northern Europe. This review also showed that more than 75% of the models have been developed in this area (America and Europe). This situation is logical because the majority of the studies are located in northern (developed) countries. In these countries, the main species of ticks that has economic and medical importance is the *Ixodes* spp. and their transmitted pathogens.

According to our study, the most modeled tick genus in Africa is *Rhipicephalus* spp. (60%). Overall two genera of pathogens (*Theileria* spp. (75%) and *Borrelia* spp. (25%)) transmitted by the ticks have been modeled by our selected articles. *Rhipicephalus appendiculatus* is known as the African tick and is the vector of *Theileria parva* in eastern, central and southern Africa [136,137]. After the first detection of the invasive tick, *Rhipicephalus* (*Boophilus*) *microplus* in the southern part of Cote d'Ivoire [4] and Benin [5] it has spread into these two countries and to other neighboring West African countries like Burkina Faso, Mali, Niger, Nigeria and Togo [138]. All these facts highlight that this genus of tick (*Rhipicephalus* spp.) has a huge economic and medical importance in Africa and thus deserves serious attention for its control and/or eradication.

The less frequently modeled genus according to this study is the genus *Ornithodoros* spp. This genus hosts the species of soft ticks involved in the transmission of African Swine Fever (ASF). ASF has resurfaced and is spreading nowadays in Asia and Europe and is becoming a major concern for domestic and wild swine in these countries. This disease is still endemic in many West African countries and the role of the *Ornithodoros* spp. tick species in the persistence of ASF is not yet clearly established. More investigations are needed to clarify the role of *Ornithodoros* spp. in the persistence, the resurgence and the spread of ASF.

Lumpy skin disease (LSD) is an emergent and financially damaging viral illness of livestock. The infection is presently endemic in the majority of African countries and has been spreading beyond Africa to the Middle East region lately [139]. The principal means of transmission of the virus responsible for this disease is believed to be by hematophagous arthropod vectors such as ticks. This review did not get find article satisfying our criteria and that models the lumping skin disease. Therefore, these diseases (i.e., AFS and LSD) should be given more attention in the future.

3.6. Focus on Modeling Ticks and Tick-Borne Diseases in Africa

Six genera of ticks have been modeled in Africa among which the genus *Rhipicephalus* spp. is the most frequent. Within this genus, two important species are of special interest: *Rhipicephalus appendiculatus* known as the African tick and *Rhipicephalus* (*Boophilus*) *microplus*, a new invasive species resistant to usual acaricides available to breeders. *Rhipicephalus appendiculatus*, also known as the "brown ear tick" because of its color and strong tendency to feed on the ears of cattle, is the principal vector of *Theileria parva*. *Theileria parva* is the parasite that causes East Coast Fever (ECF) in the eastern, central and southern regions of Africa. It is the focus of several studies because of its involvement in East Coast Fever in cattle [140]. This tick is called the "African tick" because of its distribution located exclusively in the Africa continent. The tick *Rhipicephalus appendiculatus* is often found in savannah and temperate climates, ranging from hot coastal areas to cool highlands with a humid climate. This tick is widespread from southern Sudan to the southeast coast of South Africa [136,137,140]. *Theileria parva* is the only pathogen modeled in Africa in the selected articles. This pathogen is transmitted by the African tick *Rhipicephalus appendiculatus*. This pathogen is the cause of East Coast Fever one of the most important TBD in Africa [141]. Many other TBDs namely anaplasmosis, babesiosis and cowdriosis are also constraining to domestic ruminant production in Africa [2,142] and then need attention to understand the process of their spread.

Rhipicephalus (*Boophilus*) *microplus* is the recently introduced Asian cattle tick in Africa. It is an invasive tick characterized by a high level of resistance to usual acaricides. As this tick is responsible for the transmission of both *B. bovis* and *B. bigemina*, it represents a potentially higher burden on livestock husbandry than *Rhipicephalus (Boophilus) decoloratus*. *Anaplasma marginale* and *Borrelia theileri* are also transmitted by *Rhipicephalus* (*Boophilus*) *microplus*. *Rhipicephalus* (*Boophilus*) *microplus* needs more attention in the modeling of its distribution in Africa to predict. Since its introduction in West Africa through cattle trade in 2000 in Ivory Coast [4] and 2004 in Benin [5], this tick species had spread notably in many other West African countries [138]. Scientists should pay more attention to the mechanism of the spread of this species through models and suggest its control and/or eradication strategies.

3.7. Meta-Analysis of the Models' Accuracy

The meta-analysis of the sensitivity, specificity and AUC of the various studies that provide these data reveal a very high heterogeneity between the sensitivities, specificities and the AUC of the studies. There are different effect sizes in different types of subgroups.

These studies discussed five different types of models concerning the sensitivity data, four types of models concerning the specificity and eight different types of models concerning the AUC data. This variety of model types in the studies leads to the high heterogeneity in the effect size of the sensitivity, specificity and AUC. Therefore, when the meta-analysis was done after grouping the data according to the type of model there was a homogeneity with sensitivity and specificity effect sizes and a moderate heterogeneity with the AUC effect sizes. This means the different categories of models will have similar sensitivity, specificity and AUC effect size in ticks and tick-borne diseases modeling. These results also highlighted the good performance of some models to predict the presence of tick species (MaxEnt, GLM and LDA) according to their sensitivity above the level of the pooled effect size. Results also showed that some models had a better ability to predict the absence of vectors and pathogens species (LDA, CART and GLM) according to their specificity above the pooled effect size. These two models need species presence and absence data to predict their presence in an area. The input of these various models (only presence data for MaxEnt and presence and absence data for CART and GLM) could explain the quality (sensitivity and specificity) of their outputs (prediction).

Overall, the models in the selected publications for meta-analysis had good sensitivity, specificity and accuracy (AUC). Models with poor sensitivity, specificity and accuracy are not published and could lead to an overestimation of the quality of the different types of model. Many studies did not assess the sensitivity, specificity and/or accuracy data. These parameters make it possible to assess the quality of models developed in those studies. Data about the presence or absence of species and details of calculation of sensitivity, specificity and accuracy are often missing in many studies and complicated the meta-analysis of the quality of such models. We recommend that such studies should make available all data related to the building of models to make any meta-analysis of these data feasible.

Models that do not present data to assess their performance are not very useful for tick and TBD control. The performance parameters of the models (sensitivity, specificity and AUC) besides informing about the quality of the models presented also give an idea about the level of risk of the object (tick or TBD) modeled in the area studied. This helps to raise the awareness of the authorities about the need to take urgent action to counter the potential hazard. These parameters can also be used to measure the extent of a TBD or tick species already established in an area. This information is crucial in forecasting the budget and logistics to be mobilized for control or prevention.

4. Materials and Methods

4.1. Search Strategy and Study Selection

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed in this systematic review [118,119]. PRISMA is a minimum set of elements for evidence-based reporting in systematic reviews and meta-analyses. The PRISMA guidelines aim to provide writers with standards for formatting systematic reviews and meta-analyses. The PRISMA guidelines consist of a checklist of 27 items and a four-phase flow chart (Figure 1; Appendices A and B).

Published articles related to the dynamics of ticks and TBD modeling in animals were downloaded via two online databases: Scopus (www.scopus.com, accessed on 15 January 2021) and PubMed (www.ncbi.nlm.nih.gov/pubmed, accessed on 15 January 2021). The keywords and Boolean operators used were the following: ((modelling or modeling or models) and (animals and ticks) and (tick and borne and diseases) and (distribution or spread) and dynamic)). The references of the retrieved articles and journals were also consulted to see if there were any eligible articles for our study. When there were several articles for the same study, we retained the latest version, supplemented if needed, with information from the most complete version.

4.2. Eligibility Criteria

Potentially eligible articles for this systematic review were original articles, written in English or French, published in the period 2001–2020 and that describe models of the distribution of TTBD. Articles that describe biological or economic models instead of spatial and/or temporal distribution models of tick and/or TBD were not included. Details of the inclusion and exclusion criteria are summarized in Table 7.

Table 7. Inclusion and exclusion criteria.

Inclusion Criteria	Exclusion Criteria
• Original articles written in English or French; • Articles should be published in peer-reviewed journals during the last 20 years (from 2001 to 2020); • Articles outlining quantitative and/or qualitative risk modeling of the spread or distribution of ticks and/or TBD; • Studies on spatial and temporal distribution of ticks and TBD.	• Studies focused on vectors and vector-borne diseases different from ticks and associated diseases; • Studies related to ticks and TBD concerning only humans; • Articles that describe biological models instead of statistical or mathematical ones; • Articles focused on efficacy or resistance analysis of acaricides on ticks; • Articles that did not address ticks and/or TBD distribution, and risk factors for their spread; • Review articles on modeling the risk of spread or distribution of ticks and/or TBD; • Studies related only to economic models; • Studies related to vaccine efficacy models; • Studies related to simulation models; • Studies related to TBD transmission modeling.

TBD, tick-borne diseases.

4.3. Meta-Analysis of the Accuracy of Models in the Selected Studies

The selected publications were screened according to an analysis of the performance of their models. This analysis was based on the values of the sensitivity, specificity or accuracy available of some of the models elaborated in these studies. The sensitivity was defined as the proportion of established counties classified as tick-present locations by the model [33]. Sensitivity was also described as the percentage of areas with a known adequate habitat that were ranked as appropriate by the model. Specificity is the percentage of areas where no established tick population was recorded and which were ranked as such in the model [71]. Quantitative measurement was carried out by checking predictions against observations in an unrelated test data set with the area under the curve (AUC) of a receiver operating characteristic (ROC) plot as a gauge of prediction accuracy [143]. According to J.A. Swets [144] cited by Antoine Guisan [145], the accuracy of a model was estimated with the value of AUC. If the AUC value > 0.9, the model is considered as "highly accurate". Models providing values in the range 0.7–0.9 were considered as "useful", and those lower than 0.7 "poorly accurate".

A subsequent meta-analysis was performed with these data (sensitivity, specificity and AUC) to appreciate the quality of the different models developed in the selected articles. A random-effect model was used to see the level of heterogeneity of the means of the sensitivity, specificity and AUC of the selected studies in which these data are available. We used Stata's "metan" meta-analysis command. This command allows the user to enter the frequencies of the 2 × 2 table cells for each study (for binary results), the mean and standard deviation in each group (for numerical results), or the effect estimate and standard error of each study [146]. In our study, we used the mean and standard deviation of the sensitivity, specificity and AUC data of the models developed in the selected papers. We chose the random effect option because of the diversity of the studies in their methodologies. The heterogeneity in the meta-analysis was quantified by the I2 that is the percentage of variation attributable to heterogeneity [147,148]. According to the classification of Higgins [148] adjectives of low, moderate and high are assigned to I2 values of 25%, 50% and 75%. In the case of high heterogeneity, the existence of subgroups was checked [149,150]. When the homogeneity was obtained, a funnel plot assessed the risk of publication bias. This meta-analysis was performed with Stata 14®.

5. Conclusions

Modeling ticks and TBD distribution is important to help all stakeholders in animal health and public health to identify high-risk areas of these parasites for animals and humans. Modeling the distribution of these parasites is very useful for authorities to inform decisions for the prevention and/or control programs. In addition, this review highlighted also the importance of vector surveillance and prevention/control in countries that have not yet detected invasive tick species (e.g., *Rhipicephalus microplus*) but are in the areas predicted to host suitable habitats. Indeed, awareness raising and training of different stakeholders must be reinforced for better prevention and control of this tick in these different countries according to their status.

The GLM models appear to be the most used in modeling the distribution of ticks and TBD. The maximum entropy model (MaxEnt) revealed to have good performance in the prediction of the presence of tick species. The particularity of this modeling system is the use of the tick presence data only without the need for the absence data. This aspect is beneficial in tick distribution modeling in Africa where tick absence data are rarely available. Indeed, this kind of model combined with the GLM will be very powerful in ticks and TBD modeling in Africa. Above all, the choice of a model depends on several parameters and criteria that deserve special attention to achieve objectives set during the modeling process.

Author Contributions: Conceptualization, O.M.Z. and C.S.; methodology, C.S. and E.A.; software, O.M.Z.; validation, O.M.Z., C.S. and M.C.-A.; formal analysis, O.M.Z.; investigation, O.M.Z. and A.S.O.; resources, C.S. and E.A.; data curation, O.M.Z. and C.S.; writing—original draft preparation, O.M.Z.; writing—review and editing, All; visualization, O.M.Z.; supervision, S.F. and C.S.; project administration, C.S. and A.S.B.; funding acquisition, C.S., L.L., K.P.Y. and A.S.B. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: Due to the nature of the survey and the low risk posed to participants, formal approval from an Ethics Committee was not a requirement at the time of the survey.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this survey are available from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

PRISMA checklist.

Section/Topic	#	Checklist Item	Reported on Page #
		Title	
Title	1	Identify the report as a systematic review, meta-analysis, or both.	1
		Abstract	
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number.	1
		Introduction	
Rationale	3	Describe the rationale for the review in the context of what is already known.	2
Objectives	4	Provide an explicit statement of questions being addressed with reference to Participants, Interventions, Comparisons, Outcomes, and Study design (PICOS).	4
		Methods	
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number.	4
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale.	4–5
Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched.	4–5
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	4–5
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	4–5
Data collection process	10	Describe the method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	4–5
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made.	4–5
Risk of bias in individualstudies	12	Describe methods used for assessing the risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	5
Summary measures	13	State the principal summary measures (e.g., risk ratio, the difference in means).	5

Section/Topic	#	Checklist Item	Reported on Page #
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I2) for each meta-analysis.	5
Risk of bias across studies	15	Specify any assessment of the risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	5
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	5
		Results	
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.	5–9
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	5–9
Risk of bias within studies	19	Present data on the risk of bias of each study and, if available, any outcome level assessment (see item 12).	9
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot.	9
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	9
Risk of bias across studies	22	Present results of any assessment of the risk of bias across studies (see Item 15).	9
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression (see Item 16)).	7–9
		Discussion	
Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policymakers).	9–15
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and review-level (e.g., incomplete retrieval of identified research, reporting bias).	9–15
Conclusions	26	Provide a general interpretation of the results in the context of other evidence and implications for future research.	15
		Funding	
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); the role of funders for the systematic review.	16

Appendix B

Search strategies and results for PubMed and Scopus databases

Last Date of Search	Database Consulted	Search Algorithms Applied	Results
28 September 2018	Scopus	((modelling or modeling or models) and (animals and ticks) and (tick and borne and diseases) and (distribution or spread) and dynamic)	901
28 September 2018	Pubmed	((modelling or modeling or models) and (animals and ticks) and (tick and borne and diseases) and (distribution or spread) and dynamic)	445
28 September 2018	Scopus	modelling the distribution dynamic of animals ticks AND tick borne disease	306
28 September 2018	Pubmed	modelling the distribution dynamic of animals ticks AND tick borne disease	128
28 September 2018	Scopus	qualitative modelling of the distribution dynamic of animals ticks AND tick borne disease	57
28 September 2018	Pubmed	qualitative modelling of the distribution dynamic of animals ticks AND tick borne disease	29
28 September 2018	Scopus	quantitative modelling of the distribution dynamic of animals ticks AND tick borne disease	183
28 September 2018	Pubmed	quantitative modelling of the distribution dynamic of animals ticks AND tick borne disease	63
28 September 2018	Scopus	animals ticks and tick-borne disease spread risk modelling	543
28 September 2018	Pubmed	animals ticks and tick-borne disease spread risk modelling	217
15 January 2021	Scopus	((modelling or modeling or models) and (animals and ticks) and (tick and borne and diseases) and (distribution or spread) and dynamic)	64
15 January 2021	Pubmed	((modelling or modeling or models) and (animals and ticks) and (tick and borne and diseases) and (distribution or spread) and dynamic)	36
		All results for Scopus	2054
		All results for Pubmed	918
		Overall results	2972

Appendix C

Classification of the models, which area under the curve (AUC) are available, based on J.A. Swets rules.

Models	References	Accuracy
Bayesian hierarchical model	[102]	Useful
Classification and regression tree (CART)	[17,91]	Highly accurate
	[17,33,71,77]	Useful
Ecological niche factor analysis	[39]	Highly accurate
	[39]	Useful
Environmental niche model (ENM)	[75,93]	Highly accurate
Generalized linear model (GLM)	[17,38,53,91]	Highly accurate
	[17,33,59,63,71,83,99,108,109]	Useful
Linear discriminant analysis (LDA)	[91]	Highly accurate
	[17]	Useful
Maximum entropy (MaxEnt)	[17,20,21,43,44,46,50,84,88,94,95,103,107]	Highly accurate
	[17,30,33,35,40,44,49,50,58,64,70,71]	Useful
	[44]	Poorly accurate
Multi-criteria decision analysis (MCDA)	[12]	Useful
Specie distribution modeling (SDM)	[17,41]	Useful
	[17]	Poorly accurate
Survival model	[76]	Useful

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Study 4: Modelling habitat suitability of the invasive tick *Rhipicephalus microplus* in West Africa

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Preamble of study 4

Tick-borne diseases are among the most important diseases affecting animals and humans. The rapid spread of ticks and tick-borne diseases requires the development and implementation of rapid and effective prevention and/or control programs. To achieve this, tick-borne diseases and their vectors require a thorough understanding of their epidemiology through accurate epidemiological models. The objective of this study is to develop models to predict the distribution of the habitat of *Rhipicephalus microplus*. Data on the presence of the tick were collected from ten different studies conducted in six West African countries over the last decade. Six statistical models (Maximum Entropy in a single model and Generalized linear model, Generalized additive model, Random forest, Boosted regression tree and Support vector machine model in an ensemble model) were applied and compared to predict the habitat suitability distribution of *R. microplus* in West Africa. Each model was evaluated accordingly with the area under the receiver operating characteristic curve (AUC), the true skill statistic (TSS) and the Boyce index (BI).

Modelling habitat suitability of the invasive tick *Rhipicephalus microplus* in West Africa

Short running title: Modelling *R. microplus* suitability in West Africa

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ABSTRACT

Background: Ticks have a medical and economic importance due to their ability to transmit pathogens to humans and animals. In tropical and sub-tropical countries, tick-borne diseases (TBD) are among the most important diseases affecting livestock and humans. The fast spread of ticks and TBD requires a quick development and application of efficient prevention and/or control programs. Therefore, prior investigations on TBD and related vectors epidemiology, for instance through accurate epidemiological models are mandatory. This study aims to develop models to forecast suitable habitat of *Rhipicephalus microplus* distribution in West Africa. **Methods and principal findings:** Tick occurrences were assembled from ten different studies carried out in six West African countries in the past decade. Six statistical models (Maximum Entropy in a single model and Generalized Linear Model, Generalized Additive Model, Random forest, Boosted Regression Tree and Support Vector Machine model in an ensemble model) were applied and compared to predict the habitat suitability of *R. microplus* distribution in West Africa. Each model was evaluated with the area under the receiver operating characteristic curve (AUC), the true skill statistic (TSS) and the Boyce index (BI). The selected models had good performance according to their AUC (above 0.8), TSS (above 0.7) and BI (above 0.8). Temperature played a key role in MaxEnt, while normalized difference vegetation index (NDVI) was the most important variable in the ensemble model. The model predictions showed coastal countries of West Africa as more suitable for *R. microplus*. In addition, some Sahelian areas seems also favourable. **Conclusions and significance:** We stress the importance of vector surveillance and control in countries that have not yet detected *R. microplus* but are in the areas predicted to host suitable habitat. Indeed, awareness raising and training of different stakeholders must be reinforced for better prevention and control of this tick in these different countries according to their status.

Keywords: Tick; Africa; Maximum Entropy; Random forest; Generalized Linear Model; Generalized Additive Model; Boosted Regression Tree; Support Vector Machine; Ensemble modelling.

INTRODUCTION

Livestock plays a key role in the macro economy of West Africa and provides livelihoods for millions of people. The main cattle rearing strategy in West Africa is pastoralism, including transhumance: i.e. a seasonal migration of cattle with their herders. This adaptive strategy aims to optimize livestock access to water and pastures. However, it can favour pathogens and vectors transboundary spread.

Ticks are an important threat to livestock and human health worldwide. These vectors are of medical and economic importance due to their ability to transmit various pathogens to animals and humans (Jongejan and Uilenberg, 2005; Duvallet et al., 2017). Tick-borne diseases (TBD) including protozoan diseases (e.g. theileriosis and babesiosis), rickettsial diseases (e.g. anaplasmosis and heartwater), viral disease (e.g. Tick-Borne Encephalitis, Crimean Congo Haemorrhagic Fever and Lumpy Skin Disease) and bacterial diseases (e.g. dermatophilosis and Q fever) represent major health and management problems of livestock in many developing countries. In Tanzania, Kivaria, (2006) reported economic losses from tick-borne diseases in livestock of US$ 364 million. These losses included the deaths of 1.3 million cattle representing 7.34% of the country's livestock population (Kivaria, 2006).

The most important Ixodidae ticks species hampering livestock improvement in West Africa belong to the genera *Hyalomma*, *Rhipicephalus* and *Amblyomma* (Frans, 2000). Among these species, the invasive tick, *Rhipicephalus microplus* was the most studied during the last two decades since its introduction in West Africa in 2002-2004 (Maxime Madder et al., 2007 and 2012). *Rhipicephalus microplus* the cattle tick originating from Asia is distributed in the tropical and subtropical regions of the world and has a commercial importance (Frisch, 1999; Labruna et al., 2009). Initially in Africa this tick has been established in southern and eastern countries such as South Africa, Mozambique, Zimbabwe, Malawi, Zambia, Tanzania, and Kenya (Walker et al., 2003). Its first occurrence was reported in West Africa in Ivory Coast (Maxime Madder et al., 2007) and Benin (de Clercq et al., 2012; Maxime Madder et al., 2012). After its introduction in this part of Africa it has spread in several other countries such as Burkina Faso, Togo, Mali (Adakal et al., 2013), Nigeria (Opara and Ezeh, 2011; Musa et al., 2014; Adedayo and Olukunle, 2018), and Cameroon (Silatsa et al., 2019).

The complex epidemiology of TBD includes strong ties with environmental factors (e.g. temperature, humidity, and vegetation) that influence vector abundance, host availability, and pathogen transmission (Robinson et al., 2015). The rapid spread of ticks and TBD suggests the need for implementing rapid and efficient prevention and/or control programs. Developing relevant control programs for ticks spread and the various TBD requires deep understanding of the biology of these ticks and TBD and the use of accurate epidemiological models.

Modelling is a powerful tool for informing policies development for the prevention and control of animal diseases. It has become a widely used tool to support the evaluation of various disease management activities (Eisen and Eisen, 2011). In the field of animal health, models may be useful in various ways like (e.g.) retrospective analysis, contingency planning, resource planning, training, surveillance targeting, and real time decision support (Taylor, 2003).

Ticks are not host-permanent parasites. They alternate between non-parasitic and parasitic phases. Therefore, their survival and development are strongly related to the characteristics of the biotic (e.g. host) and abiotic (e.g. host habitat, temperature, and humidity) environment (Duvallet et al., 2017). To study the distribution of ticks it is important to use models that are best suited to their biology, such as species distribution models (SDM). These last also known as climate envelop models, habitat suitability models and ecological niche models, use the environmental records for sites of occurrence (presence) of a species to forecast a response variable, like suitability, for a site where the environmental conditions are appropriate for the survival of that species and therefore where it can be reasonably expected to be found. SDM compare the locations of where a species has been observed to other location where i) it has not been observed (true absence) ii) it is not believed to be observable (pseudo-absences) iii) the background environment (background points) (Guisan et al., 2017).

One of the main applications of this method is to predict the ranges of vector species with climatic data as predictors. Modelling the habitat of a vector species requires prior knowledge of its biology and ecology. In the lifetime of ticks, they alternate between so-called "non-parasitic" life phases, during which metamorphosis, egg laying and incubation take place, and parasitic phases, during which they feed on the blood of their vertebrate host (Duvallet et al., 2017). During their non-parasitic life, they need climatic and environmental conditions (e.g. temperature, humidity, vegetation) adapted to each species in order to fulfil the different off-host phases of their biological cycle. The availability of suitable and specific hosts is also crucial for their survival in a given environment, as these ectoparasites are exclusively haematophagous. These conditions are therefore very important for the installation and expansion of a tick species in an environment (Sonenshine and Roe, 2013). A risk assessment of the introduction and spread of a tick species must address these different biological parameters.
Rhipicephalus microplus is widely distributed in tropical and subtropical areas of the world where it is responsible of a major problem for livestock owners as it causes important economic losses to animal production. It is present in Africa, Southeast Asia, South and Central America, including Argentina, Brazil, Cambodia, Malaysia, Mozambique, Panama, Philippines, Taiwan and Texas, South China, Bangladesh, India, Myanmar, Nepal, and Pakistan (Labruna et al., 2009; Agustín Estrada-Peña et al., 2012; Burger et al., 2014; Low et al., 2015; Roy et al., 2018). Climatic conditions such as temperature, humidity, and rainfall are known to directly influence the annual number of generations of *R. microplus*, notably via the non-parasitic phase. This influence suggests that climatic variables could significantly modify tick epidemiology (A. Estrada-Peña et al., 2005; Pfäffle et al., 2013). *Rhipicephalus microplus* is a species native to South East Asia which spread to America, Australia and Africa through the cattle trade (Walker et al., 2003). To improve the African cattle breed productivity, dairy cattle from Brazil were introduced in West Africa in the 2000s. Unfortunately, the invasive tick species has been also introduced through Côte d'Ivoire (Maxime Madder et al., 2007) and Benin (Maxime Madder et al., 2012). Since its introduction in the West African sub-region in the 2000s, *R. microplus* has not stopped spreading. New locations for its establishment have been reported over the last ten years (Boka et al., 2017; Kamani et al., 2017). Then, thanks to transhumance, *R. microplus* distribution area increased. It is now present in Benin, Burkina Faso, Côte d'Ivoire, Mali, Nigeria and Togo (Adakal et al., 2013; Adedayo and Olukunle, 2018; de Clercq et al., 2012; Madder et al., 2012, 2007; Musa et al., 2014; Opara and Ezeh, 2011).

The objective of this study was to highlight the extent of the spread of *R. microplus* in West Africa today and to show the suitability of the West African environment for the habitat of *R. microplus* using species distribution models. These models were used individually for some and together (ensemble modelling) for others.

MATERIALS AND METHODS

Study area

The study area included the West African countries located between 18°E - 15°W and 4°N - 16°N (**Fig. 1**). West Africa has three major climatic zones: the Guinean zone which extends approximately between 6°- 8°N, the Sudanian zone approximately between 8°- 12°N and the Sahelian zone between 12°- 16°N (Kouassi et al., 2010).

One of the main assumption of correlative species distribution modelling applied to alien species is the niche conservatism of the native environmental niche into the invaded area (Pearman et al., 2008). While usually tested using ordination techniques, here, due to lack of a sufficient number of occurrences in the native area with temporal consistency with the occurrences in West Africa, we proposed a qualitative analysis based on the similarity of the Koppen-Geiger climatic classification for the native (South East Asia, **Appendix S1)** and the invaded areas (South America and sub-Saharan Africa) to test this assumption (Romero et al., 2021).

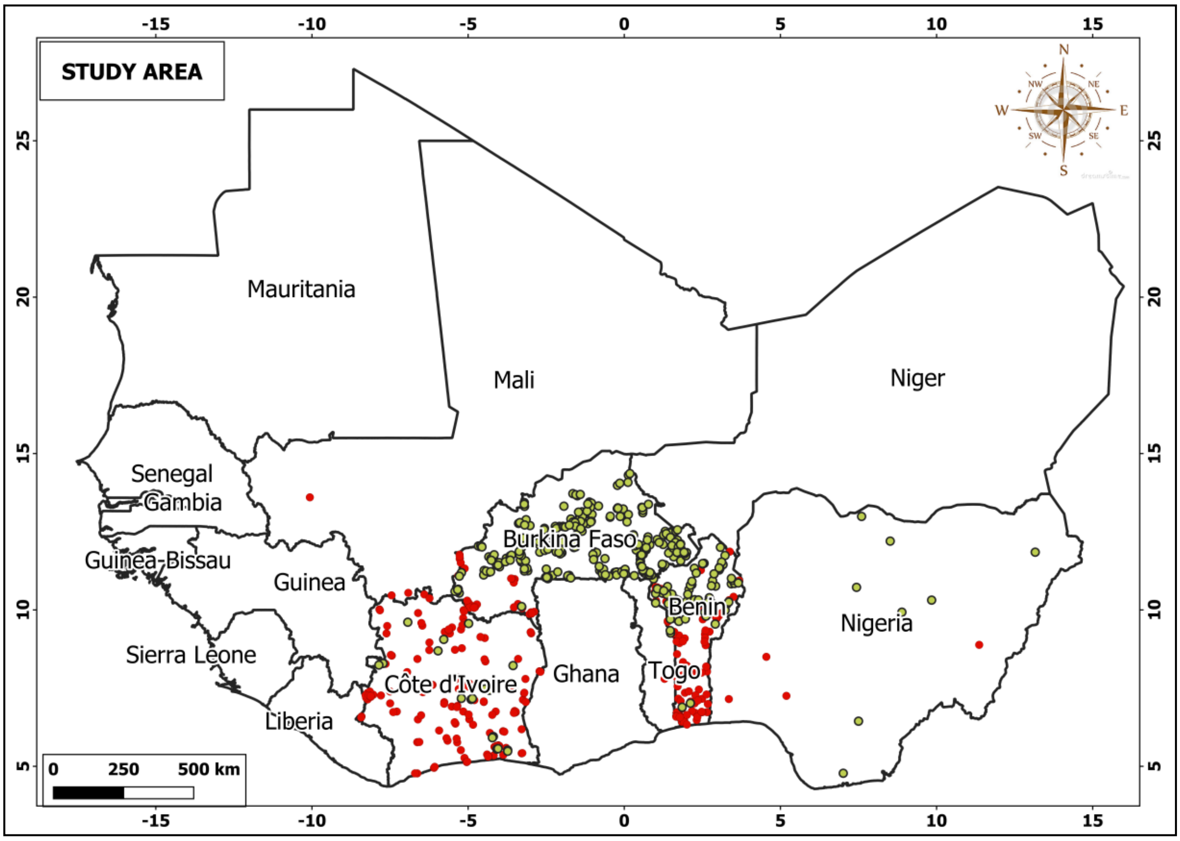


Fig.1: Study area with different occurrences of *R. microplus*

Legend: Red dot, presence of *R. microplus*; Green dot, absence of *R. microplus*.

Data

Tick occurrence data

A collection of the sampling locations was built and used here as occurrence (i.e. presence) and non-occurrence (i.e. absence) data (**Fig 1**). These different surveys, conducted between 2008 and 2017, revealed the presence of *R. microplus* in 316 locations (**Table 1**).

Table 1. *R. microplus* distribution studies in West Africa since its introduction

Place of ticks collection	Period of ticks collection	Number of occurrences	References
Côte d'Ivoire	2008	21	Madder et al., 2011
Benin	2008	33	Madder et al., 2012
Benin	2011	52	de Clercq et al., 2012
Burkina Faso; Mali and Togo	2011	12	Adakal et al., 2013
Ivory Coast	2011 to 2012	25	Toure et al., 2014
Burkina Faso	2013	23	Unpublished
Benin and Burkina Faso	2012 to 2013	8	Biguezoton et al., 2016
Ivory Coast	2015	99	O. Boka et al., 2017
Nigeria	2014 to 2015	4	Kamani et al., 2017
Benin and Burkina Faso	2017	39	Ouedraogo et al., 2021

Predictors

A set of 13 relevant variables (**Table 2**) related to the environment of the tick and its host were selected. The biotic predictor selected was cattle density, as *R. microplus* was described as a specific and the most significant parasite for cattle (Bellgard et al., 2012). The abiotic predictors selected were temperature, rainfall, vegetation index and land cover. Vegetation (pasture for herds) were considered as dependent on climatic factors (rainfall and temperature). It plays a key role in the life of the tick host (cattle). The availability of pasture and water are determinants for the presence of the cattle in an area.

Abiotic factors (temperature, humidity, vegetation index and land cover) are crucial for the survival of the tick during its off-host stages (Apanaskevich and Oliver, 2014).

The rainfall and the temperature data used in this study were climate data set for the earth land surface areas at a spatial resolution of 1 km. The rainfall data and the temperature data were annual mean patterns for the time period of 1979-2013; http://chelsa-climate.org/bioclim/ (**Table 2**).

The cattle density dataset contains the global distribution of cattle in 2010 expressed in total number of cattle per pixel (5 min of arc) according to the Gridded Livestock of the World database (GLW 3) (**Table 2**).

The Normalized difference vegetation index (NDVI) data used here is the calculation of the mean of the NDVI raster of the twelve months of 2015 downloaded from the MODIS NDVI; https://lpdaac.usgs.gov/products/mod13a3v006/ with a resolution of 1 km (**Table 2**).

The annual (2015) land cover variables (Cropland, Mosaic tree and shrub, Mosaic herbaceous cover, Shrub land, Grassland, Sparse vegetation, Urban areas, Bares areas and Water bodies) were downloaded from https://www.esa-landcover-cci.org, with a resolution of 1 km (**Table 2**).

Variable pre-processing

A collinearity test on the predictors was used to check for linear associations between two or more explanatory (predictors) variables. Two variables are perfectly collinear if there is an exact linear relationship between them. For the diagnosis of collinearity we used the Variance Inflation Factor (VIF) method to see which variables are really necessary for the computation of the different models (Akinwande et al., 2015). A VIF in the range of 5 to 10 shows a high correlation which can be problematic. If the VIF rises above 10, it can be argued that the regression coefficients are misestimate because of multi-collinearity, which must be treated appropriately (Akinwande et al., 2015). Variables with VIF greater than five will not be used further. The correlation of the predictors with the presence of the tick was highlighted by the multivariate regression preceding the VIF analysis and included in the collinearity analysis. This helped in the selection of relevant predictors for the modelling (**Table 2**). Variables with many missing values were removed from the list of predictors. The number of presence and absence data was balanced accordingly. In our data, the number of absence points was higher than the number of presence points, so we randomly sampled 316 points (total number of presence points) from all absence points. In addition, all predictors' rasters resolutions were harmonized at the spatial resolution of 10 km.

Table 2. *R. microplus* potential predictors and associated variables, sources, and their variance inflation factors

Predictors	Description	VIF	Type	Period	Sources
Rainfall	Annual rainfall [mm/year]	2.17	Climatic	1979-2013	http://chelsa-climate.org/bioclim/
Temperature	Annual Mean Temperature [°C*10]	2.15	Climatic	1979-2013	http://chelsa-climate.org/bioclim/
Cattle	Cattle density (Head/Km^2)	1.32	Host	2010	https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/GIVQ75; (Nicolas et al., 2016; Gilbert et al., 2018)

NDVI	Normalized difference vegetation index	2.23	Environmental	2015	https://lpdaac.usgs.gov /products/mod13a3 v006/
Crop (code: 10)	Cropland	2.29	Environmental (Land cover)	2015	https://www.esa-landcover-cci.org
Mosaic TSHC (code: 100)	Mosaic tree and shrub (>50%) / herbaceous cover (<50%)	1.03	Environmental (Land cover)	2015	https://www.esa-landcover-cci.org
Mosaic HCTS (code: 101)	Mosaic herbaceous cover (>50%) / tree and shrub (<50%)	1.01	Environmental (Land cover)	2015	https://www.esa-landcover-cci.org
Shrub (code: 120)	Shrubland	1.47	Environmental (Land cover)	2015	https://www.esa-landcover-cci.org
Grass (code: 130)	Grassland	1.31	Environmental (Land cover)	2015	https://www.esa-landcover-cci.org
Vegetation (code: 150)	Sparse vegetation (tree, shrub, herbaceous cover) (<15%)	0.00	Environmental (Land cover)	2015	https://www.esa-landcover-cci.org
Urban (code: 190)	Urban areas	56.54	Environmental (Land cover)	2015	https://www.esa-landcover-cci.org
Bare (code: 200)	Bare areas	0.00	Environmental (Land cover)	2015	https://www.esa-landcover-cci.org
Water (code: 210)	Water bodies	0.00	Environmental (Land cover)	2015	https://www.esa-landcover-cci.org

Legend: VIF, Variance inflation factors; NDVI, Normalized difference vegetation index; HCTS, Mosaic herbaceous Cover Tree and Shrub.

Modelling

Six models were used in this study. The Maximum Entropy Model (MaxEnt) used alone with only *R. microplus* presence data, while five other models, i.e. Generalized Linear Model (GLM), Generalized additive model (GAM), Random Forest (RF) model, Boosted regression tree (BRT) and Support vector machine model (SVM), were used to produce an ensemble model using *R. microplus* presence and absence data via the R package "sdm" (Naimi and Araújo, 2016).

In addition, a sensitivity analysis was carried out to assess the contribution of each predictor used in models through the variables importance analysis in each modelling technique. The variable importance was addressed in MaxEnt model by the permutation importance values.

Maximum Entropy (MaxEnt)

MaxEnt is a machine learning technique using a set of environmental grids and georeferenced locations of occurrence to model niches and species distributions (Phillips et al., 2006; Jane Elith et al., 2011; Zeng et al., 2016; Phillips et al., 2017). Our MaxEnt model was trained and tuned using the ENMeval package (Muscarella et al., 2014). We used the function ENMevaluate with nine arguments: “occ”, env, “bg.coords”, “method”, “algorithm”, “kfold”, “RMvalues”, “fc” and “parallel”. The “occ” argument here was *B. microplus* occurrences data. The predictor layers were stacked in the argument “env” and we sampled 10000 background coordinates for the argument “bg.coords”. We chose the “block” method for data partitioning, the algorithm of “maxent.jar” and the number of bins used in the k-fold cross-validation was k=10. The features combination used in the argument “fc” were: L, LQ, LQP and LQPH (L=linear, Q=quadratic, P=product and H=hinge). The selected model was the one with the lowest Akaike information criterion (AIC) (Warren et al., 2010). The MaxEnt model’s running and prediction were made with the following arguments: "replicates=10", "replicatetype=crossvalidate", "doclamp=FALSE", "extrapolate=TRUE", "maximumiterations=5000", "betamultiplier=1.5", "randomseed", "removeduplicates", "writeplotdata", and "pictures".

Ensemble modelling

Various methods exist for ensemble modelling and can be defined in the method specification. In this study, the R package “sdm” was used for the ensemble modelling (Naimi and Araújo, 2016). First we created a data object “d” with the function “sdmData” including argument “species” and “predictors”. The arguments of “species” summarize the presence and absence points of *R. microplus* and “predictors” the seven selected explanatory variables. We used the "weighted average" method and the evaluation statistic was the TSS. The selected models are GLM, GAM, RF, BRT and SVM. The validation methods used were cross-validation with (cv.folds=5) and bootstrapping (n=10).

Generalized linear model (GLM)

Generalised Linear Models (GLM) highlight the relationship between the response variable and a set of predictor variables by searching for the most suitable and parsimonious model (Thuiller et al., 2003).

Generalized additive model (GAM)

GAMs are useful when the relationship between variables is expected to be of a more complex form, not easily fitted with standard parametric functions of the predictors (e.g. GLM with a linear or quadratic response), or where there is no priori reason for using a particular shape (Hastie and Tibshirani, 1990; Guisan et al., 2017). A GAM can be used in addition to a GLM, to explore the general shape of the response function and to implement it in the best possible way in a GLM (Guisan et al., 2002).

Random Forest

Random forest (RF) is a supervised learning algorithm. The "forest" that it builds is a set of decision trees, usually trained by the "bagging" method (Peters et al., 2011).

Boosted regression tree (BRT)

The BRT is a technique that aim to improve the performance of a single model by fitting many models and combining them for prediction. This technique uses two algorithms: the classification and regression tree (decision tree) group of models, and boosting builds and combines a collection of models (Elith et al., 2008).

Support vector machine model (SVM)

The SVM model is able to strike the most rational balance between species adaptability and complexity in order to achieve the most likely distribution given the constrained information in the data sample (Drake et al., 2006).

Model validation and evaluation

The validation methods used were cross-validation and bootstrapping (n=10).

Cross-validation is a resampling procedure used to evaluate machine learning models on a limited data sample. The procedure has a single parameter called k that refers to the number of groups that a given data sample is to be split into. The model will train k models, each with k-1 folds, and the k^{th} (last fold) will be used to test it (Hijmans, 2012). Overall accuracy is calculated by the average of the accuracy from all k models.

Bootstrapping replicates a sampling method with replacement, each time a sample of equal size to the original data is drawn and used as training data. Observations that are not selected are used for evaluation in each round (Naimi and Araújo, 2016).

To evaluate the performance of the models three parameters were considered: the Area under the receiver operating curve (AUC), the True Skill Statistics (TSS) and the Boyce Index. We use AUC, TSS and Boyce index for the MaxEnt model and AUC and TSS for the ensemble modelling.

A model with no predictive power would have an AUC of 0.5 (e.g. a diagonal line), while a perfect model would correspond to an AUC of 1 (Boyce et al., 2002; Allouche et al., 2006).

A TSS value of +1 indicates perfect agreement and values of zero or less indicate performance no better than random (Allouche et al., 2006).

Boyce's index is an evaluation tool adapted for models predicting species distribution based on presence-only data (Di Cola et al., 2017). The Boyce index is ranged from -1 to +1 and positive values indicate consistent predictions of species presences. Values close to zero mean that the pattern is no different from a random pattern and negative values indicate counter-predictions, i.e. prediction of areas of presence more frequent as it is highly relevant to the species (Boyce et al., 2002; Hirzel et al., 2006).

Softwares

Analyses were carried out with R software version 4.0.5 R Core Team (2021). The following R packa ges were used: dismo, ENMeval, and sdm (Hijmans and Elith, 2013). The MaxEnt model was impleme nted using R packages rJava and dismo. The ensemble modelling with the five models (GLM, GAM, R F, BRT and SVM) was implemented using the R package "sdm" (Naimi and Araújo, 2016).

The cartographic outputs were computed using the software QGIS version 3.18.1 (Quantum GIS Development Team, 2021).

RESULTS

Variables and models selected

The collinearity analysis revealed that only one variable (urban area) had a variance inflation factor above 10 (i.e. 56.54). This variable that was showing a high multi-collinearity furthermore did not significantly correlate with the presence of *R. microplus*.

Seven out of the 13 predictors were significantly (p-value < 0.05) correlated with the presence of *R. microplus* through multivariate analysis preceding the VIF. These predictors are Rainfall, Temperature, NDVI, Cattle density, Cropland, Grassland and Shrubland.

Characteristics of the predictors according to presence or absence of *R. microplus* in the study area

The investigation to check if there was difference between the various predictors according to areas where the tick was found or not revealed that the rainfall was significantly ($p<0.001$) higher in areas where *R. microplus* was present (annual rainfall average: 1202.23 +/-252.24 mm) than areas where it was absent (annual rainfall average: 881.62+/- 231.71 mm). The tick was found in areas with higher rainfall than where it was absent (**Fig. 2**). Temperature was significantly ($p<0.001$) higher in areas where *R. microplus* was absent (annual temperature average: 27.99+/-0.99°C) than areas where it was present (annual temperature average: 26.44+-/0.77°C). Areas where the tick was found are cooler than places where it was absent (**Fig. 2**). On the other hand cattle density was significantly ($p<0.001$) higher in areas where *R. microplus* was absent (average head/Km^2: 229.32+/-196.48) than area where it was present (average head/Km^2: 99.76 +/-118.02). The hosts were more concentrated in areas where the tick was absent (**Fig. 2**). The NDVI was significantly (p<0.001) higher in areas where *R. microplus* is present (monthly NDVI average: 5681.17*10^{-4}+/-1024.29*10^{-4}) than area where it is absent (monthly NDVI average: 3837.59*10^{-4}). The NDVI was better in places the tick was found than where it was absent (**Fig. 2**). The cropland was significantly (p<0.001) more important in areas where *R. microplus* was absent (annual cropland classes unit average: 0.73 +/- 0.35) than area where it was present (annual cropland classes unit average: 0.52 +/- 0.41). The tick was found more frequently on cattle living in uncropped areas than cropped ones. Proportion of grassland was significantly higher (p<0.001) in areas where *R. microplus* was absent (annual grassland classes unit average: 0.05 +/- 0.18) than area where it was present (annual grassland classes unit average: 0.00 +/-0.01). The tick was found more frequently on cattle living in environment where there was less grassland (**Fig. 2**).

And lastly shrublands were found more (p<0.001) in areas where *R. microplus* is present (annual shrubland classes unit average: 0.09 +/- 0.18) than areas where it was absent (annual shrubland classes unit average: 0.06 +/-0.01). The tick was found more frequently on cattle living in environment where there is shrubland (**Fig. 2**).

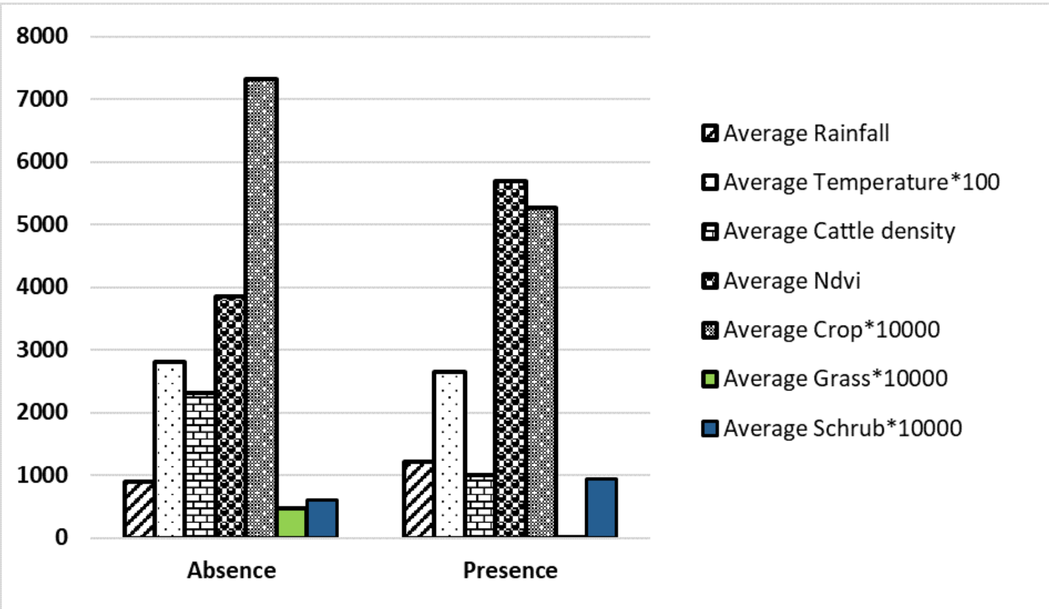
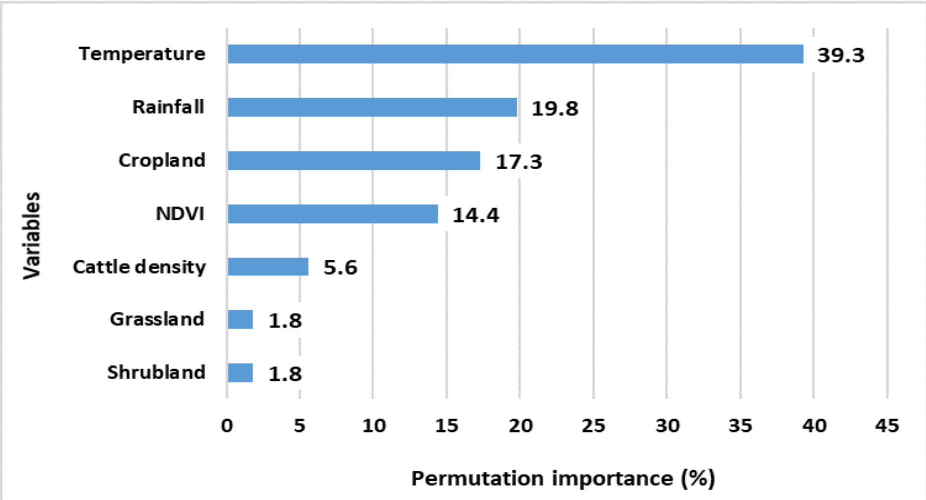


Fig. 2. Predictor values dispersion according to the presence or absence of *R. microplus* in West Africa.

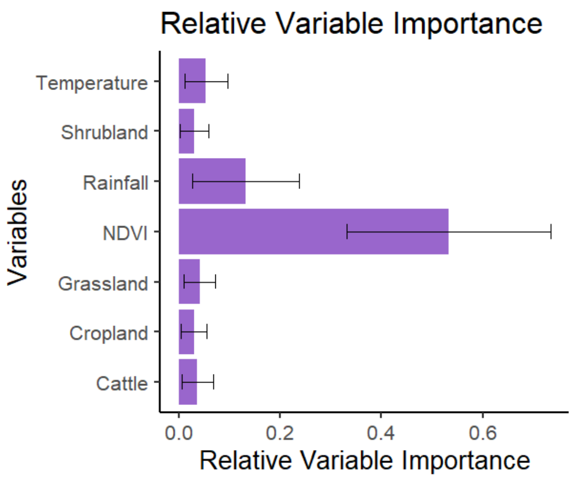
Legend: NDVI, Normalized difference vegetation index.

Variable importance

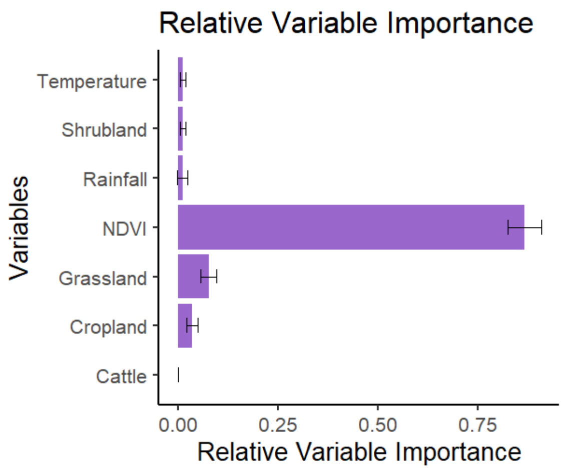
The analysis of the contribution of the different predictors to the MaxEnt model highlighted that temperature and rainfall were the main variables. Temperature contributed to more than 39% and rainfall contributed more than 19% of the model accuracy. Shrubland (1.8%) and grassland (1.8%) contributed less to the model predictions (**Fig. 3A**). The relative variable importance based on Pearson correlation metric in the ensemble model revealed that NDVI played an important role in the model. This variable was the most important in the five models that make up our ensemble model set. NDVI was the most important predictor in the ensemble model and the cropland and shrubland were the less important ones (**Fig. 3B**). In the GLM model, NDVI (88%) was the most important predictor while cattle density contributed the least to the model with 0.1% (**Fig. 3C**). In the GAM model, it was the rainfall that contributed the most with 39.3% and the cropland contribute the least with 2.4% (**Fig. 3D**). In the RF model, NDVI was the most important contributor among the predictors (20.3%) and grassland has the lowest contribution (0.4%) (**Fig. 3E**). The NDVI also was the largest contributor to the BRT model (62.6%) and grassland had the lowest contribution (0%) to the model (**Fig. 3F**). In the fifth model (SVM), the most important predictor was NDVI (18.5%) and the least important was Grassland (1.9%) (**Fig. 3G**).



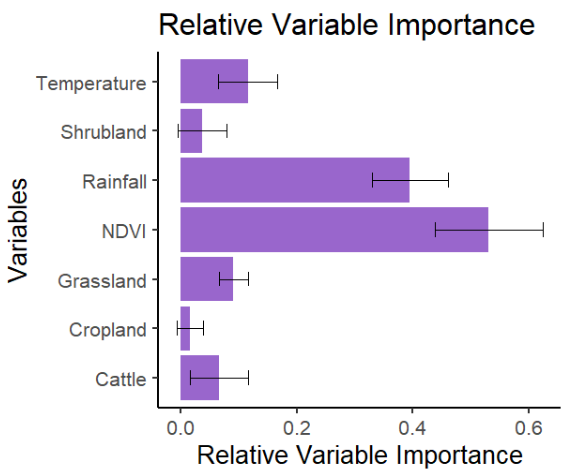
[A] MaxEnt model



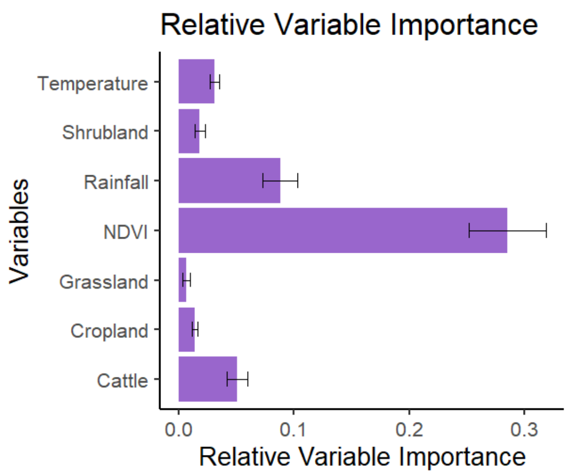
[B] Ensemble model



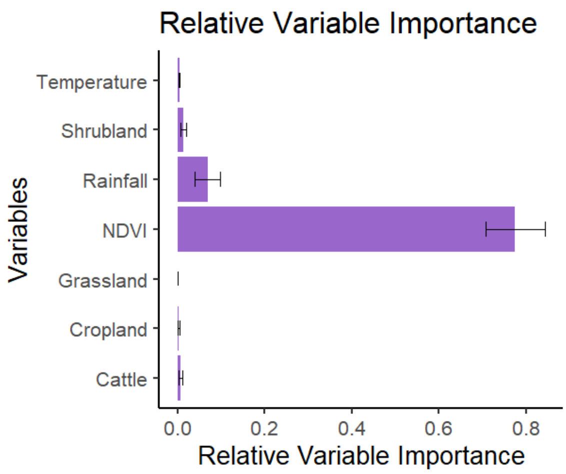
[C] GLM model



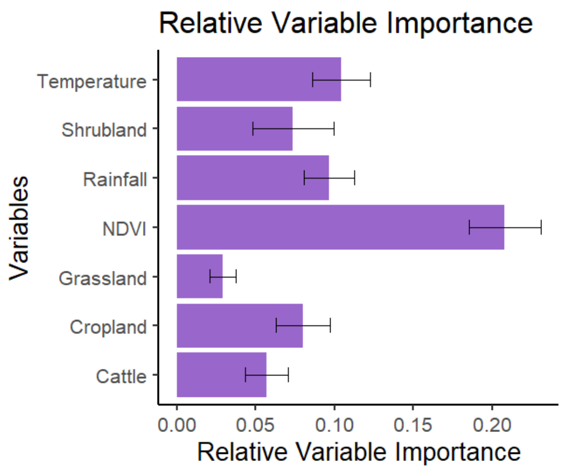
[D] GAM model



[E] RF model



[F] BRT model



[G] SVM model

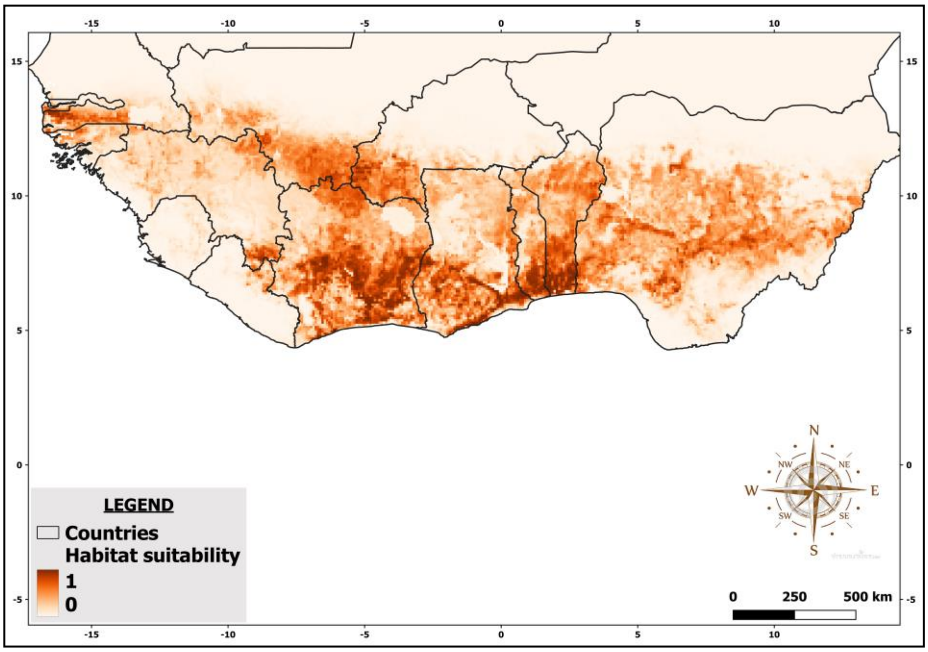
Fig. 3. Variables importance in models accuracy

Legend: NDVI, Normalized difference vegetation index.

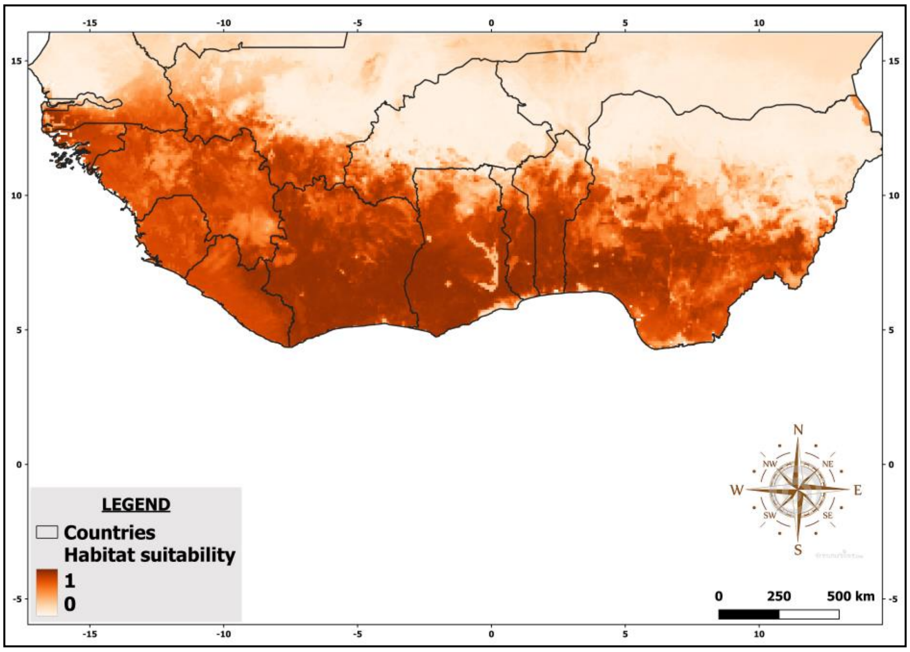
Habitat suitability for *R. microplus* in West Africa

The maps revealed a high suitability of the coastal areas of West Africa. On the other hand, the tick *R. microplus* seems very poorly adapted to the environment of the Sahelian region, a desert area (**Fig. 4**). However, the southern regions of some Sahelian countries, contiguous to the coastal areas, are also suitable for *R. microplus*. Some differences can be noted in these outputs according to the kind of model implemented. The MaxEnt model predicts differently the presence of the tick in the Sahelian region where it is not expected at all or the probability is very low to find it (**Fig. 4A**). On the opposite side, the other five models grouped in the ensemble model predict a significant presence of the tick in the

Sahelian region (**Fig. 4B**). Furthermore the suitability level of the coastal areas predicted by MaxEnt model is lower than the four other models grouped in the ensemble model.



[A] MaxEnt model with only presence data



[B] Ensemble modelling suitability map with presence and absence data

Fig. 4. Habitat suitability maps of *R. microplus* in West Africa with seven predictors (rainfall, temperature, cattle density, normalized difference vegetation index, cropland, grassland and shrubland).

Model evaluation

Three parameters were used to evaluate the models: the AUC and the Boyce index (BI) for the MaxEnt model and the AUC and the TSS for the ensemble model (**Table 3**).

The Random forest model and the BRT model had the highest AUC (0.95) and the GLM had the lowest AUC (0.93). The GAM and the SVM models had the same AUC (0.94). The Random forest model had the highest TSS (0.80) and other models had the same TSS (0.79).

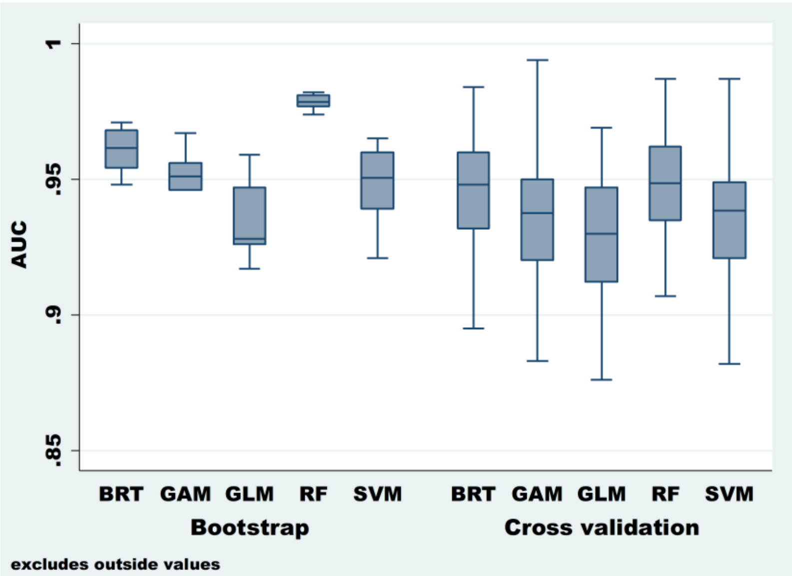
The boxplot graphics (**Fig. 5A**) highlighted the variability in the AUC among the bootstrap and cross-validation runs for each model. This figure revealed that the RF and BRT models AUC medians were above the other models ones for both bootstrap and cross-validation runs.

The boxplot graphics (**Fig. 5B**) highlighted the variability in the TSS among the bootstrap and cross-validation runs for each model. **Fig. 5B** revealed that for the RF and GLM models, TSS medians were above the other models ones respectively for bootstrap and cross-validation runs.

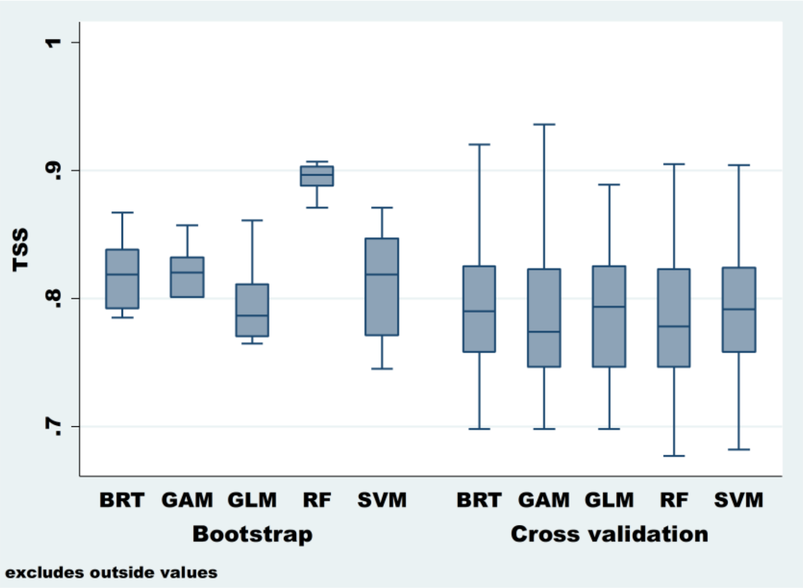
Table 3: Evaluation parameters of the various models

Models	**Average AUC**	**Average TSS**	**Average Boyce index**
GLM	0.93	0.79	NA
GAM	0.94	0.79	NA
RF	0.95	0.80	NA
BRT	0.95	0.79	NA
SVM	0.94	0.79	NA
MaxEnt	0.87	NA	0.87

Legend: NA: Not available; AUC: Area under the Curve; TSS: True skill statistic.



[A] Variation in the AUC among the cross-validation and bootstrap runs between the different ensemble models



[B] Variation in the TSS among the cross-validation and bootstrap runs between the different ensemble models

Fig. 5: Models evaluation

Legend: BRT, Boosted regression tree; GAM, Generalized additive model; GLM, Generalized linear model; RF, Random forest; and SVM, Support vector machine model.

DISCUSSION

The aim of this study was to characterise the habitat suitability of the invasive tick *R. microplus* in West Africa. Results of the habitat suitability modelling exercise showed that the coastal areas host more suitable areas for the tick than the Sahelian zone located in the north. The coastal zone, which receives more rainfall and is cooler than the Sahel have also a higher vegetation index. Moreover, the host (cattle) density is higher in the Sahel than in the coastal zone.

Model evaluation

According to the classification of Swets (1988), the MaxEnt model is “Useful” and all the ensemble models are “Highly accurate”. The RF model has the highest AUC value and the MaxEnt model has the lowest AUC among the six selected models.

For the ensemble models, TSS values indicate that the selected models were accurate. The RF model has the highest TSS among the ensemble models and all the four other has the same TSS.

The MaxEnt model was built with presence data only. These two accuracy parameters (AUC and TSS) are known to use sensitivity and specificity in their computation (Shabani et al., 2018).

The MaxEnt model has a lower AUC value than other models built with presence and absence data, so it was less accurate than these models according to this parameter.

However, on the other hand the MaxEnt model had a high BI that is an adapted parameter for presence-only models evaluation. The Boyce index is used to measure how well a model is able to predict the presence of species. The MaxEnt model confirmed by its BI value to be a model that does not require absence data to model species distribution.

The RF was the most accurate model among the ensemble models regarding its AUC and TSS means level and variance between both cross-validation and bootstrap runs.

Cross-validation tends to be less biased but has a relatively large variance. On the other side, bootstrapping tends to reduce the variance considerably but gives more biased results. Combining the two methods, as is the case here in a model set, could lead to fairly accurate prediction results without too much bias and very little variance.

Characterization of predictors and their importance in the models

The process of selecting variables for the construction of the models allowed the selection of seven variables including the annual average rainfall, the annual average temperature, the annual average vegetation index and the density of the host (cattle) and three land cover variables (cropland, grassland and shrubland).

Ticks are found in areas with significantly higher rainfall and moderate temperature. Water and temperature are important factors in tick biology. Especially in one-host ticks since the non-parasitic (and therefore environment-dependent) stage is the egg and larva stage. Ticks are very sensitive to desiccation while searching for a host, as they constantly lose water through the integument of their body surface in dry conditions through transpiration. They also lose water through their spiracles in connection with respiration during locomotor activity (Randolph and Storey, 1999; Herrmann and Gern, 2015). The development and mortality of ticks are strongly influenced by these two factors (Estrada-Peña et al., 2015). Our models show quite clearly that areas that are wetter and cooler are more suitable for ticks. Previous studies have shown in Benin and Eastern Burkina Faso that the *R. microplus* tick prefers areas of moderate temperature and high rainfall (De Clercq et al., 2015; Zannou et al., 2021). The results seem to show that high temperatures are a limiting factor for the presence of the tick in an environment of West Africa. However, it is important to note that other factors such as humidity (represented here by rainfall and the vegetation index) also contribute to the presence of the tick. So in an environment with good rainfall and adequate vegetation, temperature cannot really be the only limiting parameter. It is not uncommon to find in areas where the tick is present temperatures exceeding

28°C at certain times of the year. But generally in West Africa the regions that often experience high temperatures are the countries of the Sahel which are generally very dry (low rainfall) and therefore unsuitable for the tick.

The NDVI of areas where the tick was found was higher than where it was not. The vegetation index, itself dependent on temperature and humidity (F. Hao et al., 2012), is an important variable in that it provides information on the presence, the vitality and the photosynthesis activity of vegetation. When it is known that ticks spend almost 80-90% of their life off host, vegetation appears to be very important in its life cycle (Leal et al., 2018). Engorged *R. microplus* female after dropping off the host need shelter under vegetation with convenient temperature and humidity to lay eggs (Latif and Walker, 2004). Eggs are sensitive to heat and risk desiccation when exposed to high temperature and dry area. Incubation and hatching of eggs are only possible under some particular climatic conditions (Pfäffle et al., 2013). Our results indicate that this variable is positively correlated with the presence of the tick and the models developed show that it took a large part in predicting the presence of the tick. De Clercq et al., (2015) in Benin and Zannou et al., (2020) in Benin and Burkina Faso have also evidenced the importance of the NDVI on a smaller scale.

Host (cattle) density was higher in areas where the tick is absent than in areas where it was present. In West Africa, the cattle population is more concentrated in the Sahelian countries, which are less watered and warmer. As the tick is more inclined to areas with more water and less heat, a negative correlation between these two variables appears. Nevertheless, the frequent and periodic movements of herds between these two ecosystems enabled by transhumance should be considered. Indeed, at a certain time of the year (dry season), herds in search of pasture and water are forced to descend into areas that are still wet at that time and therefore heavily infested by ticks (Zannou et al., 2021). These regular movements and stays expose the animals to *R. microplus* and the main pathogen it transmits: i.e *Babesia bovis* and *Babesia bigemina*. These pathogens are responsible of extensive production losses (Waldron and Jorgensen, 1999; Jonsson, 2006).

Croplands were significantly higher in areas where *R. microplus* was absent than in areas it was present. Cropland is known to be the site of much human activity. Before the crops are planted, the land is well ploughed to help destroy ticks nests. During the vegetative cycle of the different crops, farmers carry out several weeding operations or use herbicides. Pesticides are also regularly used to protect these plants in order to guarantee a good harvest at the end of the season. All these anthropic actions do not allow the establishment of the non-host phase of the ticks in such environments. It must also be said that *R. microplus* is a specific tick and should be found in the areas most frequented by its bovine host. Cattle are kept away from the farmlands to avoid the destruction of crops by them. They are only tolerated in cropping areas in the dry season to take advantage of crop residues and fertilise the fields.

Rainfall was by far the most important predictor in MaxEnt model followed respectively by NDVI, cropland, temperature, cattle density and shrub. The grassland did not really play a role in the MaxEnt model prediction. The ensemble model revealed that NDVI was by far the most important predictor followed respectively by rainfall, temperature, cattle density, cropland, shrubland and grassland.

While most existing studies (De Clercq et al., 2015; Sungirai et al., 2018) on the projection of the tick distribution only take into account climatic variables, our results showed the importance of other predictors such as cropland, host density in the modelling. The type of vegetation does not seem to be very important in predicting the presence of *R. microplus*. However, it should be noted that shrub vegetation seems to have a better predictive value than grassland. Shrubland provides a better canopy for the ticks and protect them from desiccation during the off-host phase. Grass is only really useful during the quest phase of the host. However, it is important to put the importance of these two variables into perspective because the collections were made on the animals and not on the ground by flagging. Similar results on the vegetation preference were observed in the study of Omodior et al., (2021) in United States of America.

Habitat suitability for *R. microplus* in West Africa

This work qualitatively provides a broader view compared to the previous study by De Clercq et al (2015) and according to the models ouputs the coastal areas seem globally more adapted to the tick. This previous *R. microplus* distribution modelling used occurrences data from 2011. Recent work (Ouedraogo et al., 2021) had revealed the presence of the tick in areas where it was previously absent (2015). Therefore, the present work has taken into account presence data from several countries, compared to the work form De Clercq et al., (2015), which only sampled and modelled data from Benin. When looking at habitat suitability maps generated by the present study in Benin in comparison to the work from De Clercq et al., (2015), it can be clearly noticed that our models predicted suitable habitats for the species also in the northern part of Benin, while De Clercq et al., (2015) predictions emphasises mostly the southern one. This may be due to the larger dataset of observations used, as well as different predictors and the tuning of the MaxEnt model. The MaxEnt model as well as the ensemble model predicts a higher risk of tick presence in northern Benin than the De Clercq study (2015). This work provides a larger view of the situation of *R. microplus* in West Africa. It also uses different methods, the ensemble models which are based on the consensus of several models to predict the habitat suitability for *R. microplus*. The interest of the ensemble modelling is that it relies on the principle of the "wisdom of the crowd" to make a better prediction than those models used individually (T. Hao et al., 2019).
The ensemble model seems to predict a stronger fit of the Sahelian zone to the tick than the MaxEnt model. When we consider the contribution of the variables to the prediction of the models we notice that the trend is not the same. For the MaxEnt model it is the temperature variable that holds the greatest importance while for the ensemble model it is the NDVI. This may have contributed to this difference

in prediction, as we know that the Sahel countries are significantly warmer than the coastal countries, but there is still vegetation in some parts of the Sahel around the oases. It should also be remembered that the ensemble model is a consensus model among several models, so its predictions must be given special attention. Precautions must be taken in certain Sahelian countries that are at risk due to the extensive livestock farming methods used. These farming methods could favour the importation of the tick, which could adapt and continue its invasion.

According to the updated Koppen-Geiger climatic map provided by Beck et al. (2018), the coastal areas of West Africa show climatic similarities with southern Asia and South America respectively native area and previously invaded area of the tick *R. microplus*. This climatic similarities could be part of the factors that enabled the rapid adaptation and spread of the tick in the environment of some West African countries.

All six models clearly show that countries in the southern part of West Africa (coastal countries) are more suitable for *R. microplus* than those in the Sahel. As expected, temperature, humidity and vegetation influenced most the biology of the tick. Indeed the Sahelian countries are drier and hotter than the coastal countries. Moreover, the vegetation is less developed there. In spite of the higher density of cattle in the Sahel, the off-host life will be difficult for *R. microplus* larvae because of the unfavourable climatic conditions. However, as the habitat suitability maps show, the risk of having the tick in some parts of the Sahel is not null. In some Sahelian countries there are areas such as permanent water points that could provide conditions for the tick to establish itself, especially when the species is known to be highly invasive and adaptive. Recent unpublished work has revealed its establishment in the central plateau of Burkina Faso, a fairly hot area compared to the usual places where it is found (Abel Biguezoton, personal communication). In recent years, Burkina Faso has developed water reservoirs, which have the dual function of being used for the cultivation of vegetables and for watering cattle herds. These environments can present risks of introduction and dissemination of ticks from herds returning from transhumance in coastal countries. The valleys of perennial rivers also represent biotopes that can favour the establishment of the invasive tick as they are very frequented during the dry season by herds in search of water and pasture.

Although native to Asia, *R. microplus* has invaded Sub-Saharan Africa and is probably replacing progressively the indigenous *R. decoloratus and R. annulatus* (M. Madder et al., 2011; Adakal et al., 2013; Gomes and Neves, 2018). This rapid expansion was also favoured by the extensive livestock farming practised by more than 70% of cattle farmers in sub-Saharan Africa (Boka et al., 2017).

This study provides a broader view of habitat suitability for *R. microplus*. It allows decision makers in West African countries to have a better idea of the level of suitability of their area for the invasive tick. It is therefore a tool to identify areas where emphasis should be placed on raising awareness among livestock stakeholders. In areas favourable to the tick and not yet infested, measures must be taken to prevent or detect quickly its introduction (e.g. awareness campaign, avoiding purchase of cattle originating from infested areas, avoiding herds movement to already infested areas, capacity building for detection of *R. microplus*, tick surveillance). In areas where the tick is already established, it will be necessary to raise awareness of the measures to be implemented to limit its spread and, ultimately, its control (e.g. campaign of information, adequate protocol of acaricide treatment, follow up of acaricide resistance). This study is a tool to help in the development of sub-regional and local control plans for *R. microplus* tick and consequently the pathogens it transmits. The direct consequence is the improvement of food security since cattle herds will high level of tick infestation and associated pathogens had important negative impact on their development. A good knowledge of the level of the risk for tick establishment in an area allows for careful management of financial resources dedicated to vector and pathogen control.

CONCLUSION

All the coastal countries of West Africa are suitable areas for *R. microplus*. The southern region of some Sahelian countries (Mali and Burkina Faso) also seems favourable, but to a lesser extent. This new study revealed that the risk of *R. microplus* is higher in some areas than previously predicted (case of Benin). It also gave a broader view of the risk over the whole West African sub-region compared to previous studies. It would be advisable for the authorities of countries that have not yet detected the tick but are in the risk area to take mitigation measures to prevent its introduction. The modelling the distribution of the invasive tick with several strategies (single models and ensemble models) also allowed us to assess their behaviour with the available data. Several quality parameters were used (AUC, TSS and BI) and allowed us to better appreciate the accuracy of each model according to its specificities. For instance, the MaxEnt model behaves better with presence data only, whereas the RF and GLM models need absence data to give accurate results.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ETHICS STATEMENT

The activities of the research project "Support to epidemio-surveillance networks for animal diseases and associated sociological aspects in West Africa (Acronym: TransTicks)" was approved by the Ethics Committee of the International Centre for Research and Development on Livestock in Sub-humid Zones (CIRDES) (Ref. 001-02/2017/CE-CIRDES) under the strict respect of the protocol submitted to the members of the Committee and their unannounced control.

AUTHOR CONTRIBUTIONS

Conceptualization, O.M.Z., A.B., K.P.Y., L.L. and C.S.; methodology, O.M.Z., D.D.R., S.O.V. and C.S.; software, O.M.Z., D.D.R., S.O.V. and C.S.; validation, O.M.Z., D.D.R., S.O.V. and C.S; formal analysis, O.M.Z.; investigation, O.M.Z., A.S.O.; resources, A.B. and C.S.; data curation, O.M.Z., D.D.R. and C.S.; writing—original draft preparation, O.M.Z.; writing—review and editing, all; visualization, O.M.Z., D.D.R. S.O.V. and C.S.; supervision, A.B., S.F., D.D.R., S.O.V. and C.S.; project administration, C.S. All authors have read and agreed to the published version of the manuscript.

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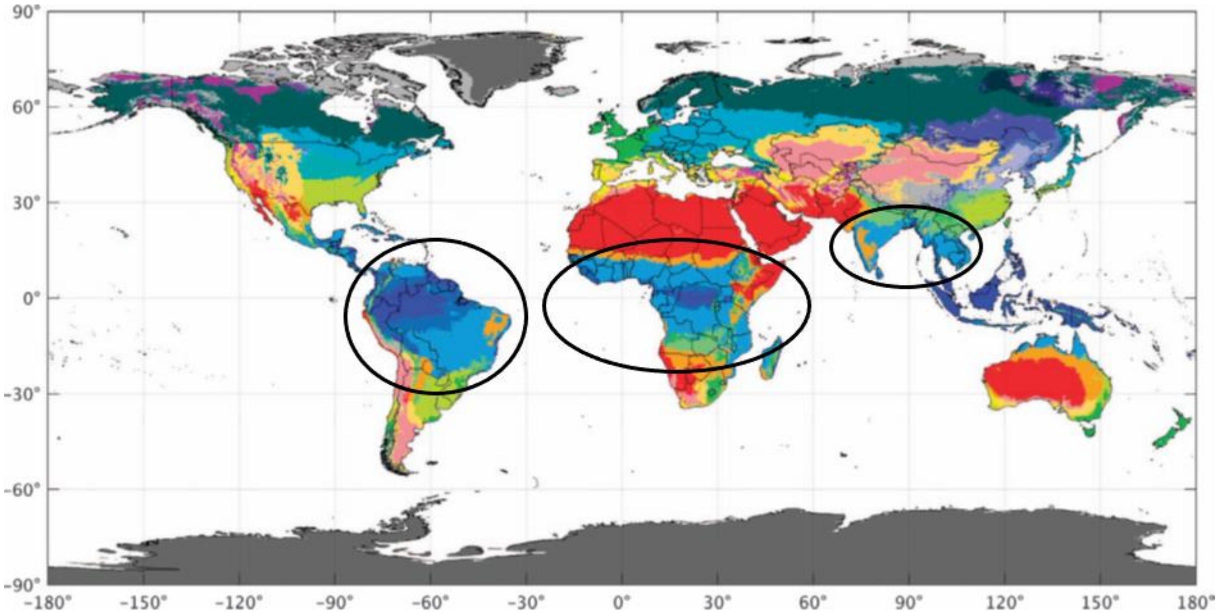
Appendix S1. New and improved Köppen-Geiger classifications present-day map (1980-2016) (Source: Beck et al., 2018*)*



Legend: Black circles= similar climatic zones

Study 5: Economic impact of tick infestation of two West African countries (Benin and Burkina Faso) cattle herds

Manuscript submitted in Transboundary and Emerging Diseases

Preamble of study 5

Ticks and tick-borne diseases remain a real constraint on livestock in West African countries. They are the most important ectoparasites of livestock in the tropics and subtropics and are responsible for severe economic losses both through the direct effects of blood-sucking and indirectly as vectors of pathogens. The objective of this study is to assess the clinical and economic impact of ticks and tick-borne diseases in cattle herds and the benefits of controlling these parasites. Based on data from an acarological and epidemiological survey conducted in 2017 in eastern Burkina Faso and northern Benin and data collected in various articles, we developed a deterministic model. This model allowed us to assess the clinical and economic impact of ticks and tick-borne diseases on herds.

Economic impact of tick infestation and tick-borne diseases in transhumant cattle herds from two West African countries (Benin and Burkina Faso)

Short running title: Economic impact of ticks' infestation in cattle

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ABSTRACT

Background: Ticks and tick-borne diseases (TTBD) remain a real constraint in livestock in West African countries. They are the most important ectoparasites of livestock in tropical and sub-tropical areas. TTBD are responsible for severe economic losses both through the direct effects of blood sucking and indirectly as vectors of pathogens. Although TTBD economic impacts are known in West Africa, few data and articles focusing on this region are available. The objective of this study is to assess the economic impact of TTBD in transhumant cattle herds and the benefits of preventing or controlling these parasites. **Methods and principal findings:** Using data from an acarological and epidemiological survey conducted in 2017 on 90 transhumant cattle herds from eastern Burkina Faso, northern Benin and data collected from published articles, we developed a deterministic mathematical model. This model allowed us to evaluate the clinical and economic impacts of TTBD at herd level (mean-standard herd size in the study area of 56 heads). Six scenarios were developed depending on whether the animals were treated with only acaricides or with drugs targeting tick-borne diseases. An annual gain of 871 euro at herd level was estimated with the acaricide treatment scenarios when compared to the losses if no treatment is applied. When preventive treatment of tick-borne pathogens was combined with acaricide treatment, an annual gain of 254 euro at herd level was estimated when compared to the losses if no treatment is applied. **Conclusions and significance:** The results of this deterministic cost-benefit analysis claim for preventive and control strategies adapted to the specificity of each area. The development and implementation of such strategies must be consensual and participatory for their success. Prior awareness of cattle holders is needed.

Keywords: Cost-benefit analysis; Acaricide; Body weight loss; Milk loss; Ticks and tick-borne diseases; West Africa

1. INTRODUCTION

Ticks and tick-borne diseases (TTBD) remain a real constraint in livestock in West African countries. Ticks are the most important ectoparasites of livestock in tropical and sub-tropical areas and are responsible for severe economic losses both through the direct effects of blood sucking and indirectly through the transmission of pathogens. The impact of ticks on cattle milk production includes a decrease in both quantity and quality. TTBD cause a drop of milk production, a decrease of nutritional status, and a poor management pattern (Duguma et al., 2012). Tick bites stress hosts and depress their immunity, affecting their zootechnical performance. In a study in Zambia, the productivity of tick-free cattle herds was almost 25% higher than that of tick-infested herds (Pegram and Chizyuka, 1990). In addition, the body weight production of weaned, tick-free calves was 28% higher and milk consumption 21% higher. High tick infestations reduce the ability of livestock to reach their full weight potential. For example, when animals are infested with an average of 40 ticks of *Rhipicephalus microplus* species per day and per animal, they can lose around 20 kg per year. When they are infested with more than 200 ticks over a six week period, they can die if left untreated (Hadush, 2016).

The financial loss results in a loss of production in addition to the cost of prevention or control of TTBD per animal per year (Jonsson, 2006).

Regarding tick-borne diseases (TBD), they have a greater impact in tropical and subtropical countries (De Meneghi et al., 2016). For example, the annual global costs of *R. microplus* and associated diseases and their control have been estimated at between US$13.9 billion and US$18.7 billion (Jaime Betancur Hurtado and Giraldo-Ríos, 2019). In the light of the recurrent problem of tick infestation in livestock and the consequences due to transmitted diseases, acaricides seem to be the most appropriate option. Despite the temporary nature of the effects of acaricides and the emergence of resistance of some species, they have so far proved to be the best solution for TTBD available right now. The challenge relies in the constant, continuous and low-cost supply of these products to livestock farmers (Walker, 2014).

Published data to illustrate the economic benefit of cattle tick control are rare, especially in the West African sub-region. We hypothesize for this study that the effective prevention and control of TTBD on a cattle farm would be economically beneficial. The cost of acaricide treatments and TBD prevention and control would be lower than the cost of economic losses caused by these parasites within a herd without any treatment.

The objective of the study is to assess the economic impact of TTBD in transhumant cattle herds and the benefits of preventing or controlling these parasites.

2. MATERIALS AND METHODS

2.1. Study area

The study area includes two West African bordering countries: Burkina Faso (eastern region) and Benin (northern region). It is located between 8° and 13°N latitude and 1°E and 4°W longitude. The eastern region of Burkina Faso (46256 km^2, i.e. 17% of the national territory) is divided into five provinces (Gnagna, Gourma, Komandjoari, Kompienga, and Tapoa), which represent a transhumance departure area (Anonyme, 2009). Three provinces (Gourma, Kompienga and Tapoa) are included in this study. The north of Benin is divided into four departments (Alibori, Atacora, Borgou, and Donga), which correspond to an arrival area of the transhumant herds from Burkina Faso. The provinces of Burkina Faso and the departments of Benin are divided into municipalities. Our study area groups a total of forty-four municipalities with twenty-seven in Benin and eighteen in Burkina Faso (**Figure 1**).

The climate in these two regions is almost similar with few particularities. The south-Sudanese climate of the eastern region of Burkina Faso is characterized by a rainy season that last five months, from May to September, and a dry season that last seven months, from October to April (Ibrahim et al., 2012). Precipitations are very variable both in the number of rainy days and in the quantity of water (between 900 and 1100mm per year) (Anonyme, 2009). Northern Benin has a Sudanese climate with a rainy season lasting 5 months from May to September and a dry season lasting 7-8 months from October to April. Rainfall is between 700 and 1100 mm of water per year. The external temperatures are between 22 °C and 37 °C throughout the country with daily thermal amplitudes in the north (greater than 10 °C) (Adam, 1993).

Livestock represents the third largest export product after gold and cotton in Burkina Faso. It contributes 26% of the country’s export earnings. Burkina Faso's cattle herd consisted of 10,003,682 heads in 2019 (FAO, 2021). Among the country's thirteen regions, the eastern region (11.37%) is the third largest in terms of cattle heads, behind the Sahel (20.15%) and the Upper Basins (16.6%) (Anonyme, 2019).

Benin's cattle herd is made up of 2,503,836 heads located more than 80% in the northern part of the country (FAO, 2021).

2.2. Nature and source of data

The data of a cross-sectional acarological survey carried out from December 2016 to February 2017 in the study area were used to make a map of the tick density at animal level in this period (Ouedraogo et al., 2021). Data were compiled by municipality for all the ticks collected with no distinction of the species of ticks. A total of 90 herds were randomly sampled including 46 in eastern Burkina Faso and 44 in northern Benin. An epidemiological survey followed the acarological survey to collect data on the acaricides used in the area, dosages and costs of these products (Zannou et al., 2021).

Additional data were provided by the veterinary services of the two countries on the number of cattle herds in the targeted departments and on the price list for livestock products such as meat and milk.

Data on the adverse effects of different tick species on meat and milk production were collected from previous published articles that have already addressed this subject (**Table 1**). Tick borne diseases mortality statistics were provided by World Animal Health Information System (OIE, 2021). Tick density at animal level was mapped with QGIS 3.18.1 (Quantum GIS Development Team, 2021).

2.3. Statistical analyses

2.3.1. Deterministic model for the estimation of clinical and economic ticks and tick-borne diseases impacts

A mathematical deterministic model was developed with the different data collected in an excel spreadsheet. Below are the different equations (boxes) that make up this model. Details are given in **Table 1** and **Appendix S1**.

2.3.1.1. Structure of the cattle population

Herds were considered as the epidemiological units. Indeed, the detection of ticks makes them a tick infestation outbreak. The structure of the herds (cattle heads, proportion of cows, heifers, bulls and young bulls in an outbreak) in the study area derived from two previous published works, one in Benin (Chabi Toko et al., 2016) and the other in Burkina Faso (Zampaligre et al., 2019). The data collected in these articles and those from our epidemiological survey were used to determine the average herd structure (**Table 1** and **Appendix S1**).

2.3.1.2. Estimation of production losses

Ticks species found in the region were *Amblyomma variegatum*, *Hyalomma truncatum*, *Hyalomma rufipes*, *Hyalomma impeltatum*, *Hyalomma impressum*, *Hyalomma nitidum*, *Rhipicephalus lunulatus*, *Rhipicephalus sanguineus*, *Rhipicephalus senegalensis*, *Rhipicephalus muhsamae*, *Rhipicephalus geigyi*, *Rhipicephalus decoloratus*, *Rhipicephalus microplus*, and *Rhipicephalus annulatus* (Ouedraogo et al., 2021). Data on the weight lost by animal due to the presence of a tick according to the species and sex of the tick were collected from scientific literature (**Table 1)**. This information was used to calculate the total weight loss of an animal according to the tick infestation rate. The meat production losses were computed as described in **Table 1** and **Appendix S1**.

Equation 1 (meat production losses due to tick infestation):

$$WLsSp = WLsESp \ast NbGnSpY \ast PTSp \ast NbT$$

With:

WLsSp: Weight losses per tick species (expressed in kg of body weight).
WLsESp: Weight losses due to an engorging tick species.
NbGnSpY: Number of generations of the species per year.
PTSp: Proportion of the tick species.
NbT: Number of ticks.

To find out the cost of weight loss in a herd, the price per kg of body weight of live animal was multiplied by the total weight loss due to all ticks in the herd.
Data on the loss of milk production caused by a tick species was collected from previous published articles (**Table 1**). These data were used to calculate the total milk loss caused by the infestation of the tick species on cows in the study area. The milk production losses were computed as presented in in **Table 1** and **Appendix S1**.

Equation 2 (milk production losses due to tick infestation):

$$MLsTSp = NbTSp * NbGnSpY * MlLsETSp$$

With:
MlTSp: Milk losses per tick species (expressed in litre of milk).
NbTSp: Number of ticks per species.
NbGnSpY: Number of generations of the species per year.
MlLsETSp: Milk loss per engorged tick of the species.

The cost of milk losses is given by the product of the price per litre of milk by the total amount of milk lost due to ticks in a herd.
Tick borne pathogens found in cattle (n = 946) in the study area were: *Theileria mutans* (91.1%), *Theileria velifera* (77.8%), *Babesia bigemina* (10.9%), *Anaplasma marginale* (4.2%), *Babesia bovis* (3.3%), and *Theileria annulata* (1.8%) (Ouedraogo et al., 2021). Some of the pathogens detected in cattle in the study area cause diseases that may result in the death of animals if no treatment is applied. These include *B. bovis*, *B. bigemina*, *A. marginale* and *T. annulata* (Bock et al., 2004; Swai et al., 2007; Gul et al., 2015). When they do not cause death of infected animals, these pathogens can cause weight and milk production losses (Manzoor et al., 2020). The others cause mild infections. As the study did not collect information on mortality caused by these different pathogens, we used the WAHIS animal health data on the OIE website (OIE, 2021). In this case, we calculated the lethality of diseases caused by these pathogens in the West African sub-region when the data was available on the site. With the prevalence data from a cross-sectional study (Ouedraogo et al., 2021), we estimated the mortality by pathogen genus. The mortality was computed as follows:

Equation 3 (mortality losses due to tick infestation):

$$MrtCtlTbdOut = MrbTbd * LthTbdWaf * CtlHdOut$$

With:
MrtCtlTbdOut: Mortality of cattle due to TBDs per outbreak (expressed in heads).
MrbTbd: Morbidity of TBDs.
LthTbdWaf: Lethality of TBDs in West Africa.
CtlHdOut: Cattle heads per outbreak.

The cost of losses due to TBD mortality was obtained by multiplying the TBD mortality by the average weight of an animal and the average price per kg of live weight.

We also computed the cost of the body weight and the milk production losses due to TBD with the following formulae.

Equation 4 (body weight losses due to TBDs):

$$CstWLsTbd = PrevTbd * CtlHdOut * WLsTbd * AvgLwPce$$

With:
CstWLsTbd: Cost of weight losses due to 3 critical days of illness in an outbreak of TBD (expressed in euro).
PrevTbd: Prevalence of TBD.
CtlHdOut: Cattle heads per outbreak.
WLsTbd: Weight losses due to 3 critical days of illness caused by TBD.
AvgLwPce: Average live weight price.

Equation 5 (milk production losses due to TBDs):

$$CstMlLTbd = PrevTbd * NbLactCwOut * MlLsTbd * AvgPceLtMl$$

With:
CstMlLsTbd: Cost of milk production losses due to 3 critical days of illness in an outbreak of TBD (expressed in euro).

PrevTbd: Prevalence of TBD.
NbLactCwOut: Number of lactating cows per outbreak.
MlLsTbd: Milk production loss due to 3 critical days of illness caused by TBD.
AvgPceLtMl: Average price of a litre of milk.

2.3.1.3. Estimation of tick control costs

An epidemiological survey conducted by Zannou et al., (2021) revealed that farmers use several acaricides in the following proportions (n = 90 farmers) : amitraz 68%, cypermethrin 13%, deltamethrin 3%, fipronil 4%, flumethrin 1% and ivermectin 1%. These data on the proportions of use of the various acaricides allowed us to estimate the proportion of animals treated with each type of acaricide. Additional data such as the cost of an acaricide treatment and the frequency of treatment were used to calculate the total annual cost of acaricide treatment in a herd. The formula used to compute the cost of acaricide treatment was the following.

Equation 6 (cost of acaricidal treatment):

$$CstAcdOut = NbAlAcd \, * \, NbTmtAlY \, * \, PlgAcd \, * \, CstmlAcd$$

With
CstAcdOut: Cost of acaricidal treatment of one outbreak (expressed in euro).
NbAlAcd: Number of animals treated by a type of acaricide.
NbTmtAlY: Number of treatments per animal per year.
PlgAcd: Posology per active substance.
CstmlAcd: Cost of one ml of acaricide per active substance.

Three scenarios were discussed. These are the cases in which the farmers spray 1) all, 2) half or 3) one third of their herd.

2.3.1.4. Estimation of tick-borne diseases control costs

Among the tick-borne pathogens detected in cattle in the study area, *B. bovis*, *B. bigemina*, *A. marginale* and *T. annulata* are pathogenic and can have significant consequences on the animal health (Bock et al., 2004; Swai et al., 2007; Gul et al., 2015). Preventive treatments are available against babesiosis by monthly injections of products based on imidocarb dipropionate. Imidocarb dipropionate is the only babesiacide on the market providing clinical protection of disease from 3 to 6 weeks (Vial and Gorenflot, 2006). This antimicrobial also shows efficacy against anaplasmosis (Alberton et al., 2015). The cost of preventive treatment by monthly injection to each cattle was computed by the following formula.

Equation 7 (cost of prevention treatment against TBDs):

$$CstTbdTmtYOut = CstmlImd * FreqTmt * PlgImd * AvgWAlOut * CtlHdOut$$

With:
CstTbdTmtYOut: Cost of one year TBDs preventive treatment in an outbreak (expressed in euro).
CstmlImd: Cost of one ml of imidocarb dipropionate.
FreqTmt: Frequency of treatment.
PlgImd: Posology of imidocarb dipropionate.
AvgWAlOut: Average weight of an animal in the outbreak.
CtlHdOut: Cattle heads per outbreak.

Table1. Model inputs to estimate the economic impacts of ticks and tick borne diseases in cattle and the costs of the acaricidal treatment and TBD prevention

Inputs data	Formula	Unit	Sources
Number of herds randomly selected in the study area (1)	Fixed=90	Heads	(Zannou et al., 2021)
Number of bovines per outbreak (2)	Fixed=56 (mean size of cattle herds in the study area)	Heads	(Chabi Toko et al., 2016; Zampaligre et al., 2019; Zannou et al., 2021); TransTicks study
Proportion of cows in the outbreak (3)	Fixed=0.34	-	
Proportion of heifers in the outbreak (4)	Fixed=0.30	-	
Proportion of bulls in the outbreak (5)	Fixed=0.18	-	
Proportion of young bulls in the outbreak (6)	Fixed=0.19	-	
Average weight of a cow (7)	Fixed=237.75	Kg	
Average weight of a heifer (8)	Fixed=121.25	Kg	
Average weight of a bull (9)	Fixed=264.17	Kg	
Average weight of a young bull (10)	Fixed=108.75	Kg	

Inputs data	Formula	Unit	Sources
Average weight of an animal in the outbreak (11)	Output((7)*(3))+((8)*(4))+((9)*(5))+((10)*(6))	Kg	
Average price per kg of milk (12)	Fixed=0.66	Euro	
Average price per kg of meat (13)	Fixed=2.48	Euro	
Average live weight price (14)	Fixed=1.53	Euro	
Total number of animals infested by ticks in the study area (15)	Fixed=888	Heads	(Ouedraogo et al., 2021)
Total number of randomly sampled animals in the study area (16)	Fixed=946	Heads	TransTicks study
Infestation rate of animals due to the presence of at least one tick (17)	Output (15)/(16)		Calculation
Number of ticks per species (18)			(Ouedraogo et al., 2021)
Total number of ticks collected in the study area (19)	Fixed=14463	Ticks	
Ticks species abundance on animals (20)	Output (18)/(19)	Ticks	Calculation
Number of female ticks per specie in the study area (21)	Variable depending of tick species	Ticks	TransTicks study
Proportion of female ticks per specie (22)	Output (21)/(18)		Calculation
Number of male ticks per specie (23)	NA	Ticks	(Ouedraogo et al., 2021)
Proportion of male ticks per specie (24)	Output (23)/(18)		Calculation
Average number of ticks per animal (25)	Output (19)/(16)	Ticks	(Ouedraogo et al., 2021)
Number of species generations per year (26)	NA	Generations	Srivastava and Varma, 1964; Londt and Arthur, 1975; Saratsiotis, 1977; Garris, 1984; Pegram et al., 1987; Logan et al., 1989; Norval, 1990; Linthicum et al., 1991; Yonow,
Weight losses due to an engorged tick (27)	NA	Kg	
Milk production losses due to an engorged tick (28)	NA	G	

Inputs data	Formula	Unit	Sources
			1995; Ioffe-Uspensky et al., 1997; Stachurski, 2000; A. Walker et al., 2003; Latif and Walker, 2004; Jonsson, 2006; Chen et al., 2012
Number of cows affected (29)	Output(2)*(3)*(17)	Heads	Calculation
Milk losses per tick species (30)	Output(18)*(22)*(26)*(28)	g	Calculation
Total milk losses (31)	Sum of losses for species considered (Outputs 30)	g	Calculation
Total milk loss in an outbreak (32)	Output (31)/(1)	g	Calculation
Cost of milk loss in the outbreak (33)	Output (32)*(12)	Euro	Calculation
Number of tick individuals per tick species (34)	NA	Ticks	(Ouedraogo et al., 2021)
Weight loss per species (35)	Output(27)*(18)*(22+24)*(34)	g	Calculation
Total weight loss due to tick (36)	Sum of losses for species considered (Outputs 35)	g	Calculation
Cost of weight losses (37)	Output (36)/(14)	Euro	Calculation
Cost of weight losses per outbreak (38)	Output (37)/(1)	Euro	Calculation
Morbidity of TBDs (Prevalence) (39)	NA	Cattle	(Ouedraogo et al., 2021)
Lethality of TBDs in West Africa (40)	NA	Cattle	WAHIS-OIE
Mortality of cattle due to TBDs per outbreak (41)	Output(40)*(39)*(2)	Cattle	Calculation

Inputs data	Formula	Unit	Sources
Cost of mortality due to TBDs per outbreak (42)	Output(41)*(11)*(14)	Euro	Calculation
Total cost of one year ticks infestation per outbreak (43)	Output(33)+(37)+(42)	Euro	Calculation
Proportion of acaricide usage (44)	NA	NA	(Zannou et al., 2021)
Proportion of animals treated by a type of acaricide (45)	Output (44)*(2)	NA	Calculation
Number of treatments per animal per year (46)	NA	Treatment	(Zannou et al., 2021)
Posology per active substance (47)	NA	NA	(Zannou et al., 2021)
Cost of one ml of acaricide per active substance (48)	NA	Euro	Calculation
Cost of one acaricidal treatment per animal (49)	Output (47)*(48)	Euro	Calculation
Cost of acaricidal treatment of one outbreak (the whole herd) (50)	Output(45)*(46)*(49)	Euro	Calculation
Cost of acaricidal treatment of one outbreak (half the herd) (51)	Output (50)/2	Euro	Calculation
Cost of acaricidal treatment of one outbreak (third of herd) (52)	Output (50)/3	Euro	Calculation
Posology of imidocarb dipropionate (53)	NA	ml/kg	TransTicks study
Frequency of treatment (54)	NA	Time/year	TransTicks study
Cost of one ml of imidocarb dipropionate (55)	NA	Euro/ml	TransTicks study
Cost of one year TBDs preventive treatment in an outbreak (56)	Output(55)*(54)*(53)*(11)*(2)	Euro	Calculation
Cost of one year TTBD treatment in an outbreak (the whole herd with acaricides) (57)	Output (50)+(56)	Euro	Calculation
Cost of one year TTBD treatment in an outbreak (half the herd with acaricides) (58)	Output (51)+(56)	Euro	Calculation
Cost of one year TTBD treatment in an outbreak (third of herd with acaricides) (59)	Output (52)+(56)	Euro	Calculation

Inputs data	Formula	Unit	Sources
Ratio costs of ticks infestation (weight and milk losses)/cost of acaricidal treatment of one outbreak (third of herd)	Output (43)/(52) (Scenario 1)		Calculation
Ratio costs of ticks infestation (weight and milk losses)/cost of acaricidal treatment of one outbreak (half the herd)	Output (43)/(51) (Scenario 2)		Calculation
Ratio costs of ticks infestation (weight and milk losses)/cost of acaricidal treatment of one outbreak (the whole herd)	Output (43)/(50) (Scenario 3)		Calculation
Ratio costs of ticks infestation (weight and milk losses)/cost of one year TTBD treatment in an outbreak (third of herd with acaricides)	Output (43)/(59) (Scenario 4)		Calculation
Ratio costs of ticks infestation (weight and milk losses)/ cost of one year TTBD treatment in an outbreak (half the herd with acaricides)	Output (43)/(58) (Scenario 5)		Calculation
Ratio costs of ticks infestation (weight and milk losses)/ cost of one year TTBD treatment in an outbreak (the whole herd with acaricides)	Output (43)/(57) (Scenario 6)		Calculation

Legend: TTBD, Ticks and tick borne diseases; TBD, Tick borne diseases; NA, Not applicable (i.e., no formula used but data from the literature); WAHIS, World Animal Health System; OIE, World Organisation for Animal Health; TransTicks study, study funded by the Academy of Research and Higher Education through the Research for Development Project "Support to the epidemiological surveillance network of animal diseases and related sociological aspects in West Africa".

2.3.1.5. Scenarios considered

Seven scenarios were considered in this assessment of the economic impact of TTBD in cattle and the benefits of preventing/controlling ticks and/or TBDs. The seventh scenario (Scenario 7), where the animals do not receive any treatment, is considered as control (reference point of departure). These scenarios were based on the recommendations of acaricide and pathogens control laboratories and on the practices of farmers in the study area. These scenarios are as follows:

- Scenario 1: third of herd received acaricidal treatment;
- Scenario 2: half the herd received acaricidal treatment;
- Scenario 3: the whole herd received acaricidal treatment;
- Scenario 4: third of herd received acaricidal treatment and all of them got preventive treatment against TBD;
- Scenario 5: half the herd received acaricidal treatment and all of them got preventive treatment against TBD;
- Scenario 6: the whole herd received acaricidal treatment and preventive treatment against TBD;
- Scenario 7: No animals received either acaricide or preventive treatment against TBD (reference).

2.3.1. Statistical comparison of the outputs of various scenarios

The economic costs and the ratio "losses incurred / cost of treatment" for the different scenarios retained were compared using a two-sample Wilcoxon rank-sum (Mann-Whitney) test. Statistical analysis was performed using Stata SE 14 software (StataCorp, 2015) StataCorp, College Station, Texas, USA). The significance level was set to 0.05.

3. RESULTS

3.1. Descriptive analysis

The descriptive analysis of the distribution of tick density per animal considering all species and biological stages revealed that the communes of Benin seemed more infested than those of Burkina Faso (**Figure 1**).

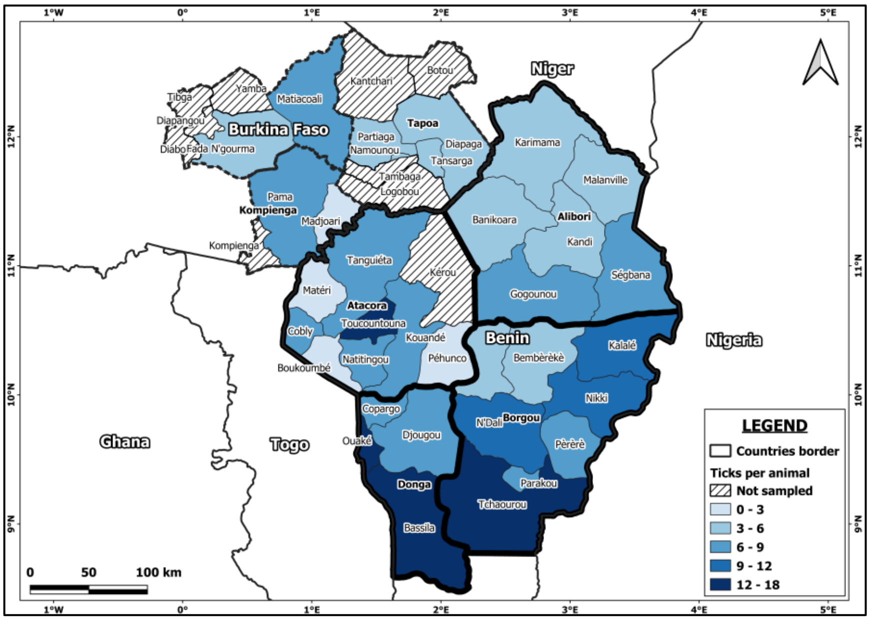

Figure 1. Tick density per animal without distinction of species per municipality in a transversal survey during the dry season of 2016 – 2017.

Regarding the cattle population distribution in the study area, the number of cattle exposed to ticks and TBD varied according to municipalities. Some municipalities recorded livestock density exceeding 1,468 cattle per 10 km^2 (**Figure 2**).

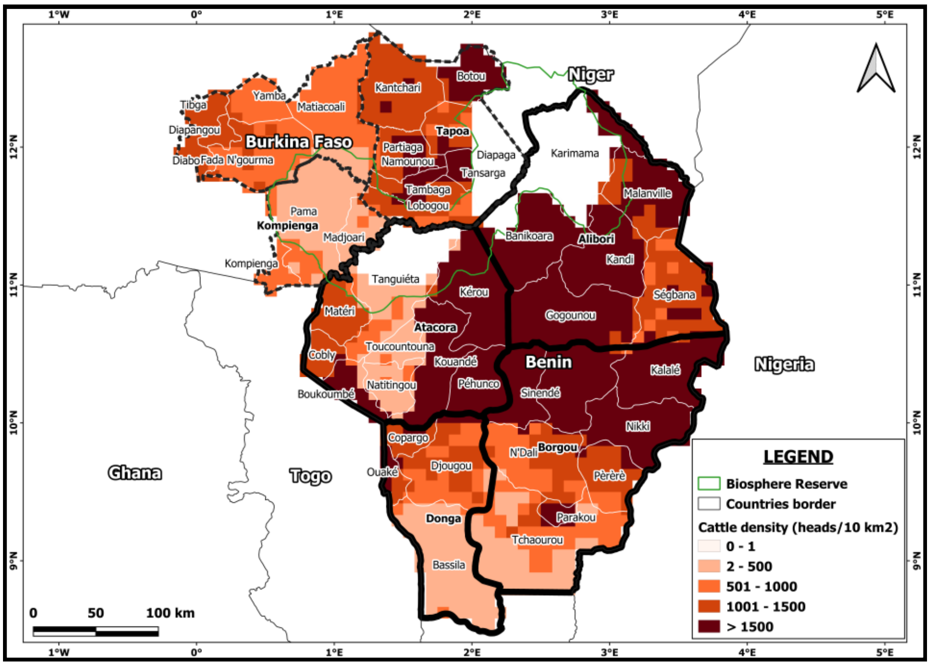

Figure 2. Cattle density in the study area. Data source for mapping: GLW3; https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/GIVQ75; (Source: Nicolas et al., 2016; Gilbert et al., 2018)

3.2. Deterministic model for the estimation of economic impacts of ticks and tick-borne diseases

3.2.1. Production losses due to ticks infestation and tick-borne diseases

The total cattle's weight losses per standard herd (i.e., herd of 56 heads) caused by ticks is about 5.07 kg for one year (**Figure 3**). The economic deficit induced by this weight losses per herd amount 7.77 euro for one year (**Figure 4**). The total losses of milk production per standard herd (i.e., herd of 56 heads) caused by ticks is 0.75 kg per herd for one year (**Figure 3**). This milk losses represent an annual economic reduction per herd of 0.50 euro (**Figure 4**).

The total cattle's weight losses per standard herd (i.e., herd of 56 heads) caused by TBD is 267.18 kg for one year (**Figure 3**). This amount corresponds to an economic deficit per herd of 409.49 euro for one year (**Figure 4**). The total losses of milk production per standard herd (i.e., herd of 56 heads) caused by TBD is 51.98 kg (**Figure 3**). This milk production losses represent an annual economic deficit per herd of 34.20 euro (**Figure 4**).

The mortalities per standard herd (i.e., herd of 56 heads) caused by TBD induced weight losses amount 312.87 kg of life meat for one year (**Figure 3**). These mortalities represent economic losses per herd of 479.51 euro for one year (**Figure 4**).

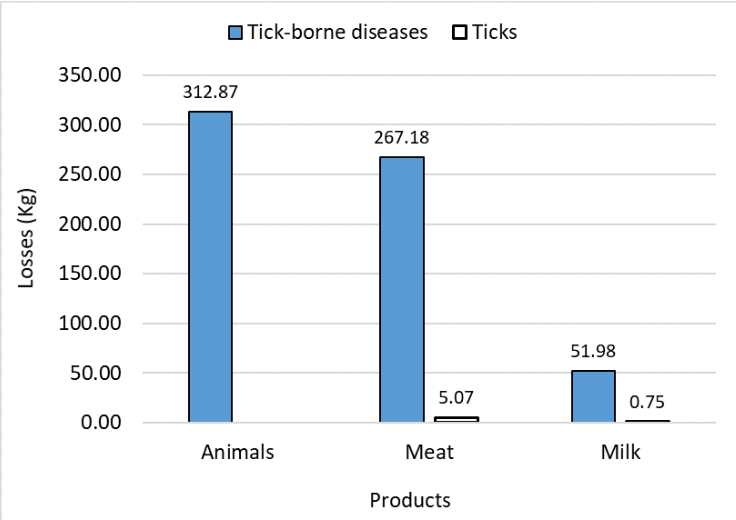

Figure 3. Clinical impact of one year ticks infestation and tick borne diseases on a mean-standard cattle herd of 56 heads in the study area.

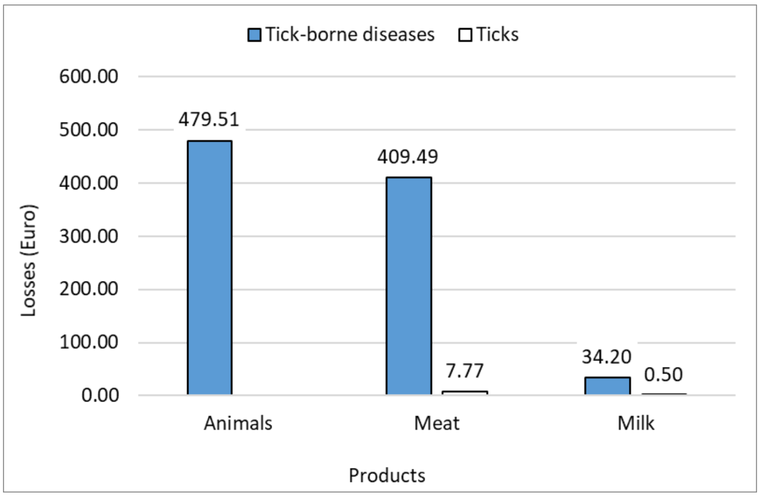

Figure 4. Economic impact of one year ticks infestation and tick borne diseases on a mean-standard cattle herd of 56 heads in the study area.

3.2.2. Ticks and tick-borne diseases treatment costs and comparison of the outputs of scenarios

Results showed that costs increase when moving from acaricide only-treatment scenarios to simultaneous acaricide treatment and TBD prevention scenarios. Conversely, the "losses incurred / cost of treatment" ratios decrease when moving from acaricide only-treatment scenarios to acaricide treatment and prevention of TBD scenarios. Nevertheless, the cost of the most expensive treatment scenario remains lower than the cost of the losses incurred when no treatment is applied (**Figure 5**).

There is an annual gain of 871 euro per herd (i.e., 56 heads of cattle) with the acaricide only-treatment scenarios, compared to the losses if no treatment is applied (**Figure 5**). When preventive treatment of TBD is combined with acaricide treatment there is an annual gain of 254 euro per herd (i.e. 56 heads of cattle) when compared to the losses if no treatment is applied at all (**Figure 5**). Finally, a significant difference was observed for both costs and ratio "losses incurred / cost of treatment" when we compared the three scenarios with acaricide only and the three other scenarios with use of both acaricide and prevention treatment of TBD (Two-sample Wilcoxon rank-sum (Mann-Whitney) test; p-value < 0.05).

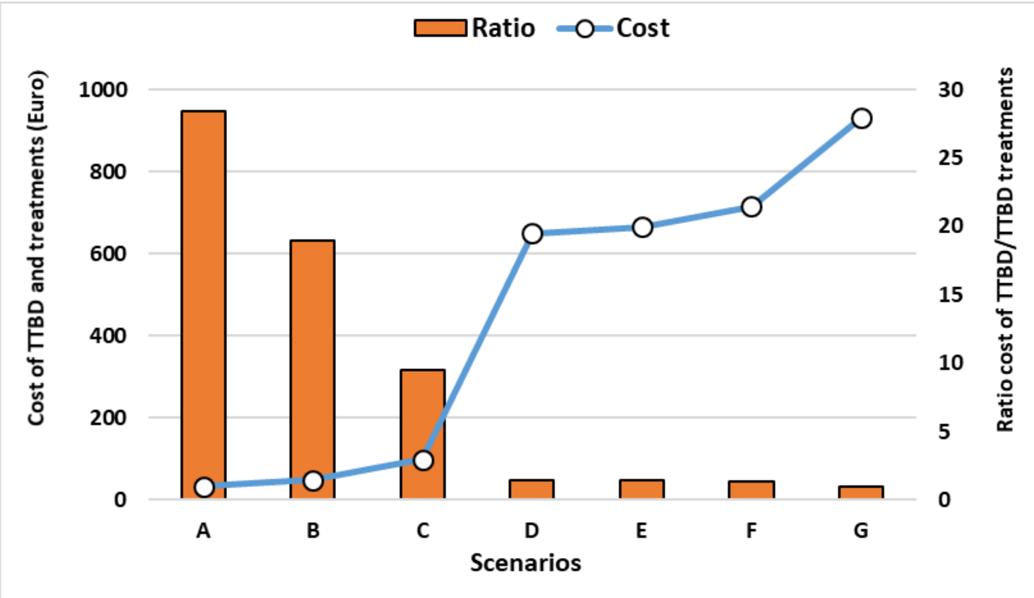

Figure 5. Comparative evolution of the costs of ticks and tick-borne diseases (TTBD) and their treatment in Euros and the ration between the cost of the TTBD and the cost of their treatment according to the scenario

Legend: **A** - Scenario 1: Third of animals had acaricidal treatment; **B** - Scenario 2: Half of animals had acaricidal treatment; **C** - Scenario 3: All of animals had acaricidal treatment; **D** - Scenario 4: Third of animals had acaricidal treatment and all of them preventive treatment against tick-borne diseases (TBD); **E -** Scenario 5: Half of animals had acaricidal treatment and all of them preventive treatment against TBD; **F -** Scenario 6: All of animals had acaricidal treatment and preventive treatment against TBD; **G -** Scenario 7: No animals received either acaricide or preventive treatment against tick-borne pathogens.

4. DISCUSSION

This study estimated the economic impact of TTBD at herd level focusing on two bordering West African countries. To the best of the authors' knowledge, this is the first time that such study was performed in Benin and Burkina Faso for this purpose.

Results of the previous study (Ouedraogo et al., 2021) revealed that all the sampled communes in the study area were infested by ticks. As well, almost all the targeting herds were at risk of TTBD. The tick hosts are also well distributed in all communes of the study area. This situation of simultaneous presence of ticks (obligate parasites) and their hosts in the same environment is quite favourable to their development if no control measures are implemented to break the parasite-host cycle.

In our model, we found that mortalities are mainly due to TBD and their translation in cost is quite high, about 489 euro per herd. Meat production losses due to TBD are also quite high with around 409 euro per herd. Meat production losses due to ticks directly are quite marginal and amount to only 8 euro in an outbreak. Tick-borne diseases therefore cause more economic damage than ticks directly. The same pattern was observed for milk production losses. Even if the cost of milk production losses is low compared to the losses due to mortality and meat production, they are mainly caused by TBD than by ticks directly (**Figures 3 and 4**). The total economic loss in milk production due to tick's infestation and TBD is about 35 Euro at herd level. It is noteworthy that these losses are underestimated because there are several variables that have not been considered in the model due to lack of data. These include, for example, teat losses. Teat losses are the result of the mechanical effect of long rostrum ticks that create wounds at their attachment points on the udder. These sores become infected and can result in the loss of one or more udder quarters, thus considerably reducing milk production. However, other causes of teat losses can be incriminated (not specific to tick bites).

Overall, the economic losses caused by TTBD in a mean-standard herd of 56 heads of cattle during a year, without any treatment, amount to about 931 euro (around 16.5 euro/head). This loss per herd was higher than the average gross domestic product per capita in the two countries (Benin and Burkina) for the year 2019, which amounts to 825 euros (World Bank and OECD, 2019). A loss of this value is very important in the study area where the economy is based on the primary sector in general and on livestock and agriculture in particular.

Therefore, strategies based on a preventive/control programme for TTBE are optimal. The epidemiological survey in the study area revealed a lack of national strategies for the prevention/control of TTBD in both countries. Overall, farmers have individual empiric strategies depending on the acaricides and pathogen control products available on the market (veterinary pharmacy and black market) (Zannou et al., 2021).

Following the different strategies identified in the field and according to the recommendations of the different laboratories producing these products, we have developed six control scenarios against either ticks alone or ticks and associated pathogens. These six scenarios range from treating only one third of the herd with acaricide to treating the entire herd plus a preventive treatment against transmitted diseases. The treatment becomes more expensive when going from the one-third of the herd scenario to the full treatment. However, the ratio of production loss to treatment cost in each scenario is always greater than one. This indicates that there is always a benefit to treat animals. It remains to find the right strategy adapted to each environment depending on the ticks and associated pathogens species present.

As ticks are the vectors of many pathogens, effective control of ticks can prevent the transmission of disease(s) to animals. Therefore, depending on tick species and the level of infestation of the herd, partial or complete treatment of the herd with acaricides could be recommended to control ticks and consequently the transmitted pathogens. Partial herd treatment is adopted by some farmers because they argue that some acaricides applied to a few animals can spread to all animals due to frequent contact between cattle in the same herd. Some farmers treat their herds partially because they can identify infested animals that need treatment.

The other challenge is the availability and quality of acaricides and pathogen control products. Effective acaricides against the species present in the study area are crucial for successful tick control. The survey in the study area revealed that, to resolve resistance problem of *R. microplus* or the effectiveness of the products available, some farmers frequently overdose (Zannou et al., 2021). This practice undoubtedly leads to additional costs for acaricide treatment. In areas of high *R. microplus* infestation, it would be advisable to combine acaricide treatment with a preventive treatment against the main transmitted diseases: i.e. babesiosis. This option is included in scenarios 4, 5 and 6 of proposed models.

This study did not consider the preventive treatment of *Theileria annulata* because this strategy does not yet exist in the study area. The control of this pathogen could be achieved by a good control of its vectors which are the ticks of the genus *Hyalomma spp* (Gharbi, 2006; Gharbi and Darghouth, 2015). These tick species have not yet shown a particular resistance to the acaricides used in the area. Chemotherapy with theilericides is also available for *T. annulata* infection but is globally expensive (about 33$ per adult cattle for parvaquone and buparvaquone based products in Tunisia). It should be noted that there is a 12% failure rate of this treatment with a risk of mortality due to post-treatment complications (Gharbi and Darghouth, 2015). This type of treatment cannot be recommended in the context of livestock farming in the study area.

Cattle skin is highly valued in cooking in this area. This skin is also used in leather goods. Hence, another limitation of this study is the unavailability of data on losses due to leather depreciation caused by tick damage. Heavy infestations of long-hypostome ticks (*Amblyomma* spp and *Hyalomma* spp) often create physical damage to the hides of infested cattle and depreciate their value in leather goods. Dermatophilosis, which is favoured by a heavy infestation of the tick *Amblyomma* spp, leads to a total degradation of the quality of the hide (Güney et al., 1993; Stachurski, 2000; Samuel, 2018; Zannou et al., 2021). Even if it gives an idea on the economic impacts of TTBD in West Africa, this study would be more complete if seasonality of circulating tick species were considered. Data on the relative abundance and seasonality of each tick species would allow for an analysis of the economic impact based on which species cause the most damage to livestock and at what time. This will allow a spatial and temporal analysis of the cost/benefit ratio.

5. CONCLUSION

Ticks and TBD are major constraints to livestock production on all continents and particularly in Africa, where they cause significant economic damage. The economic losses are found in several domains of production, notably milk and meat, and sometimes result in the death of animals. The epidemiology of the transmitted diseases is complicated by the multiple agents involved in the process, namely, ticks, their hosts and concerned pathogens. Understanding the epidemiology of these diseases is essential for the development of locally appropriate preventive/control programs. A good knowledge of the particularities of each study area coupled with an appropriate cost-benefit analysis guide the choice of appropriate control strategies. The present study showed that acaricide treatments and preventive treatments against TBD were economically beneficial to farmers. These treatments allowed farmers to significantly reduce economic losses compared to the situation where no treatment was applied. It is therefore very timely and relevant to do these treatments. It is worth to remind that Burkina Faso and Benin are developing countries and the type of livestock farming practised by the majority of the farmers in these two countries is essentially extensive. It is thus important to find low-cost control strategies that are financially accessible to the stakeholders in the livestock farming subsector. The strategies adopted for the control of the various ticks and TBD present will be subject to regular evaluation and readjustment according to the evolution of the epidemiological situation. The development of a control strategy should be participatory for all stakeholders from the design to the implementation stage.

Awareness raising and training of all stakeholders should be carried out to ensure its acceptability and proper implementation. This study, based on evidence-based data, is of prime importance to promote prevention/control of ticks and TBD for both farmers, decision-makers and (inter-)national organisations.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ETHICS STATEMENT

The activities of the research project "Support to epidemio-surveillance networks for animal diseases and associated sociological aspects in West Africa (Acronym: TransTicks)" was approved by the Ethics Committee of the International Centre for Research and Development on Livestock in Sub-humid Zones (CIRDES) (Ref. 001-02/2017/CE-CIRDES) under the strict respect of the protocol submitted to the members of the Committee and their unannounced control.

AUTHOR CONTRIBUTIONS

Conceptualization, O.M.Z., A.B., K.P.Y., L.L. and C.S.; methodology, O.M.Z. and C.S.; software, O.M.Z. and C.S.; validation, O.M.Z. and C.S; formal analysis, O.M.Z.; investigation, O.M.Z. and A.S.O.; resources, A.B. and C.S.; data curation, O.M.Z and C.S.; writing—original draft preparation, O.M.Z.; writing—review and editing, all; visualization, O.M.Z. and C.S.; supervision, A.B., S.F. and C.S.; project administration, C.S. All authors have read and agreed to the published version of the manuscript.

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Appendix S1: Clinical and economic impact of ticks and tick-borne diseases in a cattle herd

Damages	Production loss	Causes	Quantity	Unit
Milk losses due to ticks in the outbreak	Milk	Ticks	0.75	kg
Cost of milk losses due to ticks in the outbreak	Milk	Ticks	0.50	Euro
Weight loss due to tick in the outbreak	Meat	Ticks	5.07	kg
Cost of weight losses due to ticks in the outbreak	Meat	Ticks	7.77	Euro
Weight loss due to 3 days illness in an outbreak of babesiosis	Meat	TBD	245.01	kg
Cost of weight losses due to 3 days illness in an outbreak of babesiosis	Meat	TBD	375.51	Euro
Weight loss due to 3 days illness in an outbreak of theileriosis	Meat	TBD	22.17	kg
Cost of weight losses due to 3 days illness in an outbreak of theileriosis	Meat	TBD	33.98	Euro
Milk production loss due to 3 days illness in an outbreak of babesiosis	Milk	TBD	39.63	kg
Cost of milk production losses due to 3 days illness in an outbreak of babesiosis	Milk	TBD	26.07	Euro
Milk production loss due to 3 days illness in an outbreak of theileriosis	Milk	TBD	12.36	kg
Cost of milk production losses due to 3 days illness in an outbreak of theileriosis	Milk	TBD	8.13	Euro
Total milk losses due to TTBD in the outbreak	Milk and meat	TTBD	52.74	kg
Total weight losses due to TTBD in the outbreak	Milk and meat	TTBD	723.31	kg
Total mortality due to TBD per outbreak	Milk and meat	TTBD	1.70	Heads
Cost of mortality due to TBD per outbreak	Milk and meat	TTBD	479.51	Euro
Total cost of one year TTBD infestation in one outbreak	Milk and meat	TTBD	931.46	Euro
Cost of acaricidal treatment of one outbreak (Third of animals)	Milk and meat	TTBD	32.73	Euro
Cost of acaricidal treatment of one outbreak (Half of animals)	Milk and meat	TTBD	49.10	Euro
Cost of acaricidal treatment of one outbreak (All of animals)	Milk and meat	TTBD	98.20	Euro
Cost of one year TBD preventive treatment in an outbreak	Milk and meat	TTBD	616.99	Euro
Cost of one year TTBD treatment in an outbreak (Third of animals with acaricides)	Milk and meat	TTBD	649.72	Euro
Cost of one year TTBD treatment in an outbreak (Half of animals with acaricides)	Milk and meat	TTBD	666.09	Euro
Cost of one year TTBD treatment in an outbreak (All of animals with acaricides)	Milk and meat	TTBD	715.19	Euro

Legend: TBD: Tick-borne diseases, TTBD Ticks and tick-borne diseases.

General discussion, conclusions and perspectives

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General discussion and perspectives

This thesis aims to contribute to reducing the impact of tick-borne diseases by modelling the habitat suitability of an invasive tick species (*Rhipicephalus microplus*). To achieve this goal, it was important to take stock of the different types of models developed to date in the field of ticks and tick-borne diseases. It was also essential to assess the knowledge of cattle farmers about ticks and tick-borne diseases and the various strategies they currently use to curb these constraints. It is also useful to identify the social strata that own cattle in the area and the problems of acaricide resistance that they encounter in tick prevention/control. This information is crucial for the development of possible adapted and acceptable prevention/control strategies against ticks and tick-borne diseases. Secondly, it was necessary to evaluate the economic impact of ticks and associated diseases on the cattle industry in the study area. All studies in this thesis have therefore provided quite relevant and useful information for the development of prevention/control strategies for ticks and tick-borne diseases in the study area in particular and in the West African sub-region in general.

Ticks and tick damage perception among sedentary and transhumant pastoralists in Burkina Faso and Benin

According to study 1, the majority of livestock in the area is owned by the Fulani, whose main activity is livestock breeding. The most common form of livestock production is extensive pastoralism and transhumance. Cattle holders are fairly familiar with the different tick genera, except for the genus *Rhipicephalus*, and most use amitraz as their main acaricide for tick control. They do not have a clear understanding of TBD but still attribute some damage to ticks such as certain dermatoses and cow teat losses.

The Fulani are known to be good pastoralists and manager of ruminant livestock. According to Stenning (1959), there are three categories of Fulani that are distinguished by their way of life. These are the Pastoral Fulani, the Semi-sedentary Fulani and the Sedentary Fulani. The Fulani found in our study area are essentially semi-sedentary. The common characteristic of the semi-sedentary Fulani is the division of the household and the herd. The head of the household stays in the area considered as the house, where the farm is located, sometimes keeping a small herd of dairy cows. His sons, married or not, take the herd away from the home area during the dry or rainy season. They return to the locality, however, to help with ploughing and harvesting activities. Herding is an ancestral practice in this ethnic group that populates most of West Africa. The Fulani pastoralists live on dairy products. Surpluses are sold or exchanged for grain in the markets of the farming villages. In the dry season, the herds are dispersed to the south in response to the scarcity of pasture and water and reassembled in the north to avoid tsetse flies in the rainy season (Stenning, 1959). This accounts for the extensive livestock farming practised by most of the area's farmers. Pastoralism can be defined as a subsistence technique that uses the domestic animal as a primary consumer, with pastoralists living off the products of livestock. The human groups that obey this character are therefore theoretically absent from any other activity, especially agriculture (Retaillé, 2003). The vast majority of Fulani in our study area have livestock as their primary activity and practice pastoralism. This type of breeding, including transhumance, although an adaptation to difficult conditions for sedentary breeding, represents a constraint for the control of animal diseases. Indeed, the uncontrolled movement of animals does not facilitate the eradication of certain transboundary diseases and thus contributes to their dissemination in areas where they were absent. This is also the case of ectoparasites such as ticks, which are vectors of several pathogens that cause damage to cattle. Although farmers do not seem to be very familiar with the various pathogens transmitted by ticks, they are nevertheless aware of the direct visible damage that ticks can cause. Many have reported such damage as dermatitis, skin wounds and teat loss by cows due to ticks. Long-rostrum ticks such as *Amblyomma* and *Hyalomma* found in clusters on certain parts of the cattle's body create physical damage such as sores or dermatitis. These wounds can become infected or lead to myiasis. If they are found on the udders or udder quarters of cows, they lead to deterioration of the teats and therefore to a reduction in milk production.

The social group that owns the livestock in the area is known for its practice of transhumance as the main mode of breeding. It seems very important to sedentarise the Fulani cattle holders where it is possible by facilitating their access to land and by promoting the integration of livestock and agriculture. Access to land for the Fulani is often very difficult because they are rightly or wrongly considered as an alien population by the indigenous population and because of their nomadic culture. Sometimes when land is allocated to them in certain localities, after a certain period the farmers again have access to these plots, which are now very rich because of the manure. Conflicts, therefore, arise from this desire to dislodge the cattle holders after several years on these lands. Good and concerted management of the land could optimise the yields of each party through the rotation between farmers and cattle holders on these plots.

On the cultural level, the majority of transhumant being of the Muslim religion, they proceed to the spiritual preparation of the shepherds and the herd before the departure. Practical advice is given to novice herdsmen regarding good manners and politeness, vigilance during the crossing, criteria for choosing a host in the arrival area, etc. Amulets are made by the marabouts to protect the herd from predators such as wild animals (Zina, 2017).

The very low level of schooling observed among Fulani cattle holders is explained by the fact that at a very young age, the little boy begins by following his brothers in driving the cattle to the pasture. This does not allow him to attend school. When he grows up and reaches the age of marriage, his father gives him a part of the herd to make it his capital and source of income to sustain his family. This community being very Islamic, there is a higher attendance in Koranic schools. In a situation of permanent mobility of people and animals, the schooling of children is quite complicated. This low level of schooling affects the ability of pastoralists to acquire certain modern skills and may increase their level of ignorance of new technologies developed in the field of animal husbandry. The diagnosis of the very low level of literacy among livestock farmers is indicative of their behaviour in herd management and animal health care. Overdosing, underdosing and the non-respect of withdrawal periods are frequent among these farmers. The lack of schooling among farmers leads to an inability to read the instructions for veterinary products and therefore to poor use of these products. This bad behaviour harms tick and tick-borne disease control by creating resistant species in the case of frequent overdosing and underdosing of acaricides and public health problems in the case of non-compliance with waiting periods. This illiteracy results in reduced access to information. During conflicts between farmers and cattle holders, it is not rare to find that the rights of some are violated in the management of these crises. This is often due to a lack of knowledge of their rights because they are unable to read and write. Sometimes the language barrier affects the collaboration between the cattle holder and his veterinarian. Illiteracy also reduces access to livestock training. This information on the very low level of literacy among livestock keepers will therefore be used by the authorities to develop messages and training adapted to the quality of this particular target. The acaricide most commonly used by farmers to control ticks is amitraz, and supply is mainly from the unregulated market, where products are stored in unsuitable conditions. This molecule, although effective on most tick species found in the study area, has proven ineffective against the invasive tick *R. microplus*. In addition, the practices observed show that farmers very often overdose on this product to obtain the desired effect. The storage conditions, the doubtful origin and quality as well as the resistance of *R. microplus* to this molecule can explain the overdoses observed in the use of this product by the breeders. These practices (overdosing, underdosing and poor quality) may also lead to the appearance of resistance in other tick species that were previously sensitive to it. Study 1 revealed that 84% of the farmers overdose the most commonly used acaricide "amitraz" while 5% of them underdose. Overdosing amitraz may have its source in the ineffectiveness of the product leading the cattle holders to increase the recommended dosage. The conditions of storage of the products and their origins could be the sources of these problems. This practice could have been a major public health problem if amitraz had residue in milk and meat. According to De Meneghi's work (De Meneghi et al., 2016), amitraz does not have fortunately residues in meat and milk and the method of application of this acaricide (bashing) prevents direct contamination of milk. It should be noted that about 4% of the acaricides identified were based on Fipronil. Fipronil is an acaricide whose use in livestock farming requires great caution. Fipronil is classified as moderately toxic by the World Health Organisation.

Fipronil is also classified as a possible carcinogen by the US Environmental Protection Agency, but only if a high exposure threshold is reached. The brand found in cattle farmers was contraindicated in cows whose milk was intended for human consumption. It was also contraindicated in pregnant cows three months before calving. These producer recommendations are not always respected by farmers. Self-medication is a serious problem in animal health in West Africa. Farmers only seek veterinary help when they have exhausted several treatment recipes suggested among themselves without success. It is also not uncommon to see cases of administration of antibiotics by non-professional animal health workers. This situation presages serious problems of antibiotic resistance with certain germs. We can also fear public health problems because waiting periods are not always respected before delivering certain animal products for human consumption after treatment of animals with certain veterinary products. These self-medication practices were reported by Zina (2017). During transhumance, veterinary services are often inaccessible to cattle holders in certain localities. Cattle holders, therefore, leave on transhumance with a stock of veterinary products acquired in veterinary pharmacies at the start of the transhumance or on informal markets selling medicines in the localities they visit. It is not uncommon to see therapies based on plants and traditional recipes. Most of the markets in these localities are equipped with stands selling veterinary drugs of dubious origin and inadequate storage conditions. It is also observed that almost all livestock markets have stalls selling veterinary drugs. The West African Economic and Monetary Union (UEMOA) has initiated in recent years actions to fight against the scourge of fake veterinary drugs by training veterinary drug inspectors in its member countries. This fight must be intensified to clean up this environment which is a public health concern. Also, as part of the harmonization of veterinary pharmaceutical legislation, the UEMOA Commission has set up institutional mechanisms, in particular, the Regional Veterinary Medicines Committee (RVMC) and its Permanent Secretariat, the List of Veterinary Medicines Experts (LEMV) and the Veterinary Committee. This harmonization, framed by community legal texts, made it possible, starting in 2006, to set up a centralized system of marketing authorization for veterinary drugs (MA) under the responsibility of the UEMOA Commission, which is now the only body authorized to issue MA (http://infoveterinaire.uemoa.int). However, it must be noted that unlicensed veterinary products continue to circulate on the markets of Benin and Burkina Faso through smuggling.

The importance of this study lies in the fact that it provided accurate information on the type of farmers in whose hands the cattle are kept, the type of farming practised, their perception of ticks and tick-borne diseases and the practices they use to control these vectors. This information will be used to design prevention/control plans that are adapted, affordable and acceptable to the stakeholders in the cattle industry. These results will help to identify possible bottlenecks in the acceptance of tick control measures. Socio-anthropological approaches will be used to facilitate the acceptance of these prevention/control measures, the development of which must be participatory. One of the most common secondary activities of livestock keepers is farming. This information is important in the sense that it will allow the promotion of agriculture-livestock integration by improving Fulani cattle holders' access to land. The integration of agriculture and livestock will improve the sedentarisation of these cattle holders, which would avoid frequent displacements with all their consequences.

One of the main limitations of this study could be the number of people surveyed, which is only 90 in the study area. It should be noted, however, that despite the small number of livestock farmers surveyed, the distribution over the entire study is good enough to provide a good picture of the situation studied.

Another limitation is that veterinary officers were not surveyed to assess their knowledge of ticks and TBD and the difficulties they encounter in their work. Other actors in the livestock sub-sector could also have been surveyed, including suppliers of veterinary products, etc.

Transhumance corridors through Benin used by cattle herds from Burkina Faso and associated risk scoring regarding the invasion of *R. microplus*

One of the main ways of raising cattle in West Africa is pastoralism, including transhumance. This practice presents many problems despite some advantages. In the context of the regular and cyclical movement of animals, it is difficult to implement certain strategies for controlling animal diseases. This practice also contributes to the dissemination of pathogens and vectors in areas where they were not previously reported. Extensive cattle raising strategy do not allow animals to have the best zootechnical performance (meat and milk production). Indeed, the purpose of study 2 was to identify, first, the corridors and grazing areas used by transhumant herds from Burkina Faso to Benin; second, the characteristics of the departure and arrival areas for transhumance; and third, to develop a risk score related to the introduction and spread of the invasive tick, *R. microplus*, in free-ranging areas.

Drastic conditions during the dry season, notably the drying up of water points and the scarcity of grazing, force the Sahelian herds to descend to the coastal countries. These coastal countries still have forage and watering points for their herds during this period. Moreover, the climatic conditions in these countries are reputed to be more favourable to vectors than those in the Sahel (Hoste, 1992).

Some ecological conditions are essential for the survival of species in an area according to its specificities. Ticks are non-permanent parasites that during their life cycle have free stages they spend outside their hosts in nature. This free life in nature is only possible if certain conditions are met. Among these conditions, we can mention humidity, temperature, vegetation etc. Some ticks can live in warm environments while others can survive in cold environments. In many studies, *R. microplus* was described as a tick that prefers warm and humid environments (Estrada-Peña et al., 2006b). The tick was found in northern Benin and not yet in western Burkina. Northern Benin is more watered then more humid and cooler than eastern Burkina (Fadika et al., 2019). The presence of the tick was positively correlated with rainfall but negatively correlated with temperature. The *R. microplus* tick, therefore, prefers environments that are neither too hot nor too dry. However, it should be noted that the eastern part of Burkina Faso has climatic conditions that are not very hostile to the tick in terms of temperature and rainfall. The frequent and regular movements between the east of Burkina Faso and the north of

Benin may favour the displacement of the tick by its specific host, cattle, in areas where it is not yet found. The acarological survey implemented during this study revealed that Burkina Faso transhumant herds were infested by *R. microplus* during their stay in Benin. There was a real risk of importation of ticks into eastern Burkina Faso by these herds. This must have happened several times already, but it remains to be checked whether the process of its installation is possible in this new environment. Further investigations are therefore needed to elucidate this situation. The same situation happened in the western region of Burkina Faso where *R. microplus* was imported by transhumant herds from the north of the Ivory Coast (Adakal et al., 2013). During the transhumance, hundreds of herds from different regions and of different health status meet on pastures, water points, and livestock markets (Jori et al., 2021). These different meeting places of thousands of animals constitute hotspots for contagious and transboundary diseases such as foot and mouth disease, contagious bovine pleuropneumonia, nodular lymphatic disease, tuberculosis, lumpy skin disease, etc. Benin still facing Anthrax outbreaks these last ten years (Anonyme, 2018). The department of Atacora, which is one of the areas of destination of Burkina Faso transhumant herds, is also known for its cursed fields (the site of anthrax contamination). Anthrax bacteria (*Bacillus anthracis*) are known to sporulate when environmental conditions are poor and to remain there for several years while waiting for better conditions. It's responsible for deadly infection in animals and human when contaminated and untreated (Carlson et al., 2019). Indeed, cattle from Burkina Faso that come to stay in this department during transhumance could go back to their place of residence with anthrax infection.

The Pendjari Park, which is a wildlife reserve in Benin, is a place where live many wild ruminants, including buffaloes and gazelles (Sinsin et al., 2002). This area, which remains greener than the surrounding region during the dry season, attracts many transhumant cattle holders who stay there despite the ban. The risk score for *R. microplus* is not negligible in this area. The frequent stays of cattle in this area, which is normally reserved for wild animals, may favour exchanges of pathogens and vectors between wild and domestic animals. Benin has invested a lot of money in the renovation of Pendjari Park through a collaboration with "African Parks" since 2017. The Pendjari Park today represents one of the last strongholds for the 1,700 elephants in the region and 25% of the remaining 400 critically endangered lions in West Africa. There are several species of antelope, a population of cheetahs and over 460 bird species. Frequent intrusions by cattle holders with their animals could ruin all these efforts. *R. microplus* although being a cattle specific tick would use other wild animals such as wild carnivores, deer and Oryx as alternative hosts. This possibility of infestations of wild animals represents a rather serious risk for the wildlife of the Pendjari Park. It should also be noted that some wild ruminants are reservoirs for certain germs that are highly pathogenic for domestic animals. The African Buffalo (*Syncerus caffer*) was listed among the wild mammals in the Pendjari National Park. This wild ruminant is known to be a reservoir host to many pathogens responsible for economically important livestock diseases. Several livestock tick-borne diseases (theileriosis, heartwater, babesiosis and anaplasmosis) have been cited among these diseases (Eygelaar et al., 2015). Therefore, contact with domestic animals can severely affect their health and thus their production. Another example is the foot and mouth disease virus, which is a real problem for domestic ruminant farming in West Africa. Control programs have been implemented for several years without success. In recent years, hopes have been pinned on a vaccine developed in Botswana, which is quite expensive for farmers without government subsidy (Letshwenyo et al., 2004). All these efforts will only be successful if uncontrolled livestock movements and frequent contact between domestic and wild fauna are avoided.

The risk score model developed in this study could be further improved and strengthened by adding other variables such as "interaction between tick species" and "vaccination parks". These data could not be collected over the entire study area before the end of the study. Vaccination parks, as well as grazing areas and livestock markets, are meeting points for many herds and can facilitate the sharing of pathogens and parasites. Even if animals do not meet in these areas, they may infest these areas during their short stay and other animals may be infected later when they pass through as well. A study has shown that the presence and abundance of native tick species can increase the presence and abundance of the invasive tick (Biguezoton et al., 2016a). These parameters should also be taken into account to improve the model in the future. The model should be implemented in larger areas than our study area (e.g. West Africa) and externally validated with *Rhipicephalus microplus* presence/absence data collected in the mentioned areas.

Habitat suitability for the invasive tick *R. microplus* in West Africa

Before modelling the habitat suitability of the invasive tick *R. microplus*, it was important to first review the state of the art on modelling tick dispersal and tick-borne diseases with a focus on Africa. Therefore, in the framework of Study 3, a literature search allowed us to identify all articles that have developed a mathematical model to show the distribution of ticks and tick-borne diseases. This allowed us to highlight the different types of models most commonly used and most appropriate to the context of the study area.

Study 4 aimed to highlight the extent of the spread of *R. microplus* in West Africa today and to show to what extent the West African environment is adapted to the habitat of the *R. microplus* tick through habitat suitability models.
Seven variables were selected including the annual average rainfall, the annual average temperature, the annual average vegetation index, the density of the tick's host cattle and the landcover variables (cropland, grassland and shrubland). Six models were used. One in single modelling (MaxEnt) and five (GLM, GAM, RF, BRT and SVM) in an ensemble modelling. The selected models showed good performance (AUC, TSS and BI) in their evaluation.

These models had the particularity to investigate the importance of other predictors such as landcover predictors in the distribution of *R. microplus* in the environment. Thus, in addition to showing that *R. microplus* is more present in wetter and less warm areas and where host density is lower, study 4 also revealed that the tick is also more present in areas where crops and grasses are scarce and shrubs are more present.

Humidity and temperature are important factors in tick biology. The development and mortality of ticks are strongly influenced by these two factors (Estrada-Peña et al., 2015a). The results obtained by this study concerning climate predictors have already been obtained on a smaller scale by De Clercq et al., (2015) in Benin and Zannou et al., (2020) in Burkina and Benin in 2020. Climatic factors are crucial in the establishment of *R. microplus* in an environment and its overall distribution. Changes in these factors (e.g. climate change) may also influence the abundance of this species in the environment in which it is already established and consequently the prevalence of pathogens transmitted by these vectors (Estrada-Peña et al., 2006a; Marques et al., 2020). These changes may also increase or decrease the environments favourable to the tick. It should be noted that this tick could also develop an adaptation to climate change given its already known invasive and acaricide-resistant character. Predictions on these possible changes in the distribution of *R. microplus* can help competent authorities to anticipate control measures. The vegetation index is an important variable in that it provides information on the presence and quality of vegetation. When it is known that ticks spend almost 80-90% of their life off-host, vegetation appears to be very important in its life cycle (Leal et al., 2018; Zamora et al., 2020). Previous work had also shown the importance of the NDVI on a smaller scale (Benin and Burkina) (De Clercq et al., 2015; Zannou et al., 2021a). The tick was more often found in areas where there are few crops with many shrubs. The out-of-host stage is a stage of the high vulnerability of the tick. During this phase, the engorged female seeks a moist and not very warm and covered place to lay her eggs and allow them to incubate and hatch in good conditions. Vegetation plays a big role in this process as it provides shelter for the female to lay her eggs (Pérez de Leon et al., 2012). After hatching, the larvae need vegetation to lie in wait to find the host to continue the cycle. This phase is also critical because if it takes place in a sunny environment the eggs and then the larvae risk desiccation. Areas with shrubs are ideal as they provide shade for the eggs and larvae and avoid high mortality due to sunlight (Leal et al., 2018; Zamora et al., 2020). Cultivated areas are areas of high human activity where the soil is regularly disturbed following regular weeding as part of fieldwork. These regular human interventions are likely to disrupt any nesting of the gorged females or the peaceful incubation of eggs for the production of *R. microplus* larvae. Crops also have pests that constrain their proper development and the production of good crop yields. To control these pests, chemical pesticides are regularly applied to crop fields and consequently to the environment. Ticks (non-host stages) present in these environments are killed along with the plant pests. West Africa is also an area where herbicide use is very common, especially in cotton cultivation. These chemicals affect the arthropod populations that remain on the ground during their application

(Mohammed et al., 2017). Cattle in West Africa are more concentrated in the Sahel countries, which are less watered and warmer. As the tick is more inclined to areas with more water and less heat, a negative correlation between these two variables appears. The specific aptitudes of the two areas seem clearly defined. The Sahelian countries have more favourable conditions for extensive cattle and small ruminant production, while the coastal countries seem to be more suited to short-cycle livestock production. Inputs for short-cycle livestock and non-conventional species are relatively abundant and more accessible in coastal countries (e.g. Côte d'Ivoire, Ghana and Nigeria, Benin). Parasite pressure is greater in coastal countries (more favourable conditions for plagues) than in Sahelian countries. This situation also contributes to the distribution of ruminants in the Sahel and West Africa region (Kamuanga et al., 2008). Nevertheless, the frequent and periodic movements of herds between these two ecosystems enabled by transhumance should be considered. Indeed, at a certain time of the year (dry season), herds in search of pasture and water are forced to descend into areas that are still wet at that time and therefore heavily infested by ticks (Zannou et al., 2021a). These regular movements and stays expose the animals to *R. microplus* and the main pathogen it transmits, which is *Babesia bovis* and *Babesia bigemina*. These pathogens are responsible for extensive production losses (Jonsson, 2006; Waldron and Jorgensen, 1999).

The habitat suitability maps revealed that coastal countries of West Africa have better habitat suitability for the tick than Sahelian countries. This suitability decreases as one moves away from the coast towards the Sahel. This trend is similar to the one observed in De Clercq's study implemented in only Benin country (De Clercq et al., 2015). This previous *R. microplus* distribution modelling used occurrences data from 2011 and showed that the habitat suitability decrease from the South to the North of the country. Recent works have revealed the presence of the tick in some areas in the North of Benin where it was absent during the work of De Clercq et al. (2015). Therefore, the present work has taken into account presence data from several countries, compared to De Clercq's work in 2015, which only took into account presence data from Benin. Indeed, it is worth stressing the fact that this work used more data and different predictors compared to this previous study. The climatic conditions become less and less suitable for the tick the further away from the equator one gets in West Africa. Sahel countries are drier and hotter than coastal countries. Moreover, the vegetation is less developed there. Despite the higher density of cattle in the Sahel, the off-host life will be difficult for the tick because of the unfavourable climatic conditions. The ensemble model seems to predict a stronger fit of some Sahelian areas to the tick than the other two models. Ensemble models are very useful in the risk analysis of recently introduced invasive nuisance species, as they may not yet have spread to all suitable habitats, making species-environment relationships difficult to establish. Ensemble species distribution models are very interesting in that they combine the strengths of several environmental species matching models while minimising the weaknesses of any one model (Abrahms et al., 2019; Stohlgren et al., 2010). According to the ensemble model, the risk of having the tick in some parts of the Sahel is not negligible.

In some Sahelian countries, there are areas such as permanent water points that could provide conditions for the tick to establish itself, especially when the species is known to be highly invasive and adaptive. The valleys of perennial rivers also represent biotopes that can favour the emergence of the tick as they are very frequented during the dry season by herds in search of water and pasture. These biotopes exist in parts of the Sahel.

The importance of this study is that it provides a broader view of habitat suitability for *R. microplus*. It allows decision-makers in West African countries to have a better idea of the level of suitability of their area for the invasive tick. It is a tool to identify areas where the particular emphasis should be placed on raising awareness among livestock stakeholders. In areas that are favourable to the tick and not yet infested, emphasis should be placed on measures to prevent its introduction. In suitable areas where the tick has already established itself, it will be necessary to raise awareness of the measures to be taken to limit its spread and eventually its eradication. This study will serve as a tool to assist in the development of sub-regional and local control plans to ultimately control the *R. microplus* tick and consequently the pathogens it transmits. The direct consequence is the improvement of food security as the cattle herd will be rid of the vectors and parasites that were negatively impacting its development. Good knowledge of the high or low-risk areas for the establishment of ticks allows for careful management of the financial resources dedicated to vector control and their pathogens.

Economic impact of ticks' infestation in two West African countries (Benin and Burkina Faso) cattle herds

The objective of study 5 was, in addition to highlighting the cattle population at risk from ticks and tick-borne diseases, to assess the economic impact of these ticks on farmers in the area. Estimating this impact is of primary importance and should help raise awareness among all stakeholders to engage them in the implementation of prevention/control strategies against ticks and TBD.

A study by (Ouedraogo et al., 2021) showed that all investigated municipalities in the eastern region of Burkina and northern Benin were infested with ticks but to varying degrees. The distribution of cattle that are hosts to ticks also shows that the herd at risk of tick infestation and tick-borne diseases. This herd is not negligible and is spread evenly throughout the communes of the study area. The simultaneous presence of ticks (obligate parasites) and their hosts in the same environment allows the development of the ticks' life cycle and their multiplication. If nothing is done to break this parasite-host cycle, the consequences will be disastrous given the damage that ticks cause to livestock.

A deterministic model was performed to estimate the economic impact of ticks and tick-borne diseases and to analyse the benefit of treatment strategies. The model was developed both with data collected in the field and with data already published in other papers.

Tick-borne diseases, therefore, cause more economic damage than ticks directly. The same is true for milk production losses. Even if the cost of milk production losses is not very high compared to the losses due to mortality and meat production, it can be seen that they are more due to tick-borne diseases than to ticks directly. It should be noted that these losses are underestimated because several variables have not been taken into account in the model due to a lack of data. These include, for example, teat losses. Teat loss results from the mechanical effect of the long rostrum of the ticks which creates wounds in the udder. These wounds become infected and lead to the loss of one or more udder quarters, resulting in reduced milk production.

Overall the economic losses caused by ticks and tick-borne diseases in a herd during a year amount to about 931 euro. This loss per herd was higher than the average GDP per capita in the two countries (Benin and Burkina) for the year 2019, which amounts to 825 euros (World Bank and OECD, 2019). A loss of this value is very important in an area where the economy is based on the primary sector in general and livestock and agriculture in particular.

This situation calls for a strategy based on a control programme for ticks and TBD. In addition, an epidemiological survey in the area revealed a lack of national strategies for the control of ticks and TBD diseases in both countries. Overall, farmers have individual strategies depending on the acaricides and pathogen control products available on the market (veterinary pharmacy and black market) (Zannou et al., 2021b).

Following the different strategies identified in the field and according to the recommendations of the different veterinary drug producers, we have developed six control scenarios against either ticks alone or ticks and pathogens.

These six scenarios range from treating only one-third of the herd with acaricide to treating the entire herd plus a preventive treatment against transmitted diseases. The treatment becomes more expensive when going from the one-third of the herd scenario to the full treatment. However, the ratio of production loss to treatment cost in each scenario is always greater than one. This information claims for a benefit to treating animals. It remains to find the right strategy adapted to each environment depending on the ticks and pathogens present.

Since ticks are vectors of pathogens, good tick control directly involves pathogen control. An experiment should be conducted to validate the scenario that will allow the control of all tick species present in the area to hope to control the transmitted pathogens at the same time. In the case of this study, the scenario in which the whole herd is treated with acaricides only seems very interesting. It remains to experiment with its validation. Epidemiologically, eliminating vectors stops the transmission of vector-borne diseases. There is no need to spend financial resources on the treatment or prevention of vector-borne diseases as long as the vectors responsible are well controlled in this environment.

The other challenge is the availability and quality of acaricides and pathogen control products. Effective acaricides against the species present in the area are crucial for successful tick control. It should be noted that the tick *R. microplus* is the main vector of *Babesia bovis* and *Babesia bigemina*. However, this tick is described in several works as resistant to the most widely used acaricides. Our survey in the area revealed that to get around the difficulty of resistance of this species or the effectiveness of the products available, some farmers frequently overdose. This practice undoubtedly leads to additional costs for acaricide treatment. The issue of the effectiveness of acaricides against the tick species present in the area remains. The acaricides found on the informal markets are not registered and therefore do not have marketing authorisation. Their entry and distribution channels are informal and totally outside the control of the authorities. It is a very flourishing trade for the actors involved, but very dangerous for animal and public health. These products are of dubious quality and origin. As most of them have shown their ineffectiveness on *R. microplus*, the problem of this species does not yet seem to have found a solution. In areas of high *R. microplus* infestation, it would be advisable to combine acaricide treatment with a preventive treatment against babesiosis. This option is included in scenarios 4, 5 and 6 of the model.

Study 5 did not take into account the preventive treatment of *Theileria annulata* because this strategy does not yet exist in the study area. The control of this pathogen could be achieved by good control of its vectors which are the ticks of the genus *Hyalomma spp* (Gharbi, 2006; Gharbi and Darghouth, 2015). These tick species have not yet shown a particular resistance to the acaricides used in the area. Chemotherapy with theilericides is also available for *T. annulata* infection but is globally expensive (about 33$ for parvaquone and buparvaquone based products). It should be noted that there is a 12% failure rate with a risk of mortality due to post-treatment complications (Gharbi and Darghouth, 2015). This type of treatment cannot be recommended in the context of livestock farming in the study area.

Other limits of study 5 are the unavailability of data on losses due to leather depreciation caused by tick damage. Heavy infestations of long-rostrum ticks (*Amblyomma spp* and *Hyalomma spp*) often create physical damage to the hides of infested cattle and depreciate their value in leather goods. Dermatophilosis, which is favoured by a heavy infestation of the tick *Amblyomma spp*, leads to total degradation of the quality of the hide (Güney et al., 1993; Samuel, 2018; Stachurski, 2000). Cattle skin is highly valued in cooking in this area. This skin is also used in leather goods.

In perspective, data on the relative abundance and seasonality of each tick species could allow for an analysis of the economic impact based on which species cause the most damage to livestock and at what time. This will allow spatial and temporal analysis of the cost/benefit ratio.

Conclusions and recommandations

The main objective of this thesis was to contribute to the control of the incidence of vector-borne diseases, particularly tick-borne diseases. This objective was achieved by taking stock of the different models used to model the dispersal of ticks and tick-borne diseases, and the knowledge of farmers about ticks and tick-borne diseases and the current practices in the area concerning their control. The aim was also to characterise the different transhumance corridors used by Burkinabe transhumant and to develop a risk score model for the invasive tick *R. microplus* in the area. Moreover, a model of the suitability of the West African environment for the *R. microplus* tick was developed and the economic impact of a herd's infestation by ticks was assessed using a deterministic model.

The socio-epidemiological survey revealed that the majority of cattle holders are Fulani and people from this social group are the principal managers of the herds of the two countries involved in the study. This study enabled us to better understand the perception of cattle holders about ticks and tick-related damages on cattle. Cattle breeders demonstrated a high level of awareness on the seasonal tick abundance and their main visible effects on cattle such as dermatosis, wounds and teat losses. Tick-borne diseases did not appear to be well known by breeders. Therefore, sensitization campaigns are needed especially on the various diseases transmitted by ticks and the available and suitable treatments. This is very important because there are some zoonoses transmitted by ticks (Crimean-Congo haemorrhagic fever; ehrlichiosis; babesiosis and rickettsioses) that can represent a real hazard to the cattle cattle holders. The survey also permitted us to appreciate the way the cattle holders managed and controlled tick infestations in their herds. The principal active substance in the acaricides currently used to control the tick infestations in the cattle herds in the study area is amitraz. The majority of the cattle holders do not respect the dosage of acaricides when they use them. Unfortunately, more than 50% of the acaricides used are provided by the unregulated market, where good quality is not guaranteed. This highlights a serious problem of the sources of supply of veterinary drugs and their quality that is one of the sources of ticks' resistance noticed nowadays. This study shows also that transhumance (removing manually ticks on teats are more difficult) is a risk factor to cow's teats losses since cows from Burkina Faso presented more teats losses than those from Benin. Furthermore, the frequent stays of transhumant herds from Burkina Faso in the north of Benin could result in the spread of *R. microplus* in the eastern region of Burkina Faso where this species is not yet found.

The characterisation of the study area showed that Benin has a better vegetation index, temperature and rainfall compared with Burkina Faso even during the dry season. These favourable conditions led to the movement of cattle from Burkina Faso to Benin in the dry season. These transhumant cattle herds use four transhumance corridors during their displacement through Benin. The eastern region of Burkina Faso is not yet known to be infested by *R. microplus*. However, the probability of infestation of animals in this part of Burkina Faso by the invasive tick is not null. Considering its progression in the north of

Benin, cattle movements between the two countries and the suitability of some localities in Burkina Faso bordering Benin, such an event will certainly occur. Frequent intrusions of domestic cattle in the wildlife reserves (Pendjari Park) also represent a high risk of introduction of the invasive tick species in wildlife and pathogen sharing. Among wild animals that live in the park of Pendjari, African Buffaloes are known to be reservoir hosts to many pathogens. Herdsmen should avoid the meeting of their cattle or environment sharing with these animals. A screening of the ticks infesting the potential *Rhipicephalus microplus* host in this reserve is needed.

The habitat suitability modelling for *R. microplus* revealed that all the coastal countries of West Africa are suitable areas for the *R. microplus* tick. The southern region of some Sahelian countries (Mali and Burkina Faso) also seems favourable, but lesser than coastal areas. This modelling with new variables and recent presence data provide a larger view of the suitability of West African areas to the invasive tick *R. microplus*. It would be advisable for the authorities of countries that have not yet detected the tick but are in the risk area to take mitigation measures to prevent its introduction.

Ticks and tick-borne diseases are major constraints to livestock production on all continents and particularly in Africa, where they cause significant economic damage. Economic losses are found in several types of production, notably milk and meat, and sometimes result in the death of animals. Understanding the epidemiology of these diseases is essential for the development of locally appropriate control programs. Good knowledge of the particularities of each area coupled with an appropriate cost-benefit analysis will guide the choice of prevention/control strategies. As Burkina Faso and Benin are developing countries and the type of livestock farming practised by the majority of the farmers in these two countries is essentially extensive, it is important to find low-cost prevention/control strategies that are financially accessible to the stakeholders in the livestock farming subsector. The strategies adopted for the prevention/control of the various ticks and tick-borne diseases present will be subject to regular evaluation and readjustment according to the evolution of the epidemiological situation. The development of a prevention/control strategy should be participatory for all stakeholders from the design to the implementation stage. Awareness-raising and training of all stakeholders should be carried out to ensure its acceptability and proper implementation.

At the end of this thesis we make some recommendations as follows:

For ECOWAS Commission

- Support the countries of the Sahel in the construction, in areas where it is possible, of permanent water points for pastoral purposes to facilitate the watering of livestock in all seasons;
- Promote the integration of agriculture and livestock;
- Promote the development of fodder plots and the local manufacture of livestock feed (silage, hay, etc.) by livestock farmers and train them to do so;

- Facilitate secure access to land for all communities, particularly the Fulani community, who are often considered as non-native populations in some areas;
- Train more veterinary drug inspectors for each country and strengthen the regional fight against fake medicines;
- Promote a better schooling rate for cattle holders to reduce the level of illiteracy of this community in the sub-region to improve herd management.

For research centres

- Investigate the distribution of native ticks of the subgenus Boophilus in West Africa and model their future distribution concerning climate change;
- Study the future distribution of *R. microplus* in West Africa concerning climate change;
- Develop tick and tick-borne diseases prevention/control strategies according to the global context of the region, the particularities of the countries with or without infestations and with or without suitable habitats for the different tick species;
- Stimulate socio-anthropological approaches to facilitate the acceptance of prevention/control measures by local veterinarians and cattle holders;
- Develop, validate and disseminate validated treatment protocols against ticks and tick-borne diseases.

For veterinary services

- Regularly train agents in the identification of the different tick species potentially present in the sub-region;
- Strengthen the diagnostic capacities of laboratories in terms of ticks and tick-borne diseases;
- Strengthen the network of veterinary surgeries and pharmacies to make accessible and affordable veterinary products and services to livestock farmers;
- Organise regular awareness-raising sessions for livestock farmers on the subject of ticks and tick-borne diseases;
- Develop an awareness campaign on ticks and TBDs taking into account the sociological context of the actors involved in livestock management in West Africa;
- Record all animal encounter points (livestock market, water point, vaccination park, dip tanks, transhumance corridor and transhumance grazing area) to improve the tick risk score map;
- Strengthen health checks on the departure and return of transhumant herds for the early detection of new vectors and diseases introductions;
- Train veterinarians in social relations with the Fulani to improve their intervention in this community of herders.

For livestock farmers

- Respect the dosage of acaricide products and avoid under- and overdosing, which could lead to resistance or, in the case of overdosing, to health problems if the withdrawal periods are not respected;
- Buy acaricide products from veterinary pharmacies and approved pharmaceutical stores;
- Avoid self-medication and use the services of a veterinary professional for all animal care;
- Respect the time limits for reapplication of acaricides as indicated by the veterinarian;
- Apply quarantine measures to new animals to avoid the introduction of vectors and pathogens;
- Avoid areas of high tick infestation by contacting the relevant veterinary services;
- Have the herd monitored by a veterinarian and strictly follow the acaricide treatment protocol established by the competent authorities.

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Appendix

S1. Survey questionnaire

Perception - Resistance to acaricides - Role of transhumance in the spread of ticks and tick-borne disease

ID: |__|__|__|-|__|__| Investigator name: ……………………………………

Date: |__|__|- |__|__|-|__|__| Investigator phone number: ____________________________

I – General Information

I.1. Identification of the farm

Region:…………………………. Department: ………………………………..

Province/Municipality:…………….………. Village: ……………………………..……..

Geographical coordinates (dd):

Latitude : |__| |__|__|,|__|__|__|__|__|

Longitude : |__| |__|__|__|,|__|__|__|__|__|

Altitude : |__|__|__| m

I.2. Identification of the responsible

I.2.1 Herder's name: …………………………………………………………………………

Social group: ………………….Sex: Male ☐ Female ☐ Age: |__|__|

Principale activity: Agriculture ☐ ; Breeding ☐ ; Other, specify ☐…………….

Secondary activities : ………………………………………………….……………………

Phone number: +|__|__|__| - |__|__|__|__|__|__|__|__| ; +|__|__|__| - |__|__|__|__|__|__|__|__|

Breeding experience : ……………Years

Level of education: None ☐ ; Koranic school ☐ ; Primary ☐ ; Secondary and more ☐

I.2.2. Manager's name: ………………………………………………………………………

Social group: …………………Relationship herder-manager: …………………………….

Sex: Male ☐ Female ☐ Age: |__|__|

Principal activity: Agriculture ☐ Breeding ☐ Other, specify ☐…………….

Secondary activities : ……………………..………………………

Phone number: +|__|__|__| - |__|__|__|__|__|__|__|__| ; +|__|__|__| - |__|__|__|__|__|__|__|__|

Breeding experience: ……Years ; Seniority in the holding: ……Years

Level of education: None ☐ Koranic school ☐ Primary ☐ Secondary and more ☐

I.2.3. Cowherd's name: ……………………Relationship cowherd-herder: ……………….

Social group: Fulani ☐ Mossi ☐ Other, specify ☐ ....

Paid ☐ Family management ☐

Phone: +|__|__|__| - |__|__|__|__|__|__|__|__| ; +|__|__|__| - |__|__|__|__|__|__|__|__|

Breeding experience : ......Years Seniority in the holding: ......Years

Level of education: None ☐ Koranic school ☐ Primary ☐ Secondary and more ☐

I.3. Information on the herd and the farming method

I.3.1. Herd size: |__|__|__|

I.3.2. Cattle breed (specify *number*)

Bos taurus indicus ☐...... *Bos taurus taurus* ☐...... Cross with *Bos taurus indicus* and *Bos taurus taurus* ☐..... Cross with exotic breed ☐....... Other ☐.........

I.3.3. Other species raised in the farm ?

No ☐ Yes ☐ How many? Sheep|__|__| Goat|__|__| Poultry|__|__| Dog|__|__|other:....|__|__|

I.3.4. When was the last arrival of a new animal in your farm? |__|__|-|__|__|-__|__|__|__|

Origin(specify): ....

I.3.5. Which breed (s) did you introduce ?

N'dama ☐ ; Borgou ☐ ; Lagunaire ☐ ; Somba ☐ ; Mbororo ☐ ; Goudali/Fulani ☐ ; Holstein ☐ ; Girolando ☐ ; Métisse Montbéliard ☐ ; Zébu ☐ ; Crossed breed (specify) ☐ ; Others (specify) ☐ ..../............./............../............../...........

I.3.6. If introducing animals from another country, specify the origin: ....

1.3.7. What is the type of production in your farm?

Milk ☐ ; Meat ☐ ; Milk and meat ☐ ; Leather and skin ☐ ; Other, specify ☐ ....

I.3.8. Infrastructures available

Presence of enclosure: Yes ☐ No ☐

If yes , Wooden park ☐ Park with one or two barded wire ☐ Park with more than two barded wire ☐ Mobile park ☐ ; Fixed park ☐ Covered cowshed ☐ Corridor of contention ☐

I.3.9. Feeding mode:

Free grazing ☐ Private pasture ☐

If there is free grazing, what is the normal time of:

Departure: |__|__|: |__|__| Return: |__|__|: |__|__|

Confinement ☐ Pasture and confinement ☐

In confinement do animals receive a complement?

Yes ☐ No ☐ Pasture rotation ☐

If there are pasture rotations, when do they occur? Rainy season ☐ Dry season☐

I.3.10. Does the flock go for transhumance

No ☐ Yes ☐

If yes, what was the last destination: ………… Intern Trh. ☐ Transboundary Trh. ☐

Month of departure: …………………………………………….

When do you go for transhumance? Rainy season ☐ Dry season ☐ Both☐

Do other animals arrive in your area? Yes ☐ No ☐

Specify the origin of these animals: …………………/…………………

Months of presence in the park (home): from |__|__|-|__|__|-|__|__| to |__|__|-|__|__|-|__|__|

I.3.11. Veterinary in charge of the herd's health

Does a veterinary follow your herd? Yes ☐ No ☐

If yes Private ☐ or Public ☐

Veterinary docteur ☐ Veterinary technician ☐ Veterinary auxiliary ☐

Name and First name of veterinary:………………….. / Locality of residence: ……………

Phone number: +|__|__|__| - |__|__|__|__|__|__|__|__| / +|__|__|__| - |__|__|__|__|__|__|__|__|

II – Tick perception and resistance of ticks to acaricides by breeders

II.1. Types of ticks present in the farm (refer to tick identification sheet)

Amblyomma variegatum ☐ Name in local language: ……………………………………

Rhipicephalus (Boophilus) ☐Name in local language: ……………………………………

Rhipicephalus spp ☐ Name in local language: ……………………………………

Hyalomma spp ☐ Name in local language: ……………………………………

Others ☐ Name in local language: ……………………………………

II.2. At what time of the year do you find the following species on animals? (Show the species in a box)

Amblyomma variegatum ☐ Specify periods………………………/ Unknown ☐

Rhipicephalus (Boophilus) spp ☐ Specify periods ………………………/ Unknown ☐

Hyalomma spp ☐ Specify periods ………………………/ Unknown☐

Rhipicephalus spp ☐ Specify periods ………………………/ Unknown☐

Others ☐ Specify periods ………………………/ Unknown☐

II.3. Treatment for ticks control

No ☐ Some of animals ☐ All animals ☐ Why? …………………………………………

II.4. Treatment applied methods

Conventional methods

Manual pulverisation ☐ Acaricidal spray ☐ Pour-on ☐ Pediluvial ☐Dipping tank ☐ Others ☐
……………………………………………………………………………

Unconventional methods

Manual removal ☐ Plants ☐(Collect specimens if present) ; Insecticidal spray ☐ Fumigation ☐
Drain oil ☐ Cow dung ☐ Other recipe (please specify): ....

II.5. Frequency (Treatment intervals) and number of treatments

Total number per year |__|__| (to check)

Dry season ☐ |__|__|- Rainy season ☐ |__|__|-

Small dry season ☐ |__|__|- Small rainy season ☐ |__|__|-

II.6. Do you follow a treatment schedule?

No ☐ Yes ☐ If yes, indicate the main method used (see II.4): ……………………………..

Indicate the periodicity of the treatments (interval)

Dry season .... times / week / month Rainy season .... times / week / month

Small dry season .... times / week / month Small rainy season ..... times / week / month

II.7. Used products

Product name (conventional methods)	Active substance	Origin			Repackaged by who ?	
		brand	generic	reconditioned	seller	breeder
		☐	☐	☐	☐	☐
		☐	☐	☐	☐	☐
		☐	☐	☐	☐	☐
		☐	☐	☐	☐	☐
		☐	☐	☐	☐	☐

II.8- Use of products

Quantity of product1 ------------: | __ | __ | ml or lid for Quantity of water | __ | __ | liters

Quantity of product2 ------------: | __ | __ | ml or lid for Quantity of water | __ | __ | liters

Quantity of product3 ------------: | __ | __ | ml or lid for Quantity of water | __ | __ | liters

Quantity of product4 ------------: | __ | __ | ml or lid for Quantity of water | __ | __ | liters

Quantity of product5 ------------: | __ | __ | ml or lid for Quantity of water | __ | __ | liters

Sprayer capacity | __ | __ | liters ; *Contents of a sprayer for | __ | __ | __ | animals*

II.9. Respect of the waiting period for the sale

How long does it take between acaricide treatment and the sale of your animals?

No delay ☐ between 1 and 4 week (s) ☐ after one month☐

II.10. Product storage condition

Place of storage of the product (specify): …………………………………………………

Do you know if there is an expiry date ? Yes ☐ No ☐*(To be checked by the investigator)*

I.9.1. Who does the acaricide treatment of your animals ?

Herder ☐ ; Person trained for this purpose ☐ ; Manager: ☐ ; Cowherd: ☐

Public veterinary ☐ Private veterinary ☐ Others ☐(specify): ……………………..

III – Situation of resistance

III.1. When did you treat your animals for ticks for the last time?

1. Beginning of DS ☐ 2. End of DS ☐ 3. Beginning of RS ☐ 4. End of RS ☐

DS: Dry Season RS: Rainy Season

5. There is |__|__| days / weeks / months (delete useless mentions) 6. Product used: -------------

III.2. What are the observed changes in the product's action?

Presence of live ticks☐ ; Rapid reappearance of ticks☐ ; Presence dead ticks ☐ ; Other (specify) ……………………………………..

III.3. Since when are these changes observed

|__|__| days/weeks/ months/years (delete useless mentions)

Attitudes adopted: Product change ☐ Increase in dosage ☐ Use of agricultural insecticides ☐

Do you change products frequently during the year: Yes ☐ No ☐ How many times |__|__|

III.4. Which tick species are affected by this problem?

1. All of them ☐ 2. Some of them ☐

3. Species: *A. variegatum* ☐ *R. (Boophilus)* spp ☐ *Hyalomma* spp ☐ *Rhipicephalus* spp ☐
Others (Specify) ……………………..………………………

(Show them in a petri dish or in a tube or pictures)

III.5. When was the first case of treatment failure?

|__|__| Month/Year *(delete useless mention)*

III.6. Has there been a recent change?

1. In the flock (breed, import ...)........................

2. Product ☐ (Change of dilution): ☐; Change in product quality: ☐. Source of the product ☐; Storage conditions ☐; Application method ☐. Treatment interval ☐

3. Staff ☐; 4. General management of livestock ☐; 5. Other: ....

III.6. What are the reasons for change: …………………………………………………

III.7. Can you mention by year, 3 products affected by treatment failures?

2015……………………………/…………………………/……………………..

2014……………………………/…………………………/……………………..

2013……………………………/…………………………/……………………..

III.7. Can you mention by year, 3 products concerned by the success of treatments?

2015……………………………/…………………………/……………………..

2014……………………………/…………………………/……………………..

2013……………………………/…………………………/……………………..

III.9. Has the health of your animals improved or worsened since the product used no longer controls ticks?

Yes ☐ No ☐ No change ☐

III.10. What did you decide to solve the problem?

1. Nothing ☐ 2. Increase the dosage ☐ 3. Increase the frequency of treatments ☐

4. Change the product ☐ 5. Change de product supplier☐ 6. Manual removal ☐

7. Others ☐ (Specify)……………………………………………………………………

III.11. What do your animals risk if you do not treat them?

1. Injuries ☐ 2. Teat losses ☐ 3. Dermatoses ☐

4. Transmission of tick diseases (Specify the local language name) ☐ ....

5. Reduction of milk quantity ☐ 6. Abortion ☐ 7. Weight loss ☐ 8. Mortalities ☐ 9.Other ☐ (Specify) ....

III.12. Are there any cows that have lost teats due to ticks?

Yes ☐ No ☐ How many ☐ Responsible tick ☐ ------------------------------

III.15. Have ticks been harvested from animals in this herd for resistance testing (in this survey)?

1. Yes ☐ 2. No ☐ If yes, please refer to the Sample Code below:

____________ ____________ ____________ ____________ ____________ ____________

IV – Role of transhumance on the spread of ticks

4.1. Do you practice transhumance? Yes ☐ No ☐

4.2. What is the starting point of this flock (beginning of this transhumance)?

Country: ____

Department / Region: ____

Locality: ____

4.3. What is the destination locality (end of this transhumance)?

Country: ____

Department / Region: ____

Locality: ____

4.4. Can you give us the names of the main localities that are planned to cross during the transhumance of the herd that is being followed?

N°	Town and village	Transit duration (days)	N°	Town and village	Transit duration (days)
1.1			1.7		
1.2			1.8		
1.3			1.9		
1.4			1.10		
1.5			1.11		
1.6			1.12		

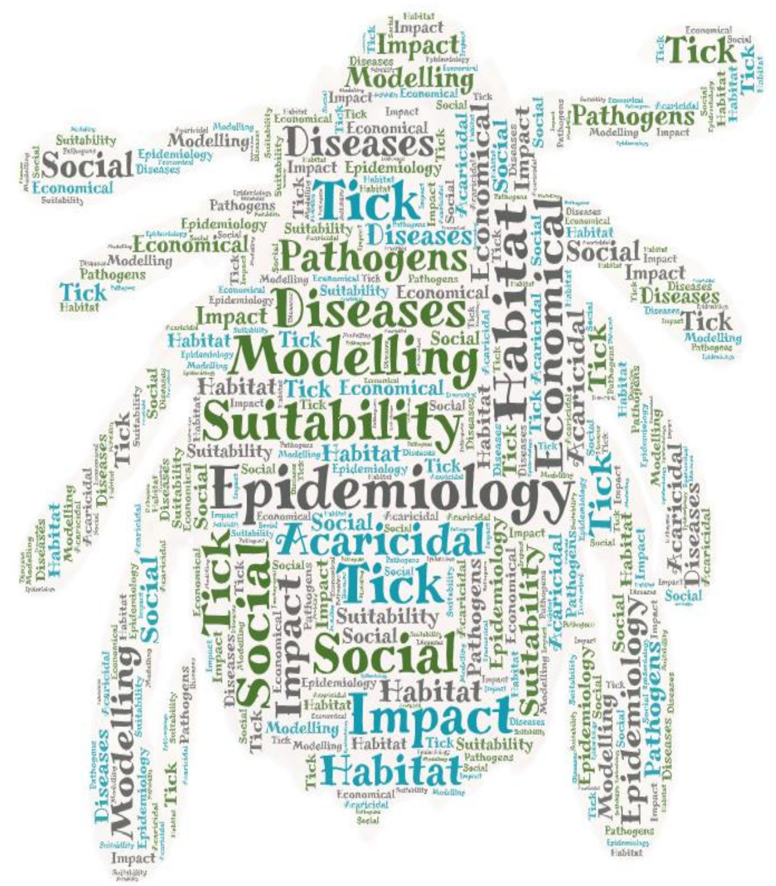
Identification of samples

N° ID Pot	Cattle breed	Age (month)	Sex	Blood (02)	Tick (02)
|__|__|/|__|__|__|- |__|__|			M☐ F☐		
|__|__|/|__|__|__|- |__|__|			M☐ F☐		
|__|__|/|__|__|__|- |__|__|			M☐ F☐		
|__|__|/|__|__|__|- |__|__|			M☐ F☐		

|__|__|/|__|__|__|-|__|__|			M☐ F☐		
|__|__|/|__|__|__|-|__|__|			M☐ F☐		
|__|__|/|__|__|__|-|__|__|			M☐ F☐		
|__|__|/|__|__|__|-|__|__|			M☐ F☐		
|__|__|/|__|__|__|-|__|__|			M☐ F☐		
|__|__|/|__|__|__|-|__|__|			M☐ F☐		

(order number / Survey ID- Country ID)

NB: Please warmly thank the respondent before taking leave of him.



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