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ASSESSMENT OF THE RISK OF SPREAD OF PESTE DES PETITS RUMINANTS IN SOUTH AFRICA THROUGH USE OF SPATIAL MULTI-CRITERIA DECISION ANALYSIS

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LIST OF ABBREVIATIONS

PPR : Peste des Petits Ruminants
PPRV : Peste des Petits Ruminants Virus
RNA : Ribonucleic acid
RNP : Ribonucleoprotein
IFN : Interferon
FAO : Food and Agriculture Organization of the United Nations
CCPP : Contagious Caprine Pleuropneumonia
RT-PCR : Reverse Transcriptase Polymerase Chain Reaction
ELISA : Enzyme-Linked Immunosorbent Assay
PCR : Polymerase Chain Reaction
qRT-PCR : quantitative Reverse Transcriptase Polymerase Chain Reaction
MAb : Monoclonal antibody
LAMP : Loop-mediated isothermal amplification
VNT : Virus Neutralization Test
OIE : Office International des Epizooties
C-ELISA : Competitive Enzyme-Linked Immunosorbent Assay
ICE-ELISA : In-Cell Enzyme-Linked Immunosorbent Assay
RPV : Rinderpest Virus
DIVA : Differentiation of infected and vaccinated animals
DRC : Democratic Republic of Congo
UN COMTRADE : United Nations International Trade Statistics Database
SADC : Southern African Development Community
TADs : Transboundary Animal Diseases
MCDA : Multi Criteria Decision Analysis
SAPS : South African Police Service
DAFF : Department of Agriculture, Forestry and Fisheries
VS : Veterinary Services
AHT : Animal Health Technician
OIE PVS : Office International des Epizooties ‘s Performances of Veterinary Services
FMD : Foot and Mouth Disease
MCE : Multi Criteria Evaluation
GIS : Geographic Information System
HPAI : Highly Pathogenic Avian Influenza
SANPARKS : South African National Parks
CIRAD : Centre de cooperation Internationale en Recherche Agronomique pour le Développement
UP : University of Onderstepoort
ENVT : Ecole Nationale Vétérinaire de Toulouse
GAP KZN : Goat Agrobusiness Project of Kwazulu Natal
CR : Consistency Ratio
CI : Consistency Index
RI : Random Index
WLC : Weighted Linear Combination
SI : Suitability Index
CSIR: Council for Scientific and Industrial Research
ASF: African Swine Fever

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RESUME LONG EN FRANÇAIS

Dans un contexte où le virus de la peste des petits ruminants (PPR) se propage en direction de l'Afrique Australe, et considérant la présence d'importantes populations de moutons et de chèvres en Afrique du Sud, un intérêt croissant est porté aux approches d'analyse de risque avec pour objectif de déterminer les zones du pays les plus à risque pour la transmission de la maladie. Notre travail porte sur une analyse spatiale conduite en appliquant la méthode d'aide décisionnelle multicritère. Dans une première partie, nous présentons les données bibliographiques concernant le virus et la maladie, avant d'appliquer la méthode dans la seconde partie – expérimentale - et produire les premières cartes de risque sur la PPR en Afrique du Sud.

1. RÉPARTITION GÉOGRAPHIQUE ET IMPORTANCE ÉCONOMIQUE

La peste des petits ruminants est une maladie hautement contagieuse due à un virus appartenant au genre *Morbillivirus*. Ce genre regroupe par ailleurs d'autres virus d'intérêt vétérinaire et médical, comme le virus de la peste bovine (éradiqué en 2011), le virus de la rougeole chez les primates et le virus de la maladie de carré chez les canidés.

La maladie fut décrite pour la première fois en 1942 en Côte d'Ivoire (Gargadennec, Lalanne 1942). Pendant plusieurs décennies, on pensait la maladie limitée à Afrique de l'Ouest. Ce n'est qu'après l'identification du virus responsable en 1979 (Gibbs et al. 1979) que les scientifiques ont détecté la présence de la maladie dans de nombreux pays d'Afrique, d'Asie, du Moyen et du Proche-Orient. En Afrique, la peste des petits ruminants était initialement observée autour de la ceinture sahélienne, puis s'est propagée au Maghreb, en Afrique de l'Est et en direction de l'Afrique Australe. En Asie, la maladie s'est récemment propagée en Asie Centrale (OIE 2017).

Quatre lignées du virus ont été définies (I, II, III, IV) sur la base des séquences de gènes du virus. Ces lignées ont été nommées selon l'ordre apparent de propagation du virus. Ainsi, les lignées I et II sont essentiellement retrouvées en Afrique de l'Ouest, la lignée III en Afrique de l'Est et la lignée IV en Asie et au Moyen-Orient. Actuellement, la lignée IV est retrouvée dans la plupart des infections récentes en Afrique et en Asie, ce qui peut suggérer une virulence accrue pour cette lignée (Kwiatek et al. 2011).

Environ 330 millions de personnes à travers l'Afrique, le Moyen-Orient et l'Asie élèvent du bétail, dont des moutons et des chèvres (FAO, OIE 2015). Ces derniers représentent une source de lait, de viande, de laine et sont considérés comme de la trésorerie qui peut être vendue pour couvrir les frais de santé ou de scolarité. La peste des petits ruminants affecte aujourd'hui presque 70 pays qui ensemble abritent plus de 80% des populations mondiales de petits ruminants. L'impact financier annuel de la peste des petits ruminants est estimé entre 1.45 et 2.1 milliards de dollars par an (FAO, OIE 2015).

Son impact sanitaire et financier important a conduit l'OIE et la FAO à mettre en place la Stratégie Mondiale pour l'Eradication et le Contrôle de la PPR. Cette stratégie vise l'éradication de la peste des petits ruminants d'ici 2030. A l'échelle de l'Afrique du Sud, la Communauté de Développement d'Afrique Australe (SADC) a mis en place une stratégie de contrôle régionale en 2012 suite à l'incursion du virus en Tanzanie et à l'épidémie dévastatrice en République Démocratique du Congo (tous deux membres de la SADC).

2. AGENT ÉTIOLOGIQUE ET TABLEAU CLINIQUE

Les virions sont des particules de forme généralement sphérique. Le génome viral est un monobrin d'ARN négatif d'une longueur de 15,498 nucléotides (Bailey et al. 2005). Ce génome code pour 8 protéines : 2 glycoprotéines de surface, une protéine matricielle, 3 protéines composant le complexe de réplication (Bailey 2007), et 2 protéines non-structurales dont le rôle précis est actuellement encore discuté (Sanz Bernardo 2017).

Le virus de la peste des petits ruminants est enveloppé, particulièrement sensible dans le milieu extérieur. Le virus est facilement détruit par les désinfectants les plus communs, et possède une demi-vie à 37°C de 2 heures (Kumar et al. 2014). Son mode de transmission est donc essentiellement direct.

Le virus induit une immunosuppression majeure qui peut durer plusieurs semaines (Jagtap et al. 2012). Une fois pris en charge au niveau de la muqueuse respiratoire, le virus se réplique une première fois au sein des nœuds lymphatiques régionaux, puis dissémine dans tout l'organisme via des lymphocytes infectés. L'infection induit une réponse immunitaire cellulaire et humorale. Chez les nouveaux nés de mères infectées ou immunisées, les anticorps maternels sont protecteurs pendant 3 à 4 mois (Libeau et al. 1992). De plus, les animaux qui survivent à l'infection développement une immunité qui les protège pour toute la durée de leur vie (Cosby, Chieko, Yamaguchi 2006).

La forme clinique la plus couramment rencontrée est la forme aigue (Lefèvre, Diallo 1990). Les symptômes ressemblent à ceux de la peste bovine, mais chez les moutons et chèvres. La période d'incubation est de 4 à 6 jours. Les premiers symptômes, rencontrés également dans le tableau clinique de la forme suraiguë, sont une hyperthermie sévère (41-42°C), une prostration, des écoulements nasaux et oculaires, parfois accompagnés d'une diarrhée profuse. S'en suivent une congestion des muqueuses buccales et oculaires associée à des zones d'ulcération et d'érosion qui évoluent en zone de nécrose épithéliale, essentiellement dans la cavité buccale (FAO 1999). Les écoulements finissent par devenir muco-purulents et former des croûtes (FAO 1999). Les complications bactériennes sont fréquentes, notamment en région pulmonaire. A l'examen nécropsique, on retrouve essentiellement des lésions de gastro-entérite (avec congestion de la muqueuse), pneumonie, stomatite ulcéreuse (FAO 1999).

3. DIAGNOSTIC ET PRÉVENTION

La peste des petits ruminants étant une maladie listée du *Code sanitaire pour les animaux terrestres* de l'Office International des Epizooties (OIE), sa déclaration est obligatoire, et le diagnostic de certitude passe par un diagnostic de laboratoire qui doit utiliser une technique reconnue par l'OIE.

Le diagnostic direct porte soit sur la détection du virus (avec le test de neutralisation virale), soit sur la détection de protéines virales (ICE ELISA) soit la détection d'acides nucléiques (RT-PCR). Le diagnostic indirect se fait essentiellement en utilisant la technique ELISA. Les tissus à échantillonner pour le diagnostic sont des écouvillons sur les muqueuses nasales, buccales ou conjonctivales. Il est également possible de prélever du sang. Sur carcasse, il est possible de prélever les nœuds lymphatiques mésentériques, bronchiques, ainsi que la rate, les poumons et la muqueuse intestinale (OIE 2013).

Quant aux mesures prophylactiques, la vaccination est la principale mesure efficace et disponible. En effet, dans les pays endémiques de PPR, la restriction des mouvements d'animaux, la désinfection approfondie et l'abattage sanitaire peuvent être difficiles à mettre en place. Autrefois interdite pour ne pas interférer avec le programme d'éradication de la peste bovine, la vaccination contre la peste des petits ruminants est aujourd'hui disponible. En effet, les petits ruminants étaient autrefois vaccinés contre la PPR avec le vaccin contre la peste bovine (vaccin hétérologue). En l'absence de vaccin DIVA disponible, la vaccination des petits ruminants avait alors été interrompue pour surveiller l'efficacité du programme d'éradication de la peste bovine. Quatre vaccins vivants atténués ont été développés, et tous protègent efficacement contre les différentes lignées du virus de la peste des petits ruminants et empêchent la transmission du virus d'un animal infecté à un autre. L'immunité protective est induite dès la première administration. Le protocole vaccinal actuel préconise une vaccination tous les 3 ans (Diallo et al. 2007; Saravanan et al. 2010). Cependant, comme les chèvres et moutons élevés dans les pays endémiques de peste des petits ruminants ne sont généralement pas gardés plus de 3 ans, une injection suffit pour la durée de vie économique de l'animal. Les principaux défis à relever concernant les vaccins vivants atténués sont leur sensibilité à la chaleur et leur incapacité à différencier les animaux vaccinés des animaux infectés. Les recherches actuelles portent sur ces deux points d'amélioration, ainsi que sur le développement de vaccins multivalents pour optimiser les dépenses liées à la vaccination dans les pays du Sud.

4. EPIDÉMIOLOGIE

Deux formes épidémiologiques peuvent être observées. La forme enzootique se rencontre essentiellement au Sahel et en Asie du Sud et se traduit par des baisses de productivité et une sensibilité accrue aux surinfections. La forme épizootique se rencontre dans des troupeaux à faible séroprévalence avec une cyclicité tous les 4-6 ans, quand le renouvellement du troupeau est suffisamment avancé pour avoir une majorité d'individus naïfs. En cas d'épizootie, les taux de morbidité et de mortalité peuvent alors atteindre 80%-90% et 50-80%, respectivement (Lefèvre, Diallo 1990). Cette forme s'observe en Afrique de l'Ouest et dans les régions récemment infectées telles que l'Afrique de l'Est.

Les sources virales sont essentiellement les individus infectés, via les sécrétions orales, nasales, lacrymales et fécales (Abubakar et al. 2012). Aucun stade de porteur sain n'a été décrit (Hamdy et al. 1976). L'excrétion de matériel viral a été détecté dès 3 jours post-infection (Couacy-Hymann, S.C. Bodjo, et al. 2007) et jusqu'à 16 semaines post-infection (Wasee Ullah et al. 2016).

La maladie de la peste des petits ruminants est avant tout une maladie du mouton et de la chèvre. A ce jour, ces deux espèces sont considérées comme les seules capables d'excréter et transmettre le virus. Des séroprévalences ont été détectées chez les bovins, les camélidés et les buffles domestiques. Des épidémies ont été observées chez des populations de petits ruminants sauvages, la plupart du temps vivant dans des conditions de semi-captivité. A l'heure actuelle, les différentes publications mettent en avant l'hypothèse pour laquelle les petits ruminants sauvages sont sensibles à la peste des petits ruminants mais incapables de transmettre le virus au sein de leurs populations (Couacy-Hymann et al. 2005).

Plusieurs facteurs de risque ont été identifiés dans la littérature. Le manuel sur la peste des petits ruminants de l'OIE décrit une sensibilité accrue des moutons en Asie de l'Ouest et du Sud, tandis qu'en Afrique les chèvres sont décrites comme plus fréquemment atteintes (FAO 1999). Les animaux âgés entre 4 et 12 mois sont considérés comme plus à risque (Diallo 2003a; Gopilo 2005). Les races guinéennes de chèvres ont été rapportées plus sensibles que les races sahéliennes (Lefèvre, Diallo 1990). Le sexe a également été décrit comme un facteur de risque avec des observations de séroprévalences plus élevées chez les femelles que chez les mâles (Waret-Szkuta et al. 2008; Aziz-ul-Rahman et al. 2016; Kihu et al. 2015). Cependant les femelles sont souvent gardées plus longtemps dans les troupeaux, ce qui peut expliquer une plus grande séroprévalence au sein de ce sexe.

Les systèmes de production avec transhumance et le pastoralisme en particulier ont été décrits comme facteurs de risque à plusieurs reprises (Abubakar et al. 2009; M. Abubakar et al. 2011; Bett et al. 2009; Singh et al. 2004; Megersa et al. 2011; Mahajan et al. 2012; Shankar 1998; Nanda 1996). Les fortes densités en animaux (Al-Majali et al. 2008; Khan 2008; Ozkul et al. 2002; Kardjadj et al. 2015) et l'élevage mixte de chèvres et moutons (Al-Majali et al. 2008; Anderson, McKay 1994; Kardjadj et al. 2015) peuvent augmenter le risque de transmission de la peste des petits ruminants. Enfin, l'introduction d'animaux achetés sur les marchés (Abubakar et al. 2009; M. Abubakar et al. 2011; Singh et al. 2004; Mbyuzi et al. 2014) et le partage des pâtures et points d'abreuvement entre différents troupeaux (Mbyuzi et al. 2014; Lefèvre 2003) ont également été rapportés comme des pratiques à risque.

Les pratiques traditionnelles (Bazarghani 2006) et religieuses (Bonniwell 1980) impliquant le commerce de petits ruminants vivants (telles que les mariages, funérailles) peuvent favoriser l'introduction d'individus infectés dans des zones indemnes. Quant à l'influence de la saison, certains auteurs rapportent une sensibilité accrue pendant la saison humide et chaude (Rony et al. 2017; Mondal 2014; M. Abubakar et al. 2011; Taylor, Barrett 1990), et d'autres pendant la saison sèche et fraîche (Obi et al. 1983; Singh et al. 2004; Abubakar et al. 2009). Enfin, la qualité de la surveillance et l'accès aux services vétérinaires influencent également la propagation de la PPR (Al-Majali et al. 2008; Bett et al. 2009; Bazarghani 2006).

5. ANALYSE DU RISQUE DE TRANSMISSION DE LA PPR A L'AIDE DE LA METHODE SPATIALISEE D'AIDE DECISIONNELLE MULTICRITERE

Alors que le virus de la peste des petits ruminants se propage vers le sud du continent Africain, l'Afrique du Sud apparaît comme un pays à risque pour la propagation de la peste des petits ruminants, et ce pour plusieurs raisons. Tout d'abord, environ 67% des chèvres et 12% des moutons élevés en Afrique du Sud appartiennent à des éleveurs de subsistance dans des zones communales (NERPO 2013). Ce mode d'élevage peut être considéré comme une pratique à risque car d'une manière générale, les éleveurs en zone communale souffrent d'infrastructures défectueuses, d'un manque d'accès aux services vétérinaires, ou encore de niveaux d'éducation inférieurs aux éleveurs professionnels. De plus, les animaux élevés en zones communales sont rarement identifiés et souvent laissés libres de vagabonder dans les villages et d'ainsi partager des zones d'abreuvement et de pâtures avec d'autres individus issus de troupeaux différents.

De plus, l'Afrique du Sud souffre d'un manque de traçabilité quant aux mouvements d'animaux au sein de son territoire et avec les pays voisins. En effet, un important marché illégal est observé, en particulier à l'occasion de fêtes traditionnelles et religieuses.

Ainsi, l'Afrique du Sud se présente comme le candidat idéal pour une analyse de risque afin de déterminer les zones les plus à risque pour la transmission du virus dans le cas où il aurait été introduit sur le territoire. Cependant, étant donné que l'Afrique du Sud est indemne de PPR, nous ne disposons pas des données de foyers nécessaires pour conduire une analyse spatialisée quantitative. Dans ce type de cas, il nous est possible d'utiliser des méthodes se basant sur la connaissance, et non sur les données. Dans ce travail, nous avons appliqué la méthode d'aide décisionnelle multicritère (MCDA) spatialisée. Cette méthode associe connaissances scientifiques et avis d'experts pour déterminer les zones géographiques les plus adaptées à la propagation du virus, et donc les plus à risque. Le résultat de ce travail est sous forme de cartes géographiques, qui apporteront un support visuel aux autorités compétentes pour déterminer où concentrer les mesures de contrôle et de surveillance tout en optimisant les ressources financières et logistiques.

La méthode MCDA spatialisée a déjà été utilisée pour identifier les zones à risque pour la Fièvre de la Vallée du Risque en Afrique (Tran et al. 2016; Clements, Pfeiffer, Martin 2006) et en Europe (Sánchez-Vizcaíno, Martínez-López, Sánchez-Vizcaíno 2013; Tran et al. 2013), pour l'Influenza Aviaire hautement pathogène H5N1 en Asie (Stevens 2013; Paul et al. 2016). Pour la PPR, la méthode a déjà été utilisée à l'échelle du continent Africain (Waret-Szkuta 2011) et à l'échelle de l'Afrique de l'Est (Tran 2013). Cependant, aucune analyse de risque concernant la PPR en Afrique du Sud n'a encore jamais été portée à notre connaissance. Ce travail constitue donc une première étape d'analyse de risque spatialisée utilisant la méthode d'aide décisionnelle multicritère.

La première étape de la méthode consiste en l'identification des facteurs de risque. Une revue bibliographique a été menée pour actualiser les facteurs de risque identifiés dans la littérature lors de précédents travaux (Waret-Szkuta 2011; Tran 2013). Ces facteurs ont ensuite été confrontés à la situation de l'Afrique du Sud et adaptés. Nous avons retenu les facteurs de risque suivants :

- La densité de chèvres
- La densité de moutons
- La proximité aux parcs nationaux et réserves
- La proximité aux rivières, considérées comme les points d'abreuvement principaux pour les animaux élevés en zones communales
- La proximité aux marchés légaux et illégaux. Le commerce illégal de petits ruminants en Afrique du Sud ayant essentiellement lieu au sein des stations de taxi.
- La proximité aux routes : qui sont la voie de transport majeure pour le commerce légal et illégal de petits ruminants
- La distance aux bureaux des services vétérinaires

La deuxième étape de la méthode consiste en l'acquisition de données géographiques correspondant aux sept facteurs de risque sélectionnés. Les données concernant les densités d'animaux ont été celles issues du modèle « Gridded Livestock of the World » (GLW) de la FAO. Les cartes représentant les parcs nationaux et les rivières d'Afrique du Sud sont issues de sites internet gouvernementaux. Les localisations des marchés officiels de petits ruminants ont été répertoriées à l'aide de magazines professionnels destinés aux éleveurs. La carte des routes ainsi que les localisations des stations de taxi (marchés illégaux) sont issues de la banque de données OpenStreetMap. Les localisations des services vétérinaires ont été repérées sur une carte en s'appuyant sur les sites internet des services vétérinaires des neuf provinces.

Chacun des sept facteurs de risque a été représenté sur une carte propre. Les données ont été visualisées et travaillées à l'aide de logiciels de géomatique, afin de produire une carte par facteur de risque sous le format raster et avec une résolution de $1km^2$ (celle imposée par le jeu de données du modèle GLW).

La troisième étape fait appel aux avis d'experts. 16 experts ont été contactés parmi des chercheurs et des membres des services vétérinaires sud-africains. Un questionnaire en deux parties a été conçu sur Word et envoyé par email. La première partie a pour but de déterminer la relation entre chaque facteur de risque et le risque de transmission de la PPR. Les experts avaient le choix entre 4 relations (linéaire, sigmoïdale, quadratique, trapézoïdale) et devaient éventuellement décider de valeurs seuil. La deuxième partie du questionnaire, concernant le poids des facteurs, est présentée sous forme de matrice de comparaison. Chaque expert comparait les facteurs de risque deux à deux et accordait un poids à chaque comparaison.

Huit experts ont renvoyé le questionnaire complété. Les données de quatre experts ont été conservées pour la suite de la méthode car ces experts ont montré un indice de cohérence (ou consistency ratio) satisfaisant ($CR<0.13$).

Les facteurs de risque n'étant pas exprimés dans les mêmes unités (par exemple, la densité est en nombre d'individus/km^2, et les proximités indiquées en mètres), ils ont été standardisés pour pouvoir les combiner et produire une carte finale. Cette standardisation utilise l'approche « fuzzy » sur les données de la première partie des questionnaires. En effet, chaque relation correspond à une fonction mathématique que l'on applique aux données brutes pour obtenir une valeur standardisée (entre 0 et 1). Ainsi, pour chaque facteur de risque identifié, on obtient une carte où chaque pixel possède une valeur allant de 0 (risque minimal) à 1 (risque maximal).

A partir des données des quatre experts retenus pour la modélisation, un poids moyen a été calculé pour chaque facteur de risque. Chacun de ses poids a été attribué à la carte du facteur de risque correspondant, en appliquant la méthode de combinaison linéaire pondérée. Le résultat de cette combinaison est une carte de risque finale, où chaque pixel possède une valeur pouvant aller de 0 (risque minimal de transmission) à 1 (risque maximal de transmission).

La carte finale établie à l'échelle nationale révèle que l'aptitude de l'Afrique du Sud à transmettre le virus dans le cas où il aurait été introduit varie de 0.12 à 0.89 en fonction des zones géographiques (avec une aptitude moyenne nationale de 0.27).

La réalisation de deux cartes additionnelles, à l'échelle de la province du Cap Occidental et de la province du Cap du Nord, a été rendue possible grâce à la collecte de données de recensement des chèvres et moutons, mises à disposition par les services vétérinaires de ces provinces. Pour la province du Cap Occidental, l'aptitude à transmettre le virus varie de 0.11 à 0.66 (avec une moyenne sur la province de 0.25). Pour la province du Cap du Nord, l'aptitude varie de 0.1 à 0.71 (avec une moyenne sur la province à 0.22). Lors de la pondération des facteurs de risque, les experts ont classé la densité de chèvres, la proximité aux marchés, la densité de moutons et la distance aux services vétérinaires comme les facteurs les plus importants, avec des poids respectifs de 0.335, 0.174, 0.169, et 0.137.

6. AMÉLIORATIONS DU MODÈLE

La méthode spatialisée d'aide décisionnelle multicritère présente de nombreux atouts, comme la capacité à produire des cartes de risque dans des régions indemnes ou lorsque les données épidémiologiques sont rares ou indisponibles. Elle permet d'apporter un support visuel relativement instinctif d'aide à la décision quant aux zones à cibler en matière de surveillance et de contrôle.

Un autre atout est que cette méthode autorise l'intégration *a posteriori* de données cartographiables qui viendraient à devenir disponibles, ou disponibles avec une plus grande précision. Cependant, le modèle a également le défaut de ses qualités : il repose sur une succession de choix discutables ; d'abord pour la sélection des facteurs de risque, puis pour les relations, pour les valeurs seuil et les poids des facteurs.

Une limite importante à prendre en compte est la dépendance du modèle à la qualité des données utilisées. C'est d'ailleurs sur ce point que sont axées nos principales voies d'amélioration. En effet, les données utilisées dans ce travail concernant les densités d'animaux sont issues d'une modélisation basée sur des données de recensement fournies à l'échelle de la province. Leur précision est donc discutable.

La difficulté de la collecte de données de recensement plus précises réside dans le fait que les services vétérinaires eux-mêmes ont des difficultés pour recenser avec rigueur et précision les animaux sur leur territoire, notamment à cause des mouvements incontrôlés au sein du pays et à travers les frontières.

De plus, la méthode utilisée dans ce travail nécessite de ne considérer que les facteurs de risque qui peuvent être cartographiés, alors que certains comme les mouvements d'animaux lors des fêtes traditionnelles par exemple peuvent constituer un facteur de risque très important mais difficilement cartographiable.

Enfin, le faible nombre d'experts ayant répondu et ayant été retenu (25% de l'échantillon initial) nous contraint à interpréter nos cartes avec précaution.

La dernière étape de la méthode d'aide décisionnelle multicritère consiste à évaluer quantitativement la sensibilité et l'incertitude du modèle, afin de vérifier que la carte finale est suffisamment indépendante des choix des experts pour être interprétable. Nous recommandons que cette analyse quantitative soit considérée comme un prérequis avant d'utiliser nos cartes en tant qu'aide à la décision.

INTRODUCTION

Peste des Petits Ruminants (PPR) is a highly contagious viral disease of sheep and goats, first discovered in 1942 in the Ivory Coast, and today spread throughout Western, Central and Eastern Africa, the Middle East and Asia. With morbidity and fatality rates up to 100 % and 90 % respectively (FAO, OIE 2015), PPR represents a major threat to food security for the 330 millions of people keeping livestock in these developing regions. Its high economic importance brought the OIE and FAO to target PPR as the next disease to be eradicated by 2030.

In Africa, PPR is progressively spreading towards Southern Africa, with first OIE notifications in Kenya (2006), Uganda (2007), Tanzania (2008) and Angola (2012) and evidence of PPRV antibodies in Zambia in 2015. This apparently rapid spread of the virus can be explained by high small ruminant densities in most of endemic countries, uncontrolled trading and transhumant movements, sharing grazing areas and watering points, etc. and that often without consideration of national boundaries.

As PPR is spreading southwards, there is a need to anticipate further PPR introduction and transmission in Southern African countries so that new infection cases can be prevented or rapidly controlled. To provide the most accurate risk prediction, epidemiological data currently known on PPR must be adapted to each considered country or region, mainly because of differences among small ruminant farming systems, livestock trade, etc.

This study focuses on assessing the risk of PPR spread within South Africa, located at the southern tip of the African continent. Our work aims at identifying high risk areas for PPR spread in South Africa through spatial risk analysis, in the case where PPRV would have been introduced on the territory. Priority areas for prevention and control of PPR were assessed through a Geographical Information System (GIS)-based risk model: spatial Multi Criteria Decision Analysis (MCDA). This "knowledge-driven" approach consists in risk factors identification and collection of the corresponding geographical data, expert opinion survey on these risk factors and how they impact on the suitability of the disease spread, and geo-processing of the collected data with a GIS software. The final output of our study is a suitability map that highlights the most likely areas in South Africa for PPR spread, providing support for prioritizing and implementing early detection and control strategies.

In a first part, we browsed literature to review the current knowledge on PPR, including etiology, medical aspects and epidemiology. In a second part, we applied the spatial-MCDA methodology to map the most suitable areas in South Africa for PPR spread. Finally, results of our work were discussed and some improvements were suggested to enhance accuracy and validity of our spatial model in a near future.

PART 1: BIBLIOGRAPHICAL BACKGROUND

CHAPTER 1: REVIEW OF PESTE DES PETITS RUMINANTS

Peste des Petits Ruminants (PPR) is also known as “goat plague”, “Kata”, “syndrome of stomatitis-pneumoenteritis” or “ovine rinderpest”. This highly infectious disease is due to a morbillivirus and causes rinderpest-like symptoms, mainly in sheep and goats.

7. CAUSATIVE AGENT : PESTE DES PETITS RUMINANTS VIRUS (PPRV)

7.1. Taxonomy of PPRV

Peste des Petits Ruminants virus (PPRV) belongs to genus *Morbillivirus*, sub-family Paramyxovirinae, family Paramyxoviridae, order Mononegavirales. There are various morbilliviruses of medical and veterinary importance, and one of the characteristics of morbilliviruses is their limited ability to infect different species. We find *Measles virus* in primates, *Canine distemper virus* in canids, *Phocine distemper virus* in pinnipeds, and several cetacean morbilliviruses that are found in marine mammals. *Rinderpest virus* has been globally eradicated in 2011. Recently, a new morbillivirus (*Feline morbillivirus*) has been described in cats (Woo et al. 2012). These morbillivirus species can be divided into monophyletic lineages following genetic analysis (figure 1).

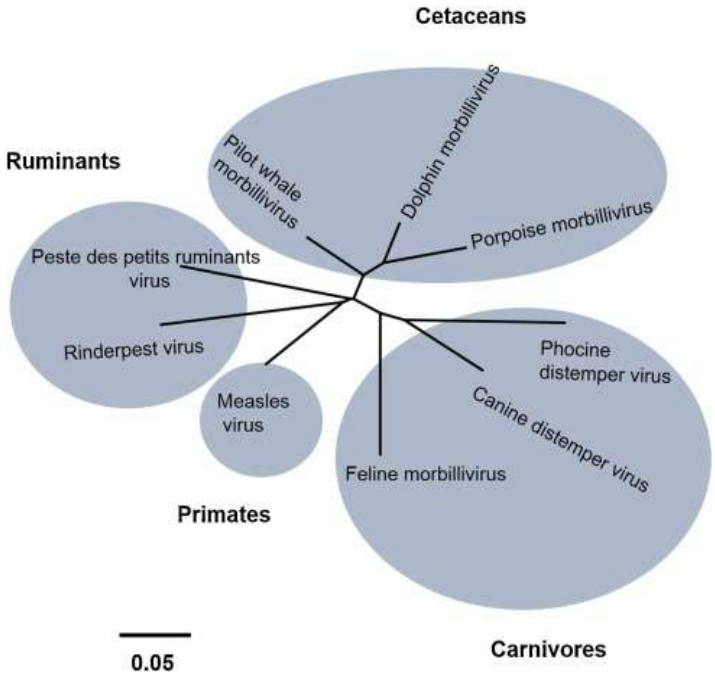

Figure 1: Un-rooted neighbour-joining tree showing the relationships between morbilliviruses. The phylogenetic tree was built using partial N gene sequences of 230 nucleotides (accession nos. NC_006383, Peste des petits ruminants virus; NC_001498, Measles virus; AB547189, Rinderpest virus; NC_001921, Canine distemper virus; KC802221, Phocine distemper virus; JQ411016, Feline morbillivirus; AY949833, Porpoise morbillivirus; NC_005283, Dolphin morbillivirus; AF200818, Pilot whale morbillivirus) with 1000 bootstrap replicates and Kimura 2-parameter model in MEGA 5.2. The scale bar indicates nucleotide substitutions per site. Cited from (Parida et al. 2015)

7.2. Virus morphology and genome structure

PPRV virions are pleomorphic – but generally spheric – enveloped particles. The virus particle size has been determined to be between 400 and 500 nm (Gibbs et al. 1979). The PPR virus genome is a non-segmented, single stranded, negative-sens RNA molecule, that consists of 15,948 nucleotides (Bailey et al. 2005) and six genes that encode eight proteins.

The genome is encapsidated by the N protein, forming a helicoidal nucleocapsid. As the genome is simple negative RNA, it cannot be translated directly into proteins; it has to be transcribed into messenger RNA. This transcription stage is done by a RNA-dependent RNA polymerase complex, formed by two other nucleocapsid proteins: the large polymerase protein (L) and the co-factor phosphoprotein (P). P, N and L proteins form the functional replication complex (Bailey 2007). The N protein is a major viral protein, produced in highest amount in Morbilliviruses (Diallo et al. 1987). It is also a strong immunostimulatory protein. The L protein is the largest viral protein and is expressed in the smallest amount of the infected cells (Kumar et al. 2014).

The nucleocapsid is surrounded by a lipoproteic envelope that is derived from infected cell membrane. This envelope contains two glycoproteins: the viral fusion protein (F) and haemagglutinin protein (H). These proteins form spikes of about 10 nm (Bourdin, Laurent-Vautier 1967) on the surface of the viral envelope, and play crucial roles during the initial steps of the virus replication. Based on what we know about Measles virus proteins, the H protein is responsible for attachment of the virion to the host cell. Then, via the F protein, the viral and the cell membranes are fused, allowing the release of the viral nucleocapsid into the cell cytoplasm (Moll, Klenk, Maisner 2002). The PPRV F protein is also responsible for the syncytium formation, a cytopathic effect common for all Paramyxoviruses. The syncytium formation consists in the fusion of the membrane of an infected cell with the membrane of an adjoining cell. PPRV F protein also has haemolysin property (Devireddy et al. 1999). As for the PPRV H protein, it has both haemagglutinin and neuraminidase activities and is thus sometimes named as Haemagglutinin-neuraminidase (HN) protein.

The inner surface of the viral envelope is coated by the matrix protein (M). This protein is thought to link the RNP and the cytoplasmic tails of the surface glycoproteins (H and F) and to play an important role in virus formation. The organization of the PPRV genome and proteins is represented in figure 2.

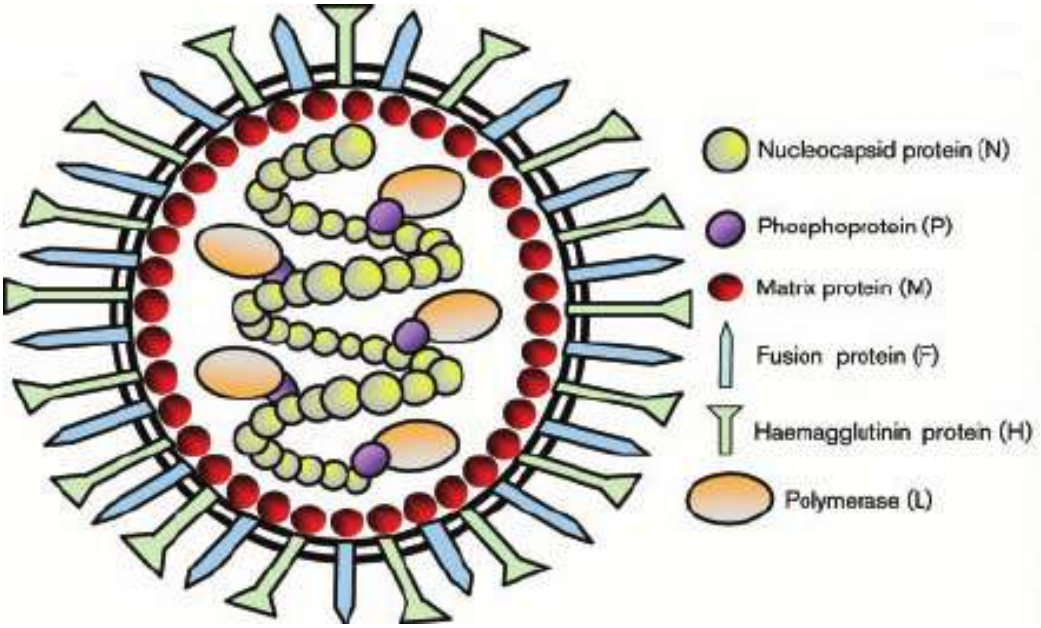

Figure 2: Schematic diagram of Peste des Petits Ruminants virion structure (adapted from (Banyard et al. 2010)). The PPRV glycoproteins (F and H) form spikes and are set inside the envelope. The M protein coats the inner surface of the envelope. The RNP is composed of N, P and L proteins in association with the genome.

Besides these six structural proteins, two non-structural proteins (C and V) are also produced from an alternative reading frame of the P protein. Their precise molecular functions for PPRV still need to be studied, but several studies on Rinderpest and Measles viruses demonstrated the role of C protein in regulation of virus replication (Escoffier et al. 1999) and RNA synthesis (Baron, Barrett 2000), virulence determination (Patterson et al. 2000), modulation of Large polymerase activity (Ito et al. 2013) and blocking of induction of type I interferon (Boxer, Nanda, Baron 2009). The V protein is thought to regulate RNA synthesis (Sweetman, Miskin, Baron 2001), and a recent study has shown that PPRV V protein blocks IFN action at multiple points in the pathway (Sanz Bernardo 2017). Finally, it appears that the C protein is thought to have an even more crucial role in blocking the induction of IFN during the initial stages of PPRV infection (Sanz Bernardo 2017).

7.3. Resistance to physical and chemical action

As an enveloped virus, PPRV is particularly easily destroyed outside the host. The half-life of PPRV is about 2 hours at 37°C and it can be completely inactivated at 50°C within 60 minutes. The virus is quite stable between pH 5.8-10.0 but inactivated in pH<4.0 or >11.0. PPRV is susceptible to the most common disinfectants such as alcohol, ether, phenol and sodium hydroxide. The virus can survive for long periods in chilled and frozen tissues (Coetzer, Tustin 2004).

7.4. Pathogenesis

The pathogenesis of PPRV is still under study. Most of the knowledge is based on comparison with related morbilliviruses, mostly Rinderpest and Measles viruses. During infection with PPRV, the virus is initially taken up by antigen presenting cells present in the intraepithelial space and lamina propria of the respiratory mucosa (naso-pharyngeal/respiratory epithelium) (Borrow, Oldstone 1995; Yanagi, Takeda, Ohno 2006). From this site of inoculation, the virus reaches the local draining lymphoid tissues, where the primary virus replication takes place. Then, the virus spreads throughout the body via infected lymphocytes, thanks to both lymphatic and vascular systems (Pope et al. 2013; Esolen et al. 1993; Osunkoya et al. 1990). Viral antigens have been observed by immunohistochemical staining in the lymphoid organs, facial epithelia and gastrointestinal tract (Kumar et al. 2004; Pope et al. 2013). PPRV is thus considered as a lymphotropic and epitheliotropic virus. PPRV infection leads to extensive necrosis in lymphoid organs (Peyer's patches, spleen, thymus, lymph nodes).

The PPRV causes transient but major immunosuppression. This feature is due to virus multiplication in lymphoid tissues and in peripheral leucocytes, but also due to its interference with IFNs production. A study reported that the proportion of circulating $WC1^+$ γ/δ T-cells and $CD14^+$monocyte/macrophage cells did not change after PPRV infection, while the CD4+ cell sub population was the only one that decreases in number from 4 days post-infection (dpi) (Herbert et al. 2014). This immunosuppression can last for weeks and hence impacts the extent and severity of the disease (Jagtap et al. 2012) with higher susceptibility to secondary infections.

7.5. Immunological features

The PPRV infection induces both cellular and humoral immune responses. These immune responses are mainly directed against the N proteins and the two surface glycoproteins (F and H) (Sinnathamby et al. 2001). However, immunisation with H and/or F induces protective humoral immunity whilst immunisation with the N protein does not (Sinnathamby et al. 2001; Diallo et al. 2007).

In new-born animals from infected and/or immunized mothers, maternal antibodies remain able to neutralise the virus for 3-4 months (Libeau et al. 1992). Finally, as for other morbilliviruses, animals that recover from PPR usually develop a life-long immunity to re-infection (Cosby, Chieko, Yamaguchi 2006).

8. CLINICAL SYMPTOMS OF PESTE DES PETITS RUMINANTS

Three main clinical pictures of PPR can be observed (Lefèvre, Diallo 1990; FAO 1999):

8.1. The peracute form

This form is mainly found in goats. The incubation period is about two days. The first clinical sign is a high hyperthermia (41-42°C) followed by prostration, apathy, harsh coat and anorexia. Animals present nasal discharge, lacrimation, and sometimes profuse diarrhea following a short constipation stage. The evolution is rapid, lasting for 5-6 days after the onset of hyperthermia, and death occurs before the onset of any other striking symptom.

8.2. The acute form

This is the most characteristic form of the disease. The symptoms resemble those of Rinderpest, but in small ruminants. The incubation period is 4-6 days (ranging from 3 to 14 days). The first symptoms are those of the peracute form (pyrexia lasting 3-5 days, anorexia, prostration, etc.) (Figure 3).

Figure 3: Apathy and prostration in a goat suffering from Peste des Petits Ruminants. Photo Courtesy of D.P. Kshirsagar (Sharma et al. 2015).

One or two days after the setting of pyrexia, the mucosa of the mouth and eyes become congestive. That congestion is followed by epithelial necrosis on gums, dental pad, palate, lips, inner aspects of the cheeks and upper surface of the tongue. Initially forming pin-point areas (figure 4A), these necrosis areas enlarged and join together. These erosive and ulcerative lesions become coated with dying cells forming a thick cheesy and malodorous deposit (figure 4B).

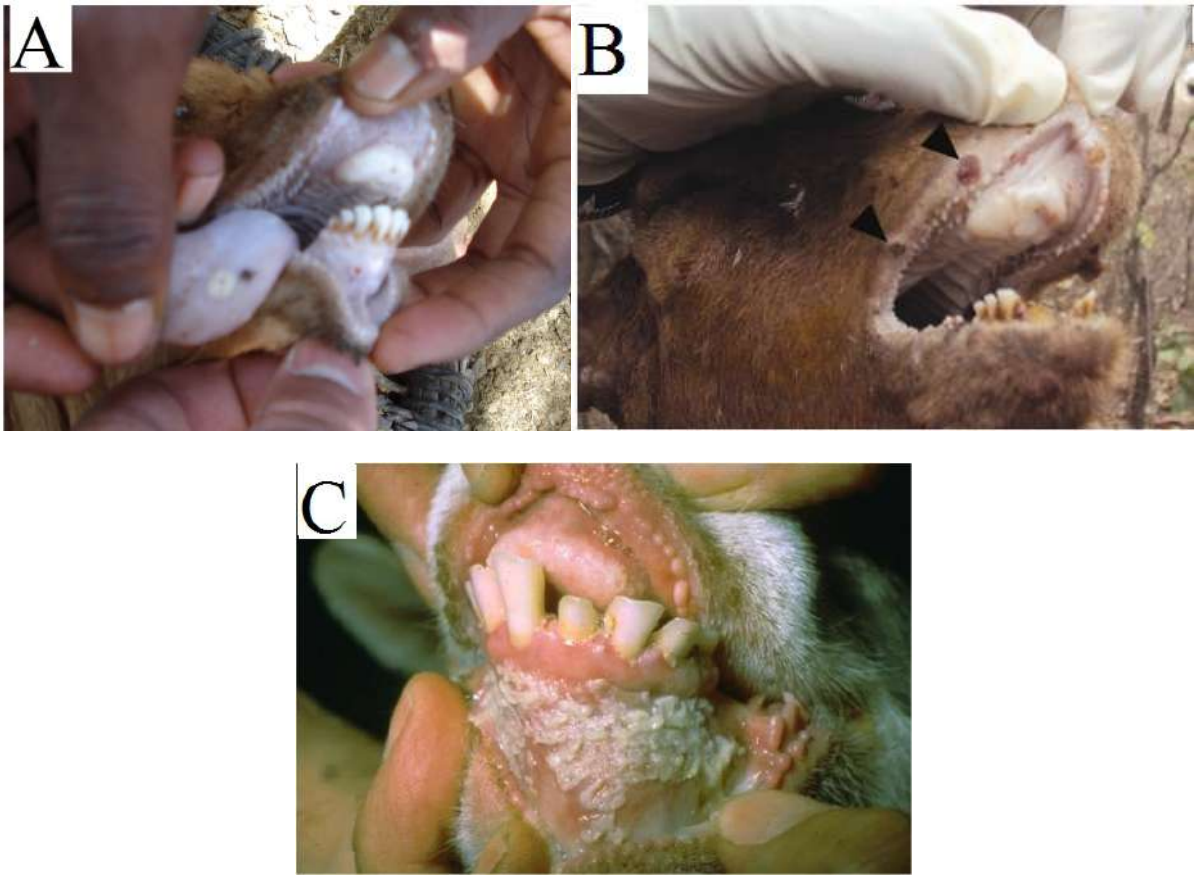

Figure 4: Ulcers on the tongue and gum (A) and on the lips (B) which can eventually lead to a coat of dying cells forming a cheesy deposit (C: photo of W.P. Taylor). Photographs Courtesy: (A) : G. Misinzo (Torsson et al. 2016); (B): G. Misingo(Kgotlele et al. 2014)) and (C): M.D. Baron (Baron 2011).

The lips tend to be covered with scabs (figure 5A). The ruminant shows excessive salivation and refuses to open his mouth because of the pain. Similar necrosis process can also be found in the mucous membranes of the nose, the vulva and the vagina. Oculonasal discharge is observed, and can last 14 days. First seromucous, it becomes mucopurulent (figure 5A) as a result of secondary bacterial infections, and tends to crust, matting the eyelids together and obstructing the nose (figure 5C).

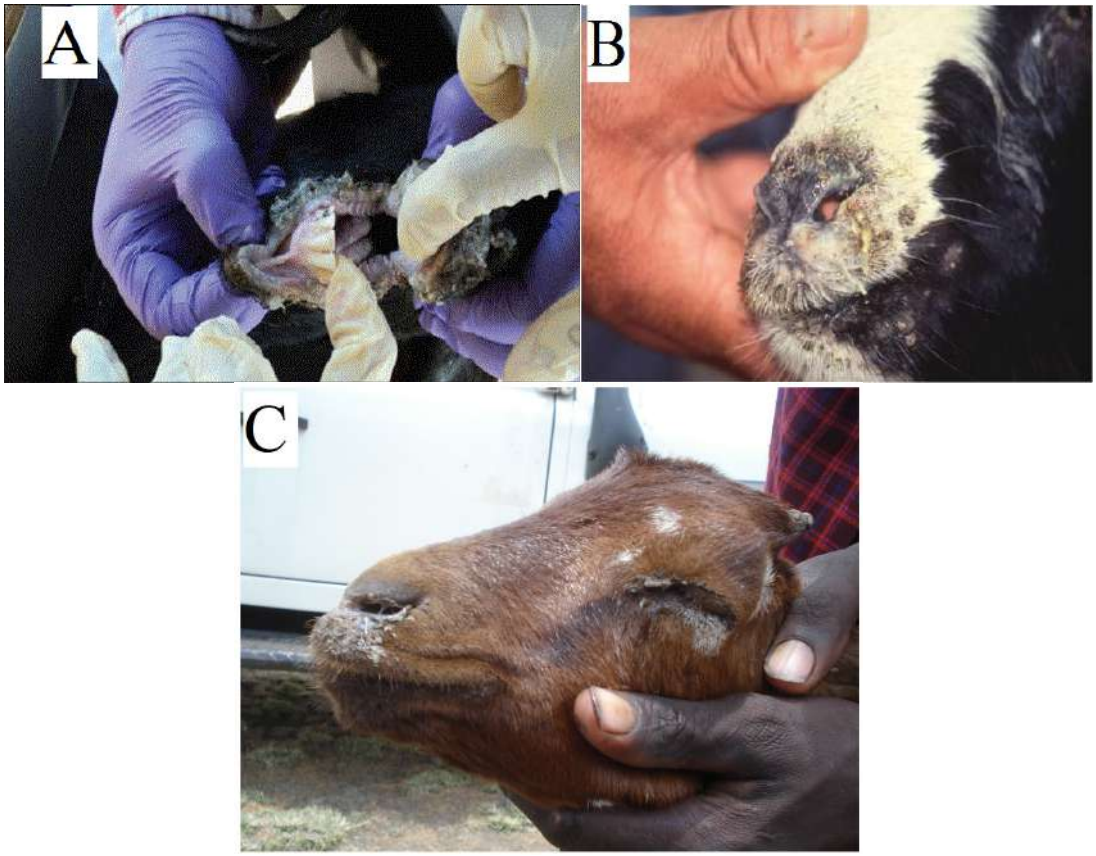

Figure 5: Upper and lower lips covered with scabs (A). Mucopurulent nasal discharge (B) (photo by P.L. Roeder). Obstructed nose and matted eyelids due to dry oculonasal discharge (C). Photo Courtesy of : (A):D.P. Kshirsagar (Sharma et al. 2015), (B): M.D. Baron (Baron 2011) and (C): G. Misinzo (Torsson et al. 2016).

Signs of pneumonia are usually observed in a later stage, with animals coughing, having pleural rales and abdominal breathing. Severely affected animals show marked dyspnea; extension of the head and neck, dilatation of the nostrils, protrusion of the tongue and soft painful coughs (figure 6).

Figure 6: Respiratory distress in a goat suffering from Peste des Petits Ruminants. Photo Courtesy of D.P. Kshirsagar (Sharma et al. 2015).

Diarrhea is commonly observed two to three days after the onset of the fever. The feces are initially soft, then watery, foul-smelling and may contain blood stains and pieces of dead gut tissue. This may not be obvious in early or mild cases.

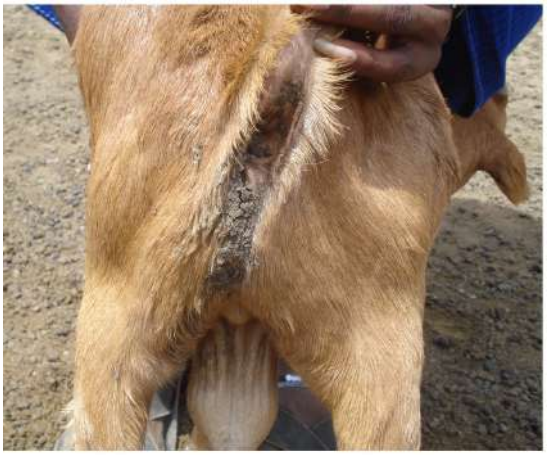

Figure 7: Diarrhea soiling the perineum in a male goat suffering from Peste des Petits Ruminants. Photograph Courtesy of G. Misinzo (Torsson et al. 2016).

In the later stages of the disease, small nodular lesions are commonly found on the outside of the lips around the muzzle and on the neck (figure 8). The cause is not exactly known but is thought to be Dermatophilus infection or reactivation of a latent contagious ecthyma infection, causing confusion for differential diagnosis.

Figure 8: Nodular lesions on the neck of a goat suffering from PPR. Note the severe ulcers on face, nostril and lips and the matted eyelids. Photograph Courtesy of E.A. Muse (Muse, Matondo, et al. 2012).

In absence of complications, illness may last about 8-10 days, leading in either death or in recovery with long-lasting immunity.

8.3. The subacute form

Subclinical form seems to be particularly prevalent in some endemic areas where some local breeds are thought to have innate resistance. The disease lasts for about 10 to 15 days, with inconsistent symptoms (prostration, serous nasal discharge, diarrhea), and sometimes papules or pustules at a later stage.

8.4. Complications

The commonest complications are:

- Pneumonia or bronchopneumonia with bacterial secondary infection, particularly *Pasteurella haemolytica* or *Pasteurella multocida* type A;
- Reactivation of a latent parasitosis (coccidiosis, piroplasmosis, trypanosomiasis) due to immunodepression
- Abortion

Factors such as co-infection with pre-existing parasites, virus or bacteria, and the nutritional status of the animals may also contribute to the disease severity and impact on the outcome (Couacy-Hymann, C. Bodjo, et al. 2007; Ugochukwu, Agwu 1991).

9. POST-MORTEM FINDINGS

The victim shows high degree of dehydration, with sunken eyeballs (figure 9) and watery feces soiling the hindquarters. We find the erosive, congestive, and necrotic lesions already observed in mouth, lips, and nose of live animals.

Figure 9: Sunken eyeballs, lips covered with scabs and congestion of the ocular mucosa. Photo: W.P. Taylor, Courtesy of M.D. Baron (Baron 2011).

Besides these external lesions, the lesions that we can observe are those of conjunctivitis, rhinotracheitis, ulcerative stomatitis, gastroenteritis and pneumonia. The erosive lesions observed in the mouth may extend on the esophagus until the reticulo-rumen junction.

The mucosa of the abomasums, small intestines and large intestines are congested (figure 10A), hemorrhagic, and sometimes zebra stripes (congestion lines) are observed on the mucosa of large intestine and rectum. The congestion is particularly observed in the ileo-caecal junction.

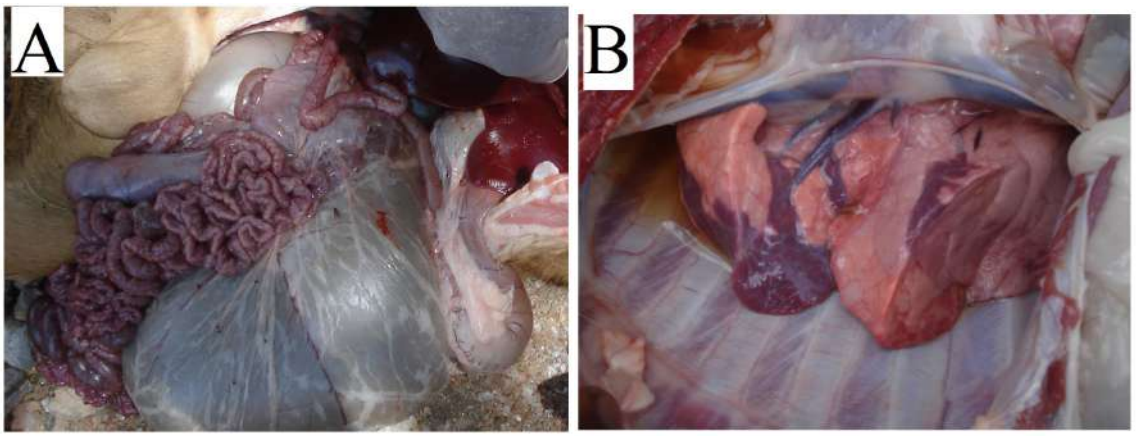

Figure 10: Congestion of the intestines (A) and pneumonia (B) in a goat confirmed with PPR in Ngorongoro, Tanzania. Photo Courtesy G. Misinzo (Torsson et al. 2016).

Peyer's patches may be necrotic, as the spleen and the liver. We can observe enlargement and congestion of the lymph nodes associated with the intestines (figure 11A) and the lungs (figure 11B). The lesions on the lungs are those of interstitial pneumonia. The anterior and cardiac lobes of the lungs are firm to the touch, dark red coloured (figure 10B).

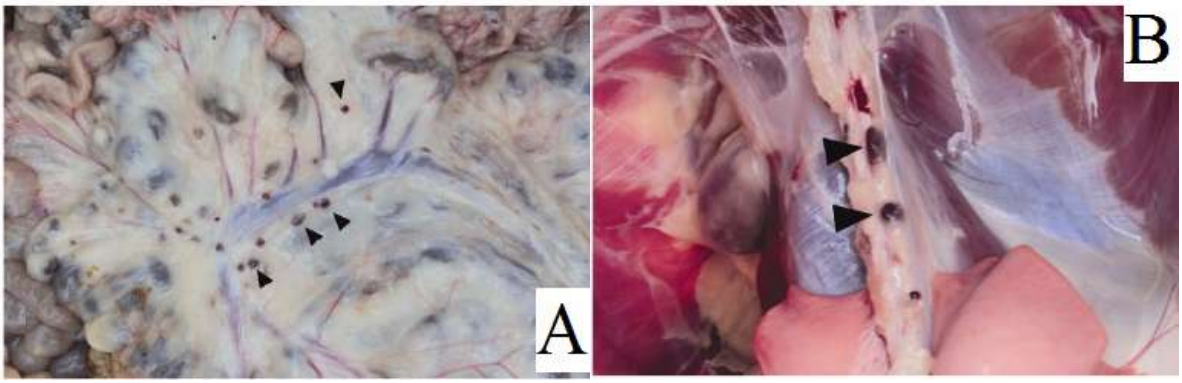

Figure 11: Hemorrhagic lymph nodes in the gastrointestinal (A) and respiratory (B) system of PPR-suspected animals (see arrow heads) in Tanzania. Photographs Courtesy of G. Misinzo (Kgotlele et al. 2014).

Histopathologically, PPRV form syncytia in the lymph nodes, splenic white pulp and gastrointestinal sub-mucosal lymphoid tissue as soon as 5-7 dpi. These syncytia eventually lead to necrosis/apoptosis. Squamous epithelial syncytia can also be observed in digestive tract epithelium and tonsillar and facial tissues (Pope et al. 2013).

10. DIAGNOSIS

There are some events that can help the farmer or the veterinarian to suspect Peste des petits ruminants (FAO 1999):

- The recent movement or gathering of small ruminants of different ages;
- The introduction of recently purchased animals;
- The return of unsold animals from the market;
- The onset of rainy or dry cold season, changing the housing and feeding;
- Or a change in husbandry such as intensification of livestock.

10.1. Differential diagnosis

Based on mouth lesions, it is possible for farmers, veterinarians and veterinary technicians to misdiagnose with rinderpest, foot and mouth disease, bluetongue, or contagious ecthyma. The difficulty in breathing can be found in clinical pictures of pneumonic pasteurellosis, or contagious caprine pleuropneumonia (CCPP). The diarrhea can be due to coccidiosis, or gastrointestinal helminth infestations. None of these diseases cause the full clinical picture of PPR (respiratory, diarrhea, necrotic stomatitis), but animals may not present all of the clinical signs. The diagnosis of PPR may also be complicated by secondary bacterial infections. Therefore, laboratory confirmation of PPR is necessary for definitive diagnosis.

10.2. Laboratory diagnosis

A comprehensive review of the available laboratory techniques and the promising techniques has recently been published (Santhamani, Singh, Njeumi 2016). In this section, we will focus on the main laboratory techniques and their application.

10.2.1. Collection of samples

Depending on what is under investigation (i.e. viral excretion or seroprevalence), the best moment for sampling will be different. Recently, very sensitive methods like RT-PCR or immunocapture ELISA techniques have been developed. Such methods can detect viral shedding 1-3 days before the onset of clinical signs (Couacy-Hymann, S.C. Bodjo, et al. 2007; Couacy-Hymann et al. 2009).

Generally speaking, sample collection for virological investigation must be done on animals showing clinical signs (mainly from 4 to 17 dpi). For retrospective serology, sampling can be made at any time within 3 years after seroconversion of the animals (Zahur 2015).

In live animals, swabs can be made of the conjunctival discharges and from nasal and buccal mucosa, ideally during the erosive mucosal phase of the disease. The use of swab is more and more common; as it is safe, simple and painless for animals, breeders are usually more compliant for sample collection with this technique.

At necropsy, samples can be collected aseptically on fresh carcasses from mesenteric and/or bronchial nodes, lungs, spleen and intestinal mucosa, ideally on 2-3 animals. The samples for histopathology must be places in 10% neutral buffered formalin solution. Biopsies can also be done on live animals during the febrile stage of the disease, although rarely achievable on the field.

Blood collection is always valuable, either at the early stage of the disease for virus isolation, PCR or hematology (whole blood collection on anticoagulant, ideally heparin) or at a later stage for serological diagnosis.

Samples for virus isolation must be kept chilled but not frozen from the collection site to the laboratory. Indeed, the efficiency of laboratory diagnosis is greatly influence by the integrity of the sample, thus care must be taken for the conditions of collection and transportation.

The laboratory diagnosis techniques can be sorted in two categories: the techniques detecting antibody response, and the techniques detecting PPRV presence (viral antigen, viral nucleic acid or virus isolation).

10.2.2. Virus isolation

Virus isolation in cell culture is considered as the gold standard technique for virus identification. The cell culture is most commonly done on Vero cells. However, this technique is time-consuming and requires cell culture facilities. Results are obtained in 10-12 days. Thus, virus isolation cannot be used routinely or as a trigger alert technique.

10.2.3. Antigen detection

Agar gel immunodiffusion and counter immunoelectrophoresis were developed in the 1980's. They detect antigens from swabs and tissues of infected animals, using PPRV-specific antibodies. As their sensitivity is low, these techniques cannot be used for mild forms of the disease nor for early stages of infection due to the low quantity of viral antigen that is excreted. Immunohistochemistry techniques have also been developed: the fluorescent antibody test (requiring fluorescent microscope and technical expertise) and the immunoperoxidase test (requiring only a light microscope, more accessible for less well-equipped laboratories). A haemagglutination test is also available, and based on the haemmagglutination property of the PPRV H protein. Although simple to perform, this test lacks specificity as many virus families have haemagglutination properties as well.

The two following methods (ELISA and immunochromatography) are the most employed are promising antigen detection methods. Immunocapture ELISA is a test using monoclonal antibodies (MAbs) against PPRV N protein. A sandwich ELISA test is also available and both immunocapture and sandwich ELISAs are available in a commercial kit. The major benefit of such tests is that they have desirable sensitivity and specificity levels and they are user-friendly. Results are obtained in 2 hours. In addition, an immunochromatographic lateral flow device has been recently developed as a pen-side test. This technique is using H protein-specific MAb (Brüning-Richardson et al. 2011). This method is considered cost effective and easy to perform, giving results in a matter of minutes. It has recently been validated under field conditions for early diagnosis (from 4 dpi, so before the onset of the severe clinical sign)

(Baron et al. 2014). Another pen-side test using anti-N protein MAb has been developed. Although they show a lesser sensitivity compared to nucleic-acid detection methods or immunocapture/sandwich ELISA, their major interest is that they give an almost immediate result, avoiding sample transportation to the laboratory which can take days in PPR-endemic countries with often poor infrastructures. Using these tests, stakeholders can make a rapid decision about the PPR-status of the animal flock/herd, mitigating the risk of further spread in the neighbouring areas.

10.2.4. Nucleic acid detection

The RT-PCR technique targets PPRV F and N protein genes, and is 1000 times more sensitive than classical virus isolation on Vero cells (Couacy-Hyman et al. 2002). Results are obtained in 5 hours. However, these tests are laborious and require expensive facilities that may not be available in laboratories with fewer resources. This makes the RT PCR unaffordable for routine diagnosis are large sample size screening. Moreover, RT-PCR is very sensitive to cross contamination, giving false positive results. It is also very sensitive to the quality of the sample and manipulation, leading easily to false negative results if care is not taken.

A RT-PCR-ELISA technique, based on PPRV N gene, has also been developed. It is 10 times more sensitive than the classical RT-PCR. However, this technique is considered as time-consuming and prone to cross-contamination.

The development of real time RT-PCR has improved the set of nucleic acid detection methods available. This test is 10 times more sensitive than the conventional RT-PCR. Another asset of the real-time RT-PCR compared to the RT-PCR is the lesser risk of cross-contamination. However, although more rapid than the RT-PCR, it is still a costly and time-consuming method.

Finally, LAMP assay has been developed for diagnosis of PPR based on M and N genes. This test still needs to be tested on various clinical samples and for different PPR lineages. However, LAMP PCR is considered as a promising technique, especially for laboratories with poor resources, as it doesn't require sophisticated thermo-cycler and can be used without much technical expertise and equipment. Other RT-PCR improvements are currently under study, such as TaqMan probe assays and SYBR Green assays, mainly improving the detection rate.

10.2.5. Antibody detection

The virus neutralization test (VNT) is considered as the gold standard for antibody detection, as it is an OIE accepted diagnostic tool for international trade. The disadvantage of this technique is the need of culture facilities and sterile serum, making this technique hardly suitable for routine sero-surveillance and monitoring.

Competitive ELISA (C-ELISA) and blocking ELISA tests have good sensitivity and specificity. Both anti-N protein and anti-H protein MAbs based ELISAs are available as commercial kits, enabling large scale sampling when needed. They are simple, quick and cost-effective techniques.

The table 1 gathers the main laboratory diagnosis techniques and their recommended purpose.

Table 1: Main test methods available for the diagnosis of Peste des Petits Ruminants and their purpose. Key: +++: recommended method; ++: suitable method. Adapted from (Baron et al. 2016; OIE 2013)

	Virus isolation	ICE-ELISA	RT-PCR & qRT-PCR	VNT	C-ELISA
Target	virus	protein	gene	antibody	antibody
Confirmation of clinical cases	++	+++	+++		
Individual freedom from infection				+++	++
Immune status in individual animals – post vaccination				+++	+++
Prevalence of infection - surveillance				+++	+++
Population freedom from infection				+++	++

11. VACCINES

Sanitary preventive measures such as restriction of animal movements, stamping out, and extended disinfection are difficult to implement in the PPR endemic regions that are also developing countries. Therefore, the vaccination is the main means of prophylaxis effective and available. In the past, small ruminants were vaccinated with the tissue culture rinderpest vaccine that was used as a heterologous vaccine against PPR. Small ruminants vaccinated with this vaccine were successfully protected against PPR, due to the antigenic similarity between RPV and PPRV (Mariner et al. 1993). However, the use of this heterologous vaccine became forbidden in 1996, when there was a need to differentiate rinderpest infected and vaccinated animals during the final stages of the rinderpest eradication programme. As there was no DIVA vaccine for RPV, once a country was declared free of rinderpest, the use of the rinderpest vaccine in any animal species was forbidden.

11.1. Live attenuated vaccines

In 1989, Diallo et al successfully produced an attenuated PPRV vaccine from the Nigeria 75/1 strain by serial passage in Vero cells of a virulent strain (Diallo et al. 1989). Similarly, 3 more vaccine strains, Sungri 96, Arasur 87 and Coimbatore 97 have been developed. Currently, Nigeria 75/1 (lineage II) is extensively used, mostly in African countries, and Sungri 96 (lineage IV) is widely used throughout India.

Vaccines are protective against the different lineages of PPRV (Singh et al. 2009). As they are live attenuated vaccines, they induce both cellular and humoral immune responses. Once

vaccinated, animals are unable to transmit the virus to animals to which they are in close contact.

Current vaccination schedules require immunization of susceptible animals at least every 3 years (Diallo et al. 2007; Saravanan et al. 2010). Indeed, the durations of protective immunity for Nigeria 75/1 and Sungri/96 vaccines have been shown to be at least 3 years (Diallo et al. 2007; Sen et al. 2010; Zahur 2015; Singh et al. 2009) and at least 6 years (Saravanan et al. 2010), respectively. Protective immunity is induced upon a single vaccine administration. Nigeria 75/1 induces a neutralizing antibody response from 7 days post-vaccination (Diallo et al. 1989).

As small ruminants in PPR-endemic countries are generally not kept more than 3 years in a flock, which means that a single vaccination protects efficiently one animal for its whole economic life-span.

Young animals should be vaccinated between 4-6 months, but not before 3-4 months of age (Ata et al. 1989; Balamurugan, Sen, et al. 2012) since maternal antibodies can interfere with vaccination. Nigeria 75/1 and Sungri/96 are both safe in pregnant animals (Parida et al. 2015).

The live attenuated vaccines are available in freeze-dried form and are thermo-sensitive; the shelf life is about 1 year when kept at 4°C (Singh et al. 2009). Thus, an effective cold chain from the manufacturer to the field is required to ensure maximal virus titre for inoculation and to obtain the expected immune response. Unfortunately, PPR-endemic countries are mostly found in subtropical areas and often have poor infrastructure with inconsistent electric supply.

To address this issue, improvements have been made on freeze-drying methods and stabilizers: to date, PPR vaccine is able to resist temperature of 45°C for 14 days without any major loss of potency (Worrall et al. 2000).

11.2. Recombinant sub-unit vaccines

Vaccinated animals produce high amount of neutralizing antibodies against H, F and N proteins, similar to the animals that recovered from natural infection (Diallo et al. 1987; Sinnathamby et al. 2001). Thus, serologic investigations cannot differentiate infected animals from vaccinated animals, which is an obstacle for the smooth running of the PPR control and eradication programme. Therefore, current research focuses on the development of a DIVA (Differentiation of Infected and Vaccinated Animals) vaccine. A DIVA vaccine enables to differentiate vaccinated from infected animals through either adding or removing some viral proteins to be expressed in the viral genome used for the vaccine.

A recombinant capripox virus vaccine has been developed. The capripox virus is used as a vector expressing PPRV H and/or F proteins, but no N protein. Thus, it is possible to identify the vaccinated animals by the absence of anti-N antibodies. Another benefit of this bivalent vaccine is that it enables the simultaneous vaccination against two major pathogens of small ruminants. Indeed, this recombinant vaccine has been shown to protect efficiently goats and sheep against both PPRV and capripox infections (Chen et al. 2010; Berhe et al. 2003; Caufour et al. 2014; Diallo et al. 2002). However, a recent study (Caufour et al. 2014) has shown that vaccination of animals with pre-existing immunity against capripox virus was only

inducing partial immune response against PPRV. Given the fact that capripox is a common disease in PPR-endemic areas, the capripox-PPR bivalent vaccine may seem of lesser interest.

Recently, additional research has been made on adenoviruses as potential vectors for PPRV H and/or F proteins. Human adenovirus type 5 has shown to induce protective immune response against wild-type PPRV infection (Rojas et al. 2014; Wang et al. 2013; Herbert et al. 2014). A canine adenovirus-PPR recombinant vaccine is also under study; it has shown to induce the production of PPRV-neutralizing antibodies, though protection from challenge has not been assessed yet (Qin et al. 2012). As these adenoviruses are not found in small ruminants, it is unlikely that there is any pre-existing immunity that could affect the immune response as for the capripox-PPRV vaccine. Furthermore, adenoviruses have a greater thermotolerance compared to other morbilliviruses and thus could be an asset as we already mentioned the sensitivity of PPRV to the heat. To date, recombinant subunit vaccines are still under investigation.

CHAPTER 2: EPIDEMIOLOGY OF PESTE DES PETITS RUMINANTS

1. EPIDEMIOLOGICAL PATTERNS

Two epidemiological patterns have been determined (adapted from (Lefèvre, Diallo 1990)):

- **The enzootic pattern:**

The virus circulates in the area causing mild disease (mainly lower productivity and higher susceptibility to secondary infections that are the only events to be noticed by farmers). Animals display no PPR clinical signs, but there is a high PPR seroprevalence among the flock. Clinical outbreaks are rare, and usually happen because of mixing these flocks of immunologically naïve flocks. Endemic regions are those of the Sahel (Mali, Niger, Chad) or South Asia (India, Pakistan) for example. Morbidity and mortality rates are usually lower than in the epizootic form.

- **The epizootic pattern:**

PPR outbreaks are apparently cyclic and occur every 4-6 years. Indeed, the animals recovering from PPRV infection develop a life-long immunity. Given the turnover of sheep and goats (90% of small ruminants are replaced in 3 years), the immune status of the flock is progressively evolving towards a naïve status for PPR. When the proportion of naïve animals (mainly animals born after the last outbreak) has reached a certain point, PPR outbreaks can occur again (Lefèvre 2003; Waret-Szkuta 2011). Epizootic regions were reported to be mainly humid zones along African coasts (Mauritania, Senegal, Nigeria).

When naïve populations experience epizootic outbreaks, the morbidity rate can be up to 80-90% and mortality rate between 50 and 80% (Lefèvre, Diallo 1990). These epizootics are often linked to the introduction of infected animals during incubation phase into naïve and susceptible populations. The virus then spreads rapidly in immunologically naïve flocks. Such outbreaks were seen in newly infected areas such as Maghreb for example.

PPRV can only persist in large populations with intense animal movement and gathering, and only if there are new susceptible hosts regularly available (newborns, migrating/transhumant animals, newly purchased animals) (Anderson 1995).

2. SOURCES OF VIRUS

As PPRV is quickly inactivated outside the host, the main (if not only) source of virus is infected animals. There is no carrier state (Hamdy et al. 1976). Infected animals transmit the virus to susceptible animals which are in close and direct contact, through exhaled aerosol or clinical excretions: oral, nasal, lachrymal secretions and faeces (Abubakar et al. 2012). Therefore, animals can also become infected through ingestion of feed and water contaminated by faeces.

PPRV nucleic acids can be detected in lachrymal, nasal and mucosal discharges as early as 3 dpi, being few days before the onset of visible clinical signs (Couacy-Hymann, S.C. Bodjo, et al. 2007) but no infectious virus has been isolated from conjunctival swabs until 7 days post-infection (Pope et al. 2013). These results highlight the possible role of incubatory carriers in PPRV transmission. In addition, it has been shown that goats which recovered from natural PPR infection were shedding the PPRV antigens in faeces for at least 11 weeks (Ezeibe et al. 2008), although we still do not know if this is infectious virus. Recently, a longitudinal study detected viral RNA in faeces using rRT-PCR up to 16 weeks after infection in goats (Wasee Ullah et al. 2016) without being able to isolate the virus on Vero cells.

Finally, we cannot exclude indirect transmission through recently (within hours) contaminated material. This idea could be supported with the report of PPR seroprevalence of 12% in Goitered Gazelles (*Gazella subgutturosa subgutturosa*) living in a park, where the nearest domestic animal location was a cattle barn 2 km away (Gür, Albayrak 2010). Thus, it is believed that it should be considered in further epidemiological models and risk based control measures (Baron et al. 2016).

3. HOST RANGE

Peste des petits ruminants is primarily a disease of sheep and goats. To date, they are considered as the only species to be able to excrete and spread the virus.

PPR antibodies seroprevalence has been reported in camels sharing range with sheep and goats, without any clinical consequence (Abraham et al. 2005; Haroun et al. 2002; Woma et al. 2015; Ismail et al. 1992; Swai et al. 2011). A recent study found PPR antigens in 45% of the sampled lungs in slaughterhouses in Sudan (Saeed et al. 2015). However, some PPR outbreaks in camels did cause clinical signs and death in Ethiopia, Sudan and Tajikistan (Roger 2001; Khalafalla et al. 2010; Kwiatek et al. 2011). Recently, another outbreak in Sudan has been reported in a camel herd just imported from Kuwait (Zakian et al. 2016). However, experimental reproduction of the disease in camels has not been successful (Wernery 2011). Further research is needed to determine if infected camels can transmit the virus or not.

Conversely to camels, PPR is not considered as pathogenic in cattle and in both wild and domestic African buffaloes (*Syncerus caffer*). Observations of PPR seroconversions, without any clinical signs, have been reported several times in cattle (Abraham et al. 2005; Khan et al. 2008; Ozkul et al. 2002; Haroun et al. 2002; Abubakar et al. 2017; Lembo et al. 2013;

Albayrak, Gür 2010; Anderson, McKay 1994), and buffaloes (Khan et al. 2008; Balamurugan, Krishnamoorthy, et al. 2012; Abubakar et al. 2017).

Both large ruminants were living in mixed farming systems, sharing grazing areas and watering points with small ruminants in PPR-endemic areas. So far, only one PPR clinical event (with a case fatality rate of 97%) has been observed in domestic Indian buffaloes (*Bubalus bubalis*) (Govindarajan et al. 1997).

Experimental PPR infection in calves induced clinical signs and case fatality (Mornet et al. 1956). An experiment on pigs revealed that after inoculation or contact with infected goats, pigs underwent a subclinical disease without being able to transmit the virus (Nawathe, Taylor 1979). To date, cattle and probably buffaloes are considered as dead-end hosts for PPRV (Munir 2014), which means that they are resistant to infection and unable to maintain the infection without external source.

Several PPR outbreaks in wild ruminant species, mostly living under semi free-range conditions, have been reported. The first description of natural PPR cases in wildlife was in 1987, among a zoological collection, with disease report in Dorcas gazelle (*Gazella dorcas*) and Gemsbok (*Oryx gazella*) and subclinical infection in Nilgai (*Tragelophinae*) (Furley, Taylor, Obi 1987). In March 2002, a collection of about 200 gazelles kept under semi range conditions in Saudi Arabia experienced a highly fatal peracute disease that revealed to be due to PPRV (Elzein et al. 2004). In 2005/2006, a PPR outbreak was reported in a private collection of wild small ruminants, mainly gazelles and antelopes, in the Arabian Peninsula (Kinne et al. 2010). Very recently, PPRV lineage II has been reported in a water deer (*Hydropotes inermis*) farm in China (Zhou et al. 2017).

PPRV has also been found in free-living small ruminants. In 2007, PPRV has been reported both serologically and genetically in free-living bharals (*Pseudois nayaur*) in Tibet, China. The transmission was thought to happen when bharals shared pasture with domestic small ruminants (Bao et al. 2011). A PPR outbreak in Sindh Ibex (*Capra aegagrus blythi*) ranging in a National Park in Pakistan has been reported (Muhammad Abubakar, Rajput, et al. 2011). It was observed that wild animals and sheep and goats from the near villages were sharing grazing areas and water sources. There was also a history of a recent introduction of goats' herd in a village close to the park, just before the onset of disease symptoms in Sindh Ibex.

The latest PPR clinical outbreaks in wildlife happened in January 2017 in Israel and Mongolia. 30 Nubian Ibex (*Capra nubiana*) living in a zoo in Jerusalem have been clinically affected, with a mortality rate of 70% and a fatality rate of 100%. The veterinary services stated that no contact with domestic or wild ruminants was possible, and thus suggested human or fomites as the source of introduction (OIE report). In a Natural Park in Mongolia, almost 2000 free-living Mongolian Saigas (*Saiga tatarica mongolica*) were infected by PPR, with a mortality rate of 100%. This event happened only 6 months after PPR first introduction in domestic small ruminants in Mongolia.

A recent study in the Serengeti Ecosystem, Tanzania, reported antibody seroprevalence in resident wildlife living near resident livestock and sharing range with them (Mahapatra et al. 2015). The results suggested a regular PPR exposure in wildlife populations sharing areas with domestic small ruminants. Similarly, a serological survey in Northern Tanzania reported that cattle living with small ruminants in mixed livestock systems had high PPR seroposivity. Conversely, samples from wildlife living in wildlife-protected areas, with few opportunity for contact with sheep and goats, revealed no PPR seropositivity (Lembo et al. 2013).

These results support the thought that wild small ruminants are susceptible to PPR but unable to maintain the virus within their populations: outbreaks are linked to close-contact with infected sheep and goats living in the area (Couacy-Hymann et al. 2005). To date, wild ruminants are considered as spillover hosts.

4. RISK FACTORS

Various risk factors for PPR seroprevalence have already been identified in the literature, and are listed below. They were first identified in 2008 and gathered in a table format (Waret-Szkuta 2011) that has been updated in 2013 for a FAO project (Tran 2013).

4.1. Individual risk factors:

Species has been reported as a susceptibility factor several times. While it is thought that goats are more susceptible than sheep (Roeder et al. 1994; Singh et al. 2004; Ozkul et al. 2002; Kihu et al. 2015), there have been some severe outbreaks in sheep (Khan 2008; Khan et al. 2008). The OIE field manual states that in Africa PPR is mostly seen in goats, while in Western and South Asia sheep are usually the most susceptible (FAO 1999). As regards age, young animals from 4 to 12 months are reported to be more susceptible to the virus (Diallo 2003a; Gopilo 2005). Breed is also believed to impact PPR susceptibility: Guinean breeds (West African dwarf, Iogoon, Kindi and Djallonke) for example are reported to be highly susceptible compared to most of the Sahelian breeds, perhaps because PPRV survive longer in dry regions (Lefèvre, Diallo 1990). Seroprevalence has been found higher in female than in male several times (Waret-Szkuta et al. 2008; Aziz-ul-Rahman et al. 2016; Kihu et al. 2015) however some authors state that this may be explained by the fact that female are kept longer in the flock, mainly for reproductive purpose.

4.2. Production systems:

Pastoralism and/or nomadic pastoralism are production systems that are often reported as risk factors for PPR transmission (Abubakar et al. 2009; M. Abubakar et al. 2011; Bett et al. 2009; Singh et al. 2004; Megersa et al. 2011; Mahajan et al. 2012; Shankar 1998; Nanda 1996). Large herds or high ruminant densities seem at higher risk for PPR transmission (Al-Majali et al. 2008; Khan 2008; Ozkul et al. 2002; Kardjadj et al. 2015). Raising both sheep and goat together may enhance the risk of PPR transmission (Al-Majali et al. 2008; Anderson, McKay 1994; Kardjadj et al. 2015).

Open flocks are supposed to be at higher risk, as the introduction of animals purchased at the market has been already reported as risk factor for PPR transmission (Abubakar et al. 2009; M. Abubakar et al. 2011; Singh et al. 2004; Mbyuzi et al. 2014) and some PPR outbreaks have been linked to recent introduction of animals from a market (Muse, Karimuribo, et al. 2012; Abubakar et al. 2009). Small ruminants sharing grazing areas or watering points (Mbyuzi et al. 2014; Lefèvre 2003), are thus in close contact with each other and more likely to transmit the virus through fresh secretions. Sedentary production systems are likely to present a lower risk of disease than systems which involve seasonal migrations for water and pasture (Tran 2013).

4.3. Markets/Trade/theft:

Uncontrolled and/or frequent movements of animals are reported to enhance the risk of PPR transmission, as importation of live small ruminants (legal/illegal) (Al-Dubaib 2009; Ozkul et al. 2002; Al-Naeem 2000; Almeshay et al. 2017), animal movements between neighboring countries (Ozkul et al. 2002; Singh et al. 2004; Wang et al. 2009; Osman 2009) or livestock theft (Bett et al. 2009). In Libya, a study reported that PPR seroprevalences were higher in illegally imported animals than in legitimately acquired or animals belonging to the same herd, and that prevalence in illegally imported animals was higher compared to local breeds (Almeshay et al. 2017). Visiting live animal markets is considered as a practice that can put the flock at risk for PPR transmission (Al-Majali et al. 2008; Martrenchar et al. 1997; Shankar 1998). Traditional and commercial practices (Bazarghani 2006) and festival periods (Bonniwell 1980) (such as sacrifices for funerals, weddings, religious calendar events) are reported to be linked to increased small ruminant movements and thus may cause the introduction of infected animals into PPR-free areas.

4.4. Season:

PPR outbreaks seem to occur more often either during the hot and wet season (Rony et al. 2017; Mondal 2014; M. Abubakar et al. 2011; Taylor, Barrett 1990) or during the cold dry season (Obi et al. 1983; Singh et al. 2004; Abubakar et al. 2009). The authors tend to explain this trend by the fact that during the wet season, more small ruminants are kept inside, thus in higher concentration and in stressful conditions favouring virus transmission. In dry season however, they are mainly kept outdoor but the lack of food available enhances the contact between animals through shared watering points and grazing areas. However, it has been suggested that this increased incidence might rather reflect the increased introduction of susceptible young animals to the flocks (Taylor 1984). (Lefèvre, Diallo 1990) also pointed out the greater resistance of Paramyxoviridae in regions of low relative humidity, implying that PPRV would survive longer in dry regions.

4.5. Veterinary services:

Inefficient quarantine, limited access and availability of veterinary services along with a lack in surveillance systems have been reported in several articles as risk factors for PPR transmission (Al-Majali et al. 2008; Bett et al. 2009; Bazarghani 2006).

5. ORIGIN OF THE DISEASE

Peste des Petits Ruminants was first described in 1942 in the Ivory Coast (Gargadennec, Lalanne 1942). At this time, authors observed that this disease was causing Rinderpest-like symptoms to small ruminants, without being transmissible to cattle in contact with them. A similar disease was also reported in Benin about ten years later (Mornet et al. 1956). Thus, for a few decades, Peste des Petits Ruminants was thought to be restricted to West Africa. It is only after identification of the causative virus in 1979 (Gibbs et al. 1979) that scientists highlighted the apparent spread of PPR throughout many countries of Africa, the Near and Middle East and some parts of Asia.

There may be several reasons for the apparently rapid spread of PPR worldwide in the last 50 years. The main reason is thought to be the misdiagnosis of PPR as rinderpest when rinderpest was still present, since Rinderpest and Peste des Petits Ruminants have similar clinical signs. Indeed, even if rinderpest clinical cases in small ruminants were a relatively rare event, several publications recorded rinderpest outbreaks in small ruminants. For example, in India in the 1930's, some "rinderpest" outbreaks in goats were reported (Bawa 1940), without affecting the neighbouring cattle. In Sudan, an old outbreak in small ruminant appeared to be due to PPR, 10 years after being first described as rinderpest outbreak (El Hag Ali 1973; El Hag Ali, Taylor 1984). In the same way, it is possible that some rinderpest outbreaks reported in Senegal in 1871 and French Guinea in 1927 were in actually due to PPRV (Taylor 1984). Furthermore, as sheep and goats being immunized against RPV (with vaccination or natural subclinical infection) are also immunized against PPRV (Taylor 1979), it is possible that PPRV had less ability to spread in areas where rinderpest was endemic. When the rinderpest became eventually eradicated, the sheep and goats' flocks became more susceptible to PPRV.

The increase of livestock movements across regions is also thought to have played a role in PPR worldwide spread. Finally, it is admitted that PPR cases identification is now also facilitated with the availability of PPR-specific diagnostic tests and the increasing awareness and knowledge about the disease.

6. GLOBAL DISTRIBUTION

Initially found in Western Africa, Peste des petits ruminants has first extended across Sahara-Sahel Belt in Africa. Spreading throughout the Eastern Africa and the Arabian Peninsula, PPR finally reached Central and South Asia (figure 12).

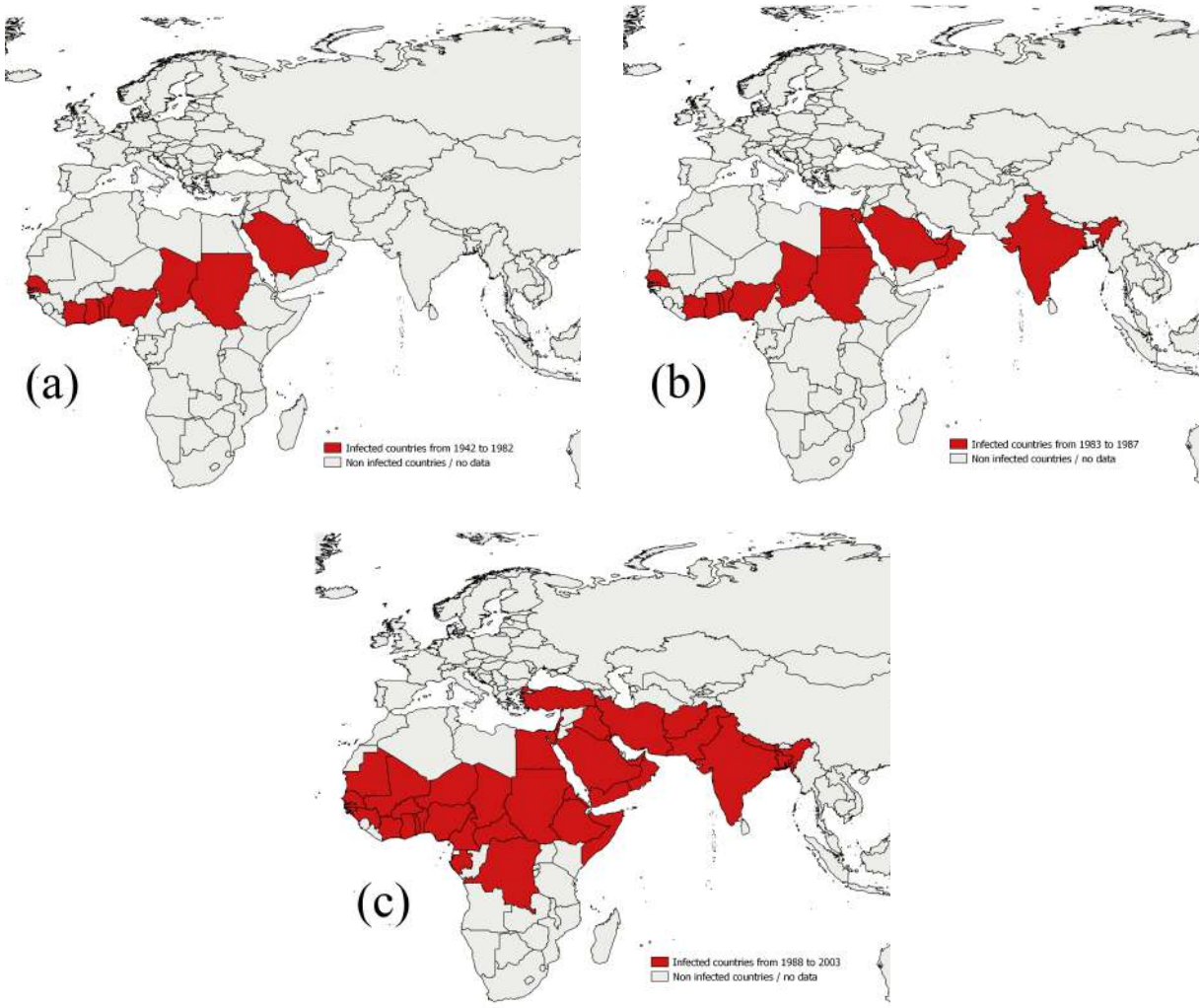

Figure 12: Spread of PPRV throughout the world. (a) From 1942 to 1982; (b) From 1983 to 1987; (c) From 1988 to 2003. Adapted from (OIE 2017; Parida et al. 2015).

In Turkey, the PPR was officially reported in 2000, and several outbreaks occur every year since. Disease has been reported both in the Asian part of Turkey (Anatolia) and in the European part of Turkey (Thrace) (Albayrak, Gür 2010; Yesilbag et al. 2005). Georgia reported its first and single PPR outbreak early 2016, which was resolved in 3 months through the conduction of mass control measures (OIE 2017).

Although already present in Egypt in 1989 (Ismail, House 1990), PPR infection in North Africa was reported only few years ago, with the first report of PPR infection in Tunisia in 2006 (Ayari-Fakhfakh et al. 2011), in Morocco in 2008 (Kwiatek et al. 2011), and in Algeria in 2011 (De Nardi et al. 2012). The origin of the outbreak of 2008 in Morocco was suggested to be consecutive of an outbreak in Sudan (Baazizi et al. 2017). After the outbreak, Morocco implemented mass vaccination campaigns, but once completed, PPRV finally re-emerged in 2015. Since then, PPR has re-emerged several times, and the latest outbreaks happened in June 2015 in Morocco, February 2016 in Algeria, and August 2016 in Tunisia.

In the same time, PPR extended southwards, with first OIE notification of the Republic of Congo in 2005, in Kenya in 2006, Uganda in 2007, Tanzania in 2008, Angola in 2012. The veterinary services stated in their OIE notification that the outbreak in Congo was happening in a herd in which animals bought in a border livestock market had been introduced. In Angola, they reported that the detection of PPR antibodies during routine surveillance was positive on animals brought from DRC (OIE 2017). Serologic evidence of PPR in Gabon was already reported in 1993 and 1996, but the first virus confirmation became only possible during the outbreak of 2011 (Maganga et al. 2013). In Comoros, a first outbreak was reported in 2010. In 2013, several outbreaks were reported again, affecting young goats (4-8 months) of native breed in a traditional breeding system on pasture, and goats imported from Tanzania (OIE 2017). The origin of the outbreak is thought to be from the import from Tanzania (Cêtre-Sossah et al. 2016). In Zambia, the infection was suspected in 2010 but the first serological evidence of PPR was in 2015. Since, several seropositivity outbreaks have been reported to the OIE, and the Zambian veterinary services pointed out that the affected areas were near the borders with PPR infected or high risk countries (OIE 2017). Clinical disease has never been reported in Zambia so far. In 2015, Liberia reported its first PPR outbreak, which is still continuing to date. Djibouti reported PPR outbreak for the first time in 2016.

In Asia, the disease has spread to Tibet autonomous region in 2007 (Wang et al. 2009). Then, PPRV re-emerged in China in 2013-2014 (Wu et al. 2016). In 2010, Bhutan reported its first outbreak to the OIE, and the veterinary services linked this outbreak with the introduction of new animals coming from a southern border town. Maldives reported its first PPR outbreak to OIE in 2009. PPR finally reached Mongolia in August 2016, spreading further north in Asia. Some countries did not officially notify PPR presence in their territory but publications have reported PPR infection, either through serological investigation or virus detection. PPR antibodies were reported in Kazakhstan as early as 1997 (Lundervold 2004), but the virus isolation was only possible recently with the identification of lineage IV (Kock et al. 2015). Western Sahara (Baazizi et al. 2017), Syria (Hilan et al. 2006), Jordan (Lefèvre et al. 1991; Al-Majali et al. 2008) and Qatar (Banyard et al. 2010). PPR antibodies have also been reported in various farms in Vietnam, close to the Chinese border (Maillard et al. 2008). 3 countries are currently considered suspects to OIE but not confirmed yet: Rwanda, Equatorial Guinea, and Sao Tomé e Principe (figure 13).

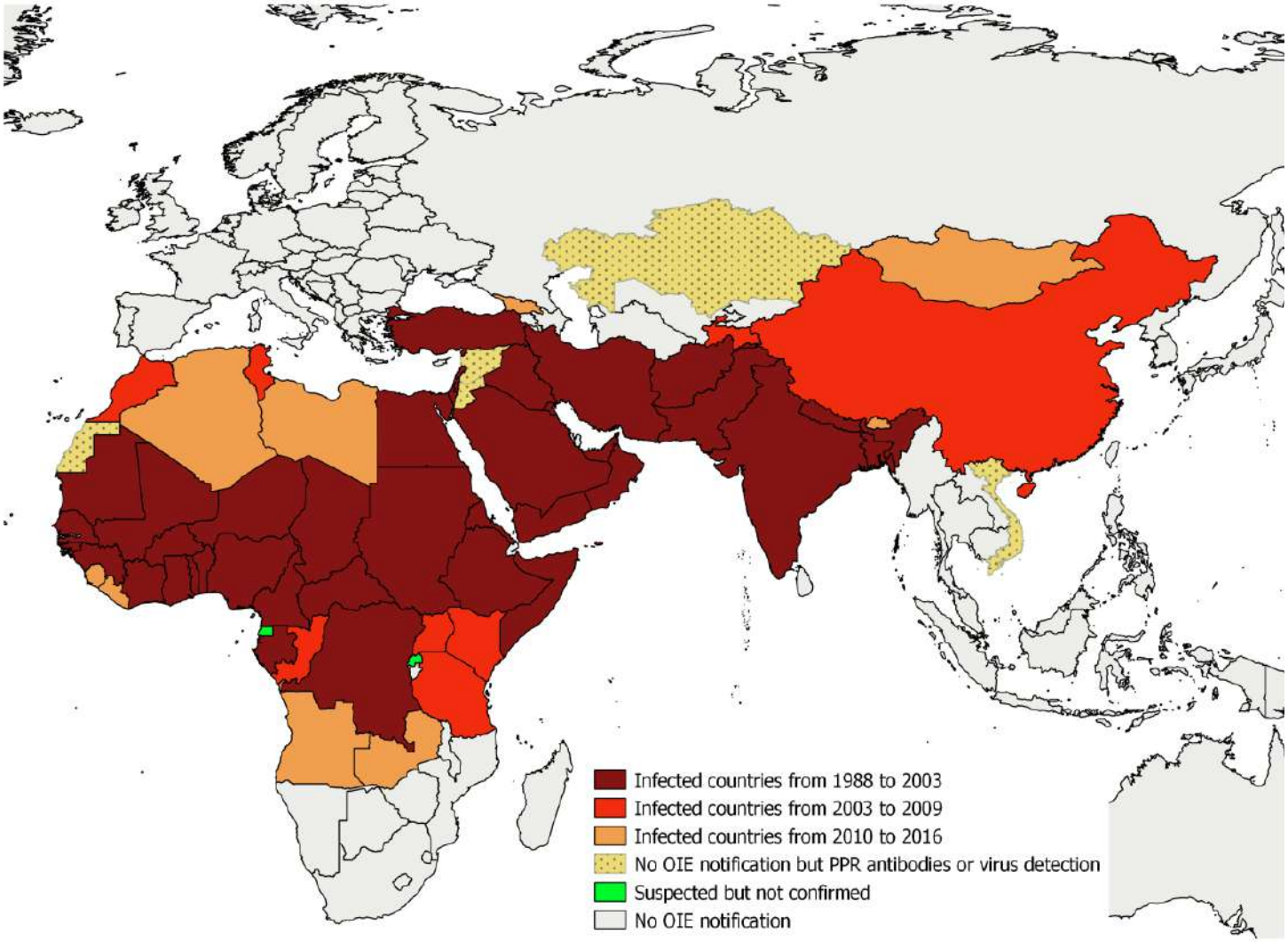

Figure 13: Countries infected by PPRV from 1988 to May 2017, according to OIE. Some countries did not report PPRV presence to OIE yet. Adapted from (OIE 2017; Parida et al. 2015)

7. MOLECULAR EPIDEMIOLOGY

Four distinct lineages of PPRV (I, II, III and IV) have been defined. The molecular distinction is based on partial sequence analysis of F, N or H genes, depending on the method of sequence analysis. They all draw the same 4 distinct lineages, except that the lineage II of the F gene analysis is considered as lineage I based on the N gene analysis, and vice-versa. Recently, a comparison study has been made between genetic data from F, N and H genes, showing that the N gene has the greatest variability among these three genes. Thus, the lineage classification based on the N gene should be considered as the most accurate way to type novel isolates (Senthil Kumar et al. 2014).

According to a bayesian phylogenetic analysis (M. Muniraju et al. 2014), the most recent common ancestor of these four lineages is thought to be at the beginning of the 20th century, a few decades before the first recorded description of the virus in 1942.

The different lineages were named according to the apparent spread of the virus, from West Africa (I and II) to East Africa (III). Unlike lineages I-III that are mostly found to Africa, lineage IV was thought to be mainly restricted to the Middle East and Asia (with few exceptions of lineage III in Yemen and Oman and mixed lineages of lineage III and IV in the United Arab Emirates and Qatar).

However, recent studies pointed out the expansion of Asian lineage IV into North, Central and Eastern Africa. Indeed, the first incursion of PPRV into Maghreb in the mid-2000 was owed to lineage IV. In Central Africa, lineage IV has been identified as the circulating lineage (Parida et al. 2015). While declared PPR infected since 2002, the Democratic Republic of Congo reported in 2012 an outbreak with an increase in PPR incidence (10% → 70%), morbidity (10% → 80%) and mortality (5% → 60%) that killed over 75 000 goats (OIE). This outbreak is thought to be due to lineage IV (Libeau, Diallo, Parida 2014). Similarly, lineage IV co-circulates with lineage II in Nigeria, Chad, and is slowly replacing lineage III in Sudan and Ethiopia (Banyard et al. 2010; Kwiatek et al. 2011; Muniraju et al. 2016; Murali Muniraju et al. 2014). The apparent expansion of the Asian lineage in Africa, and its responsibility for large epidemic outbreaks suggest that lineage IV may be of higher virulence (Kwiatek et al. 2011).

When looking at figure 14, we notice that all the PPR outbreaks being notified for the first time between 2006 and 2016 are due to the Asian lineage IV (China, Kazakhstan, Bhutan, Maghreb, Central Africa). PPRV lineage IV has also been characterized in Mongolia in 2017 (Shatar et al. 2017). However, lineage II has recently been reported in wild animals in China (Zhou et al. 2017).

Contrastingly, lineage IV has not reached Western Africa yet, were we still find lineages I and II. It seems like lineage II is spreading in countries where lineage I was identified (Muniraju et al. 2016). Recently, a study showed that in Benin lineage II was the only one to persist for over 42 years (Adombi et al. 2016). A co-existence of lineages I, II, III and IV (Luka et al. 2012; Banyard et al. 2010) and lineages II, III and IV (Mahapatra et al. 2015; Misinzo et al. 2015) has been reported in Uganda and Tanzania, respectively.

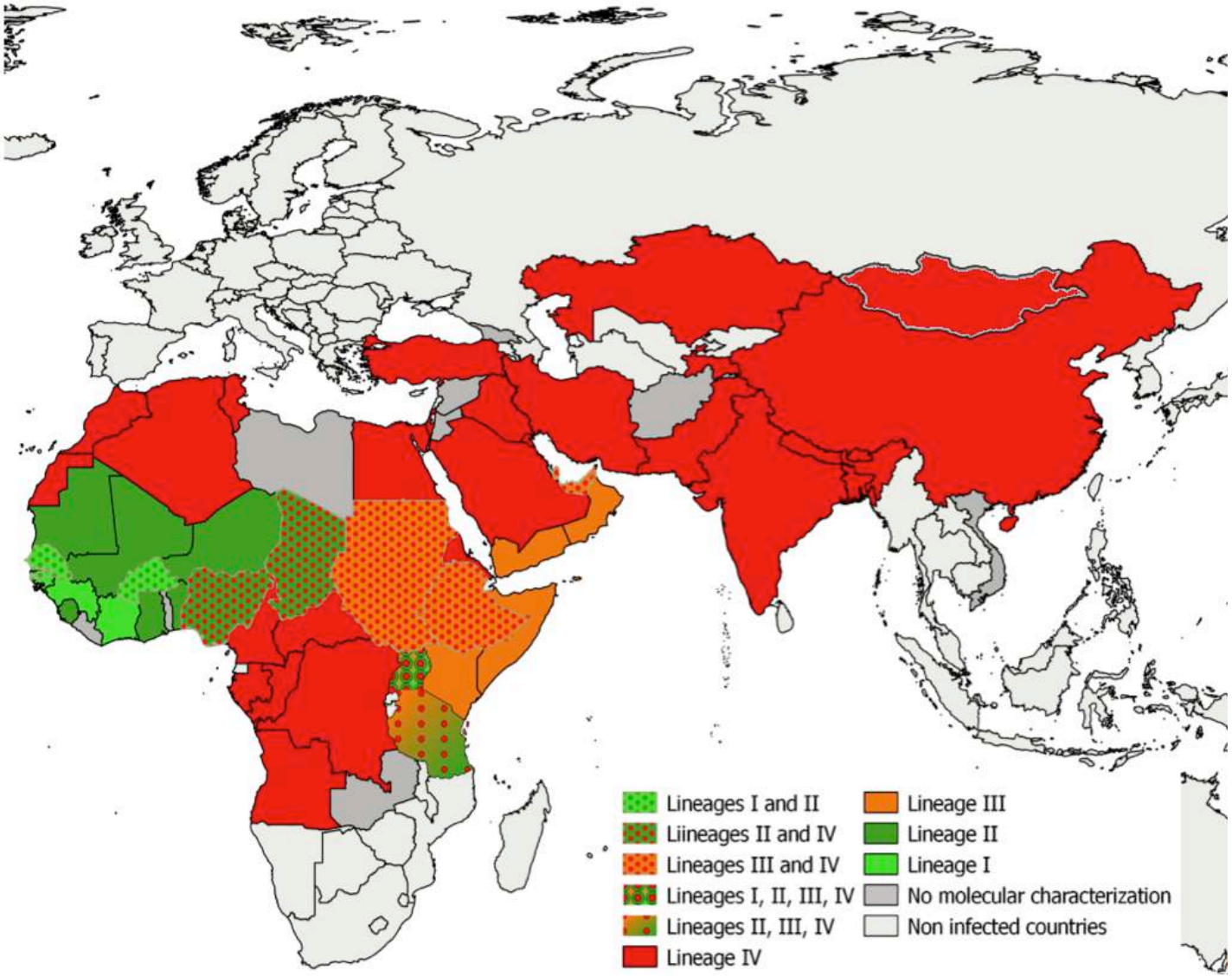

Figure 14: Distribution of PPRV lineages. Adapted from (Parida et al. 2015; Banyard et al. 2010; Libeau, Diallo, Parida 2014; M. Muniraju et al. 2014).

Genetic characterization has also enabled to link outbreaks in different neighbouring countries. The PPRV responsible for an outbreak in Kenya in 2011 was found to be closely related to the viruses isolated in Uganda in 2012 and in Tanzania in 2013 (Dundon et al. 2017). Similarly, the strain found in the 2011 outbreak in Gabon clustered with the Cameroon strain (Maganga et al. 2013). The major outbreak experienced by China in 2013-2014 was owed to a virus that was closer to viruses identified in Pakistan of Tajikistan than to those isolated from the first outbreak in Tibet autonomous region (Wu et al. 2016). Finally, the lineage of the PPRV during the 2013 outbreak in Comoros turned out to be lineage III and was closely related to the strain found in Tanzania (Cêtre-Sossah et al. 2016).

These reports point out the importance of small ruminants' movements in the spread of PPRV. According to Baron 2016, livestock trade is the most likely route of PPR introduction into new territories.

Given the geographical proximity of Europe to North Africa and Turkey, it seems reasonable to ask ourselves about the possible PPR introduction ways to mainland Europe. Three possible ways of introduction of PPRV into France were reported: through introduction of infected animal, infected animal product, or contaminated vehicle (Miller et al. 2009).

Although importing live animals from countries endemic for sheep and goat pox is forbidden, introduction of live small ruminants from Turkey and Maghreb do happen. Indeed, some movements of live small ruminants have been recorded in Eurostat and the UN COMTRADE database in 2011 from Turkey to Bulgaria and Hungary (Parida et al. 2016). Similarly, small ruminants may be smuggled in vehicles from Maghreb into France for domestic consumption (Miller et al. 2009). Movements from Spain, France, Italy and Romania to Morocco, Algeria and Tunisia are registered (Parida et al. 2016), particularly during religious festivals (e.g. Ramadan). Returning trucks, if not properly cleaned and disinfected, could thus enable PPRV incursion into Europe. However, this would apply only for short durations of transport as PPRV is very sensitive outside the host. It is also possible that PPRV enters Europe through passenger's luggage carrying contaminated animal products, as the virus can survive for 2-3 days in meat (Parida et al. 2016). However, this implies that the infected animal was slaughtered during the viremia stage and that the virus survives to product transformation, which is very unlikely, but not impossible. Finally, Turkey hosts the same community of wild ruminants as Europe. As the epidemiological role of wildlife is still poorly understood, we could consider that they could act as a bridge for PPRV transmission between Turkish infected populations and European healthy wild and domestic populations.

The risk of PPR introduction into Europe is further enhanced by the fact that import checking at points of entry (borders, airports, etc.) is not systematic and more generally by the lack of awareness of domestic importers and travellers, veterinary staff and customs officers.

CHAPTER 3: PESTE DES PETITS RUMINANTS TARGETED AS THE NEXT ERADICATED DISEASE

1. IMPORTANCE OF PESTE DES PETITS RUMINANTS

1.1. Socio-economic importance of small ruminants

About 330 million poor people across Africa, the Middle East and Asia keep livestock, including small ruminants (FAO, OIE 2015). Sheep and goats play an important role in the livelihoods and food security of poor families. Small ruminants provide source of milk, meat, meat and milk products, fibre and wool. They are also considered as a store of wealth, being kept and eventually sold to pay for expenditure such as school fees. In addition, small ruminants have a role in returning nutrients to the soil through the production of manure for use in cropping systems. A particularity of small ruminants' production it the big part of keepers being women, especially in smallholder systems.

Sheep and goats also play a critical role in the livelihoods of the traders who buy the animals and bring them to urban centres. Trade involves the use of transport and is a source of additional employment. People are also involved in running businesses to slaughter animals, dress carcasses and cure skins. In the case of Kenya, for example, the trade in small ruminant is geographically dispersed, with sheep and goats being brought into the city of Nairobi from Somalia, Ethiopia and Sudan. In Somalia, Djibouti and Ethiopia, the trade of live animals also extends into the Middle East and Arabian Peninsula, with 3-4 million live sheep and goats being exported every year (FAO, OIE 2015).

In the regions affected by PPR, there are about 5.4 billion people (and consumers), living in both rural and urban areas (FAO, OIE 2015). Developing countries have recently been experiencing a rising urbanization process, which results in a change in the consumer demand, with people having more access to high quality food products such as milk, dairy products and meat. Therefore, as more and more people settle to work in urban areas, the demand rises. To meet this demand while maintaining reasonable prices, the sheep and goat production systems have to be improved and fluctuations in the supply have to be avoided.

In the production systems and their associated value chains, millions of people are dependent on sheep and goats to generate income for their businesses and food for their families. These people are generally poor compared to other groups in society, and are the most vulnerable to small changes in the small ruminant production.

1.2. Medical and economic importance of PPR

PPR severely affects small ruminant in almost 70 countries in Africa, the Middle East and parts of Asia, that are home to over 80% of the world's sheep and goat populations (FAO, OIE 2015). In the worst situations, PPR morbidity is as high as 100%, with a mortality rate that can reach 90%. In endemic areas, the mortality rate may be lower but the disease has more insidious impact on flocks, hampering the development of lambs and kids, and decreasing the immune defences of adult animals against other diseases. Annual losses of production and death of animals due to PPR have been estimated to be between USD 1.2 and 1.7 billion. To these losses, we can add the ongoing expenditure on PPR vaccination, which is estimated to be between USD 270 and 380 million. In total, the current annual impact of PPR is between USD 1.45 and 2.1 billion per year (FAO, OIE 2015).

2. ERADICATING PESTE DES PETITS RUMINANTS: ADVANTAGES AND CHALLENGES

2.1. Favourable factors for PPR eradication

To date, rinderpest and smallpox are the only two viral diseases have been eradicated worldwide. Several factors enabled these eradications; such as good diagnostic tools, effective vaccines, strong induced immunity in recovered animals, a single sensitive host species, etc. and these characteristics are shared with PPRV.

The epidemiology and biology of PPRV are very similar to those of RPV. Therefore, after rinderpest eradication, PPRV appeared to be the most suitable candidate (Albina et al. 2013; Mariner et al. 2016; Baron 2011). Indeed, several factors are in favour of a successful eradication (FAO, OIE 2015; Kumar et al. 2014):

Epidemiological factors:

- Close-contact between animals is needed to transmit the virus, since PPRV is unable to survive outside the excreting host and is readily destroyed by heat and sun,
- There is no long-term carrier state in animals,
- Animals that recover develop a strong and life-lasting protective immunity,
- There is no known reservoir in wildlife or other domestic animals (cattle, camels),
- Only sheep and goats are involved in the maintenance and spread of the virus, as human was the only host for smallpox, and cattle the only maintenance host for rinderpest,
- The disease is severe, with high morbidity and mortality rates, leading to easy detection.

Control assets:

- Effective, safe and inexpensive vaccines are available, giving life-long immunity and covering all known strains/lineages of PPRV,
- A battery of sensitive, specific and easily implemented diagnostic tools has been developed.

Socio-economic factors:

- We gained experience and learnt lessons from eradicating Rinderpest,
- There is a growing political support for the control and eradication of PPR, following the successful rinderpest eradication programme,
- This political commitment has led to the necessary financial investment and international coordination of the programs,
- The prospect of gaining official OIE recognition of PPR free status can provide incentives.

2.2. Threats and Challenges

Despite all the assets in our favour for PPR eradication, there are still challenges to face (FAO, OIE 2015; Baron et al. 2016):

Vaccination challenges:

- All the current vaccines require the maintenance of cold chain, which can only be hardly ensured in developing countries. The quality has to be ensured from their reception at point of entry, and the cold chain has to be maintained from central purchase to distribution centres, to finally reach the vaccinators in the field.
- DIVA vaccines are still lacking, although there would be valuable tools for the latter stages of eradication
- A sufficient flock immunity is difficult to sustain as there is high turnover in small ruminant populations (30%/year in small ruminants, compared to 10%/ year in cattle (Baron et al. 2016))
- Vaccine delivery systems often not very effective in reaching all small ruminant holders in remote or insecure areas, or in certain production systems like crop-based systems with low animal density. Local stakeholders and community health workers would be of valuable help to reach those areas.
- A mass vaccination targeting a herd immunity of 80% seems difficult to achieve in terms of availability of required doses of vaccines, and veterinary infrastructures. Furthermore, the targeted population is about 2 billion sheep and goats, being 3 times the number of cattle that were targeted in the rinderpest eradication programme.

Epidemiological challenges:

- The precise role of wild and other domestic ruminants in the maintenance of PPRV is still poorly understood.

Veterinary and Control challenges:

- There is a lack of reliable information on size of small ruminant populations (making difficult to estimate the true required vaccine quantity and ensure a proper coverage)
- There is little if any individual identification of small ruminants in most developing countries
- There is insufficient control of live small ruminant movements while increasing mobility of live small ruminants for trade
- The endemic or at-risk countries share long land borders between each other, while there is still a gap in border controls and a lack of veterinary facilities and governance

Sociological challenges:

- There is insufficient understanding by the livestock owners of the benefits of preventing and controlling animal diseases
- Owners have limited willing to pay for health services for small ruminants that are of limited economic value compared to cattle
- In consideration of the customs/cultural taboos prevalent in countries endemic with PPR, it seems difficult, particularly at the time of festivals, to restrict animal movements.

Political threats:

- There is a lack of transparency in some countries regarding their PPR situation
- Political instability and security problems, such as a country under crisis, constitutes a threat to neighbouring countries (which is currently happening with Middle East and Near East)

3. THE PPR GLOBAL CONTROL AND ERADICATION STRATEGY

After that PPR became a notifiable disease to OIE in 2014, the PPR Global Control and Eradication Strategy (FAO, OIE 2015) has been developed and presented at the FAO and OIE International Conference for the Control and Eradication of Peste des petits ruminants held in Abidjan, Cote d'Ivoire, from 31 March to 2 April 2015. Participants including high-level authorities from 15 countries, donors, international and regional organizations made the political commitment to eradicate PPR by 2030 (FAO, OIE 2015).

The Global Strategy proposes to first control the disease in highly endemic areas, and then extend these control efforts to areas where a low endemic level is reached and where eradication is feasible or already on its way. For countries already free of PPR, the Strategy aims at maintaining this status through early detection, early warning and rapid response.

3.1. Objectives

The overall objective of the Global Strategy is to strengthen small ruminant sector to improve global food security and the economic growth of the developing countries. The objectives are divided into 3 components: PPR eradication, reinforcement of the veterinary services in the countries, and combined control of other important small ruminant diseases (FAO, OIE 2015).

- Component 1: PPR eradication

The objective is PPR eradication in 15 years. This goal can be reached by improving laboratory capacity for diagnosis, and by using effective vaccination for all livestock holders. The vaccination scheme plans to cover 100% of the small ruminants above 3 months old, in order to get 80% level of immunity post-vaccination (FAO, OIE 2015). Vaccination will be implemented during 2 successive years, followed by vaccination of new born animals during one or two successive years. Vaccination is therefore considered as the tool to reduce progressively incidence and spread in infected countries and to maintain the official recognition PPR free status in non-infected countries.

- Component 2: reinforcement of the Veterinary Services

PPR eradication cannot be achieved without the strengthening of the veterinary services (FAO, OIE 2015). This consists in improving the different animal health systems, provide information and training on PPR clinical and pathological signs. In exchange of such support, the veterinary services of the different countries will be asked to become compliant with OIE standards on quality of veterinary services.

- Component 3: reduction of the incidence of other priority small ruminant diseases

As most of PPR-infected countries also suffer from other small ruminant diseases (sheep and goat pox, CCPP, pasteurellosis, etc.), the logistical efforts (cost, time, technicians) deployed for PPR programme implementation could also be combined for control and surveillance of these other diseases (FAO, OIE 2015).

3.2. The step-wise approach

The Global Strategy has adopted a step-wise approach (figure 15). The four stages correspond to a combination of decreasing levels of epidemiological risk and increasing levels of prevention and control capabilities.

Figure 15: The step-wise approach of the PPR Global Control and Eradication Strategy (FAO, OIE 2015).

- Stage 1: Assessment Stage

This stage aims at assessing PPR situation in the countries (prevalence and distribution of PPR, hotspot and risk factors identification, value chain analysis of the small ruminant sector, etc.). This stage should last 1 to 3 years (from 2015) (FAO, OIE 2015). Every country needs to go through this stage to understand the situation and decide the relevant steps forward.

- Stage 2: Control Stage

If Stage 1 is successfully completed, countries upgrade to Stage 2. During this stage, the strategy consists in focusing control activities (such as vaccination) on high risk/priority areas (identified in Stage 1) in the country. The recommended duration of Stage 2 is 3 years (FAO, OIE 2015).

- Stage 3: Eradication Stage

During Stage 3, the control and preventive measures implemented in Stage 2 are extended to the whole country. At the end of Stage 3, no outbreak is detected in the whole territory. However, introduction of PPRV may still occur because of its presence in neighbouring countries. In this case, targeted vaccination in high risk areas should be considered (FAO, OIE 2015). As Stage 2, Stage 3 is expected to last 3 years.

- Stage 4: Post-eradication Stage

Countries enter into Stage 4 when vaccination is suspended and no clinical outbreak has been detected in the previous 24 months (FAO, OIE 2015). Once in Stage 4, vaccination is prohibited, and PPR incidence is limited to occasional incursion from other countries. The objective is to obtain official OIE recognition of PPR free status. The countries are entitled to apply at the end of Stage 4, which is recommended to last between 2 and 3 years. When the

country is granted on OIE official free status, it leaves the PPR step-wise approach (it becomes a "beyond stage 4" country) (FAO, OIE 2015).

3.3. Timelines and Costing

The Global Strategy is divided into three 5-year phases. After five years, around 30% of countries are expected to have reached Stage 3 and 30% to have reached Stage 4. It is expected that 40% of countries will be implementing a control programme (Stage 2) and less than 5% will still be in Stage 1. After ten years, more than 90% of countries will be in Stages 3 or 4 (FAO, OIE 2015).

The estimated maximum cost for the Component 1 (specific activities against PPR) for a 15-year Global Strategy is between USD 7.6 and 9.1 billion (FAO, OIE 2015). As nearly a billion sheep and a billion goats are being to be protected by the measures proposed, that makes, in average, about USD 0.27 to 0.32 spent per sheep/goat each year (FAO, OIE 2015).

In total, the current annual impact of PPR is between USD 1.45 and 2.1 billion per year (FAO, OIE 2015). The USD 0.5 billion annual cost of the 15-year Global strategy seems small compared to this current annual impact. Moreover, it is important to note that without the strategy, between USD 4 and 5.5 billion would be spent over a 15-year period on poorly targeted vaccination campaigns, which are unlikely to lead to eradication (FAO, OIE 2015).

4. THE SADC CONTROL STRATEGY FOR PESTE DES PETITS RUMINANTS

The PPR Global Control and Eradication Strategy was designed by OIE and FAO at the global scale. At the regional scale, a similar strategy (SADC 2012) has been implemented by the Southern African Development Community (SADC). The SADC is an inter-governmental organization based in Gaborone, Botswana, that aims to improve socio-economic, political and security cooperation and integration among 15 southern African states, including South Africa. Two years after the incursion of PPRV in Tanzania and the severe outbreak in DRC (both members of the organization), SADC Transboundary Animal Diseases (TADs) project organized an urgent meeting in Zambia on the control of PPR. The objectives of the strategy were:

- To immediately contain PPRV circulating in DRC and Tanzania,
- To prevent the disease from spreading to Angola, Malawi, Mozambique and Zambia,
- To propose a methodology for the long-term eradication of PPR from the SADC region.

It is estimated that 50 million sheep and goats are at risk in the entire SADC region (SADC 2012). Lesotho, where mohair industry is very developed, and Namibia, where goat exports to South Africa are significant, would be particularly impacted if PPR spreads further south. Three distinct regions were identified (figure 16 (a)):

- Infected countries: infection and clinical cases are confirmed in most of the country
- High/immediate-risk countries: these countries share borders with infected countries
- Low-risk countries: there countries are disease-free but there is still a risk, although lower, due to their northern neighbours being at risk.

Between 2012 and today, PPR presence has been detected in Angola in 2012 and in Zambia in 2015 (SADC 2012). However, no clinical signs were ever reported. In Angola, positive serology and virology have been detected, whereas in Zambia was detected only positive serology (figure 16 (b)).

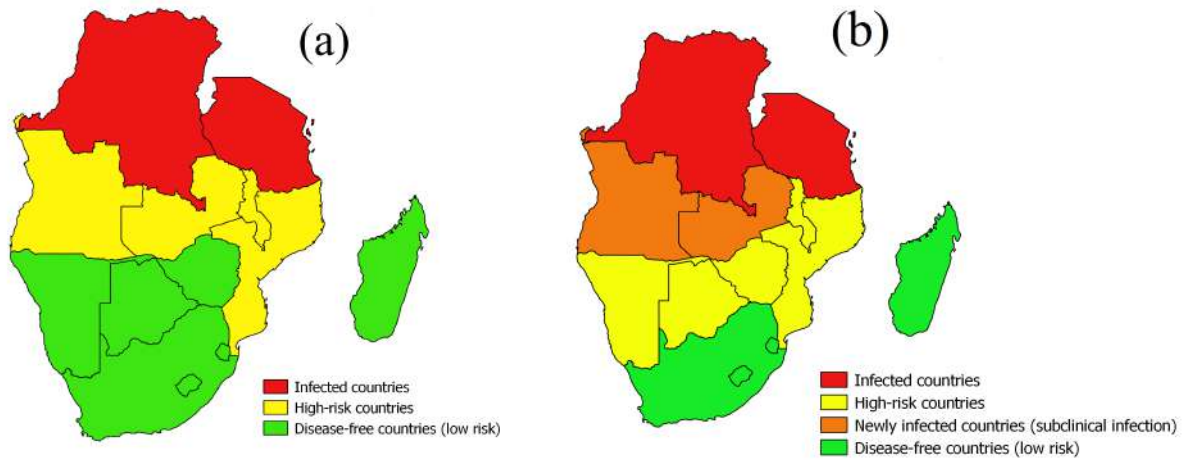

Figure 16: SADC Situation for PPR infection in 2012 (a) and in 2017 (b). Adapted from (SADC 2012).

The strategy plans restriction of live animal movements from infected to neighbouring countries, with stiff penalties for offenders. It also plans increased surveillance along borders and risk-based vaccination, with a focus on hotspots such as livestock markets and transport routes. In addition, the strategy recommends the building of quarantine facilities at border points and more generally the implementation of strict bio-security measures (SADC 2012). However, if these measures seem achievable in theory, they are more difficult to put in practice. Indeed, the first outbreak reported in Angola in 2012 was linked to an import of sheep and goats from Democratic Republic of Congo (OIE 2017).

As SADC region is tending to become a borderless region, collaboration and transparency between countries regarding animal movements and their control are encouraged. Emergency plans and simulation exercises in the event of PPR outbreak should be developed. In addition, focus should also be made on awareness rising and training among animal health stakeholders (SADC 2012).

In addition to animal movements restriction, the main control measures recommended by the SADC are risk-based vaccination (provided efficient animal identification) and zoning around potential outbreak (with a surveillance zone and a vaccination zone). Stamping out is expensive and socially and economically devastating for farmers. Therefore, it should be only implemented where infected population is small and where governments are able to compensate the affected owners (SADC 2012).

The SADC strategy recalls the recommendations of the FAO and OIE Global Strategy. As for the SADC, implementation of the recommended control measures can be challenged by the fact that PPR is quite new to its member countries and affects mostly small-scale farmers. Thus, given the characteristics of small ruminant sector in most member states (smallholder, poor, rural, poorly organised, communal grazing), the disease may fail to attract the necessary attention and resources, especially compared to cattle diseases like FMD (SADC 2012).

5. RESEARCH NEEDS

The literature review evidenced knowledge gaps and pending questions which still need to be answered. Regarding vaccines, the current improvements are mainly about (Parida et al. 2015):

- The development of live attenuated vaccines of greater thermo-resistance, to ensure a proper vaccine delivery in PPR-endemic countries, independently from the poor infrastructures.

- The development of DIVA vaccines to be able to differentiate vaccinated from infected animals, which will be particularly useful at stages of the eradication campaign where disease surveillance will be implemented with vaccination in the same time. We would finally be able to differentiate PPR-infected or PPR-vaccinated countries.

- The production of multivalent vaccines, enabling the effective immunization of small ruminants against several diseases. Indeed PPR-infected countries are also infected by many other small ruminant diseases (bluetongue, contagious ecthyma, border disease, etc.). Protection against several diseases in one single vaccine would reduce the costs of vaccination programmes and would be more convenient to put in practice. This echoes to the Component 3 of the Global Control and Eradication Strategy.

In addition, a multi-disease diagnostic assay should be developed: as it is planned to encourage vaccination against other small ruminant diseases (Component 3 of the Global Strategy), diagnostics for simultaneous surveillance of those diseases in PPR have to be made available. Similarly, during the final stages of the programme, PPR-like disease clinical syndromes will have to be correctly identified to confirm the presence or absence of PPR, and give the owner the correct diagnosis and advice on curative and prophylactic treatments.

The necessary level of immunity to break the PPR virus transmission cycle still needs to be determined. Classically this level is considered to be 80% but this percentage appears to be very difficult to obtain and some recent field experiences have shown that 70% could be satisfactory. These estimates were obtained in field situations with many uncertainties. Much more data are needed to provide the animal health stakeholders with more reliable estimates (Baron et al. 2016).

Similarly, more epidemiological data are still needed to design reliable quantitative models and risk analysis, such as: basic reproduction number R0, the expected number of cases generated by the introduction of a single infectious individual to a fully susceptible and immunologically naïve population (Baron et al. 2016). These data will help improving PPRV transmission models and risk analysis for PPRV introduction into disease-free areas by livestock trade or transhumance (Baron et al. 2016).

To date, PPRV antigen and RNA has been proved to be shed in faeces for as long as 11 (Ezeibe et al. 2008) and 16 weeks (Wasee Ullah et al. 2016) after recovery, respectively. However, no infectious virus was detected. Further investigations need to highlight the duration of infectious PPRV particles shedding in faeces (and urine) after recovery.

Finally, from what is currently known, cattle and buffaloes are considered as dead-end hosts, and wild ruminant species are considered as spill-over hosts. However, these assumptions are made on what was reported in the last decades, and actually, only very little is known; we are still unable to determine if these species along with camels are able to excrete and transmit the virus to susceptible animals or not. As various severe clinical outbreaks have been reported in Indian buffaloes and camels, there is a need to determine the nature of their susceptibility; is it due to secondary infections or to specific strains of PPRV?

The exact epidemiological role of other domestic animals (cattle, camels) or wildlife species also needs to be further investigated, particularly as PPR is spreading southward Africa, where wild ruminant density and sheep/goat density is high (Baron et al. 2016).

PART 2: APPLICATION OF SPATIAL-MCDA TO ASSESS THE RISK OF SPREAD OF PPR IN SOUTH AFRICA

CHAPTER 1: INTRODUCTION

1. SOUTH AFRICAN CONTEXT

To understand why South Africa is at risk for PPR spread and why there is an urgent need to assess this risk, South African situation has to be introduced. In the following, we will detail the particularities of small ruminant farming in South Africa and we will highlight the major issue of uncontrolled small ruminant movements.

South Africa, officially the Republic of South Africa, is a country located at the southern tip of Africa. It is divided into nine provinces: Gauteng, Mpumalanga, Limpopo, Eastern Cape, Western Cape, Northern Cape, KwaZulu-Natal, North West and Free State. The provinces are divided into metropolitan and district municipalities, with the district municipalities being further divided into local municipalities. To the north are the neighbouring countries of Namibia, Botswana and Zimbabwe; to the east are Mozambique and Swaziland. Lesotho is an enclave surrounded by South African territory (figure 17).

Figure 17: Geographical situation of South Africa.

South Africa is host of 55.7 million people (GHS 2013). About 80% of the South African population is of black African ancestry, divided among a variety of ethnic groups. South Africa is considered as a newly industrialized country. However, about a quarter of the population is unemployed and lives on less than US$1.25 a day (Statistics South Africa 2012).

The average annual rainfall decreases from >800 mm at the East (by the Indian Ocean) to <200mm at the West of South Africa, towards the Namib desert. 80% of South Africa is considered semi-arid to arid land (FAO 2005). Due to the aridity of the land, only 13.5% of the overall area can be used for crop production, and only 3% is considered to be high potential land.

South Africa has a generally temperate climate, as it is surrounded by the Atlantic and Indian Oceans on three sides. The average elevation is rising steadily towards the North and further inland. Due to this varied topography and the oceanic influence, various climatic zones exist.
In the East, along the Mozambique border and the Indian Ocean, there is a subtropical climate. In the farthest northwest, lies the desert of the southern Namib. The vast, flat and sparsely populated scrubland found inland is named the Karoo. The extreme southwest has a climate similar to that of Mediterranean areas, with wet winters and hot, dry summers. North to Johannesburg, elevation decreases and landscapes are characterized by a mixed dry forest and an abundance of wildlife.

1.1. Dual agriculture

The agricultural sector of South Africa is comprised of mainly two categories of farmers. On one side, there is a well-integrated, highly capitalized commercial sector, with approximately 35000 white farmers, producing around 95% of agricultural output on 87% of total agricultural land. On the other side, there is the smallholder sector, which consists of around 4 million black farmers farming in the former homeland on 13% of agricultural land (Aliber, Hart 2009). Smallholder livestock farmers are reported to own 40% cattle, 67% goats and 12% sheep but only accounts for 5% market share in the red meat production value chain (NERPO 2013).

Generally, most of the commercial farmers run their farms as a business; they may have employees and entrepreneurial skills, and are well-integrated in the market channels. They use services as artificial insemination, castration, dehorning, etc. Contrastingly, smallholder farmers are very few (about 160 000) to market their products (GHS 2013). Indeed, most of the smallholder farmers are involved in agriculture for domestic use only (milk, meat, traditional practices or cash savings). Most of these people are women, children, and elderly people (Fenyes, Meyer 2003). Whereas commercial farmers make their living of their agricultural activities, the households' income in communal areas comes from three major sources, namely migrant worker remittances, government pensions and non-rural sources (trade, handcraft, etc.) (Cousins 2008). Some factors have been identified in the literature as limiting factors preventing subsistence farmers to progress to commercial farmers. Generally, the smallholder farmers suffer from poor infrastructure; poor roads, high transportation costs, lack of credit access, poor agricultural and management skills, low education levels, poor access to market information (what are the market prices, the products in supply/in demand, etc.) (Khapayi, Celliers 2016).

The commercial farms share similarities with the farms we can find in Europe in terms of infrastructures and objectives. Therefore, we thought it would be important to detail the farming system found in communal areas to understand the dualistic situation of South African agriculture.

In communal farming systems, there are three main ways of keeping livestock (Kululeko 2015). Animals can be free-ranging, that means they are released early in the morning and allowed to forage freely. With this system animals are more prone to predation and can cause crop damages. To avoid such damages, animals can also be tethered to a rope along roadsides, crop alleys or on communal rangelands so that their range of movement is limited. Finally, livestock can be herded, mostly by women and school children, again to control their movements and limit the potential damages.

Therefore, livestock browse and graze on communal rangelands, eating mainly natural veld, throughout the year and receive little or no supplement during the dry season period (Kululeko 2015). As the animals are kept all together in a communal way, there is no structured breeding season and animals mate throughout the year, which eventually leads to inbreeding. Contrastingly, in commercial farming systems, livestock are supplemented and follow a breeding schedule. In the commercial sector there are usually higher reproductive rates (calving percentage of 62% against 35% in communal farming) and lower mortality rates (5.8% against 35.4%) (RPO, NERPO 2014).

1.2. Sheep farming sector

Sheep farming is practiced throughout the country but concentrated in the most arid parts of South Africa, i.e. Eastern Cape (29% of sheep population), Northern Cape (25%), Free State (20%) and Western Cape (12%) provinces. There are about 8000 commercial sheep farms, which employ approximately 35 000 workers. Communal farmers owning sheep are estimated to be 5800. The estimated number of sheep in South Africa is 23.9 million (of which 12% are kept by communal farmers). Sheep numbers are however declining, mainly because of predation and stock theft (DAFF 2015a).

South Africa is a net importer of mutton to satisfy the growing local demand. Sheep imports are mainly from Namibia (71% of the imports), Australia (21%) and New Zealand (7%). South Africa also exports mutton, with the main export destinations being Lesotho (35% of the exports), Botswana (14%), Mozambique (8%), Swaziland (8%), Kuwait (8%) and DRC (5%) (DAFF 2015a).

As regards commercial farming (88% of the sector), most of sheep farming is for wool and mutton/lamb. After about 5-6 years of shearing, the sheep are sold directly to feedlot or abattoir or sold through auction. Abattoirs are distributed all over South Africa and meat is mainly consumed locally.

1.3. Goat farming sector

South Africa is a relative small goat producing country and possesses only about 3% of Africa's goat and less than 1% of the world's number of goats. Production areas are mainly Eastern Cape (38% of the goat population), Limpopo (18%), Kwazulu-Natal (14%) and North-West (11%). They are only 250 stud breeders in the country (DAFF 2015b). As regards the commercial goat farming, the main breeds are the Boer goat, the Savanna and the Kalahari red (for meat and skin production) and, in a lesser extent, Angora goats (for mohair production).

For milk production, Saanen, Toggenburg and Alpine goats are used but the main reason to commercially farm goats is for meat production. South Africa imports mainly fresh, chilled or frozen carcasses or cuts of goats, and exports goat meat to Namibia (63% of the exports in 2014) and Lesotho (12%) (DAFF 2015b). However, the informal market drives the goat farming sector and these import/export figures are only valid for the commercial part, which concerns only 33% of the goat population.

67% of the goats in South Africa are Indigenous goats, which are kept by smallholders on communal lands. These goats have not been subjected to any selection/improvement process, and therefore have poor milk and meat production abilities. Their main asset is their hardiness, which make these goats particularly adapted to dry areas such as encroached rangelands (Webb, Mamabolo 2004). Goats play an important role in communal farming. They have several advantages compared to other livestock species; they are able to utilize low quality forage, they can walk long distances in search of feed during the dry season, and they have high reproductive rates and short generation intervals. They also have an inherent ability to flock, allowing easy herding. Finally, they are very adaptable and can withstand drought better than cattle (Kululeko 2015) and high temperature-humidity conditions. Communal farmers mainly keep goats for traditional purposes and slaughter them on an informal basis (backyard slaughter) for bridal ceremonies, burial rituals, etc. Besides being a source of food, they are also considered as an investment, which can be easily converted in cash to pay domestic fees.

The marketing channel in goat farming sector is driven by the informal market. The majority of goats marketed in South Africa are sold by private transactions in the informal market to be slaughtered for religious or traditional purposes. Therefore, it is very difficult to get accurate data on the number of goats being marketed and slaughtered. Although rarely retailed, goat meat is widely eaten in South Africa. Indeed, there is a high demand for goats in the informal market, and farmers are getting good prices, which may explain why producers consider supplying local market before thinking about the export market (DAFF 2015b).

1.4. Stock theft

South African farmers have to face important issues regarding stock theft, which is considered as the fifth largest crime in the country (Kruger 2003). Nationally, 377 114 animals (cattle, goats and sheep) to the value of more than R1 billion were reported stolen from 2006 to 2010 (Zwane 2013). Only 30% of these animals were recovered (Mare 2012). According to SAPS statistics, the theft of cattle, goats and sheep has increased by more than 128% percent since 2011 (Duze 2012). The incidence of stock theft among smallholder farmers is three times higher than in emerging farmers (Zwane 2013). Similarly, a study (Scholtz, Bester 2010) found out that that stock theft was much higher on communal land than on private land, and was particularly a concern in the case of sheep, irrespective of land owner system. The unattended grazing of livestock, the keeping of unmarked livestock and the poor documentation of livestock movements are the main contributing factors to stock theft (Zwane 2013).

To curb stock theft, livestock (cattle, sheep, goats and pigs) identification was made compulsory in 2002 through the Animal Identification Act. However, this measure has to face several challenges. Indeed, the registration cost of 120 ZAR is too high for most of communal farmers. In addition, most of them let their animals roam freely; if they are identified, the owners will be liable for the damages they cause (road accident, drop damage, etc.) and will be called to pay. Therefore, communal farmers are not very compliant with animal identification (DAFF 2010). In addition, non-reporting of stock theft has increased from 36.3% in 2011 to 70.7% in 2016. This is thought to be due to lack of trust in the criminal justice system and also because owners think that stock theft is not important enough to be reported (SAPS 2017).

1.5. Veterinary Services of South Africa

The South African Veterinary Services (VS) comprises a decentralized system with national VS (located in Pretoria) and 9 separate provincial VS. The national VS set national policy/protocols/guidelines and finance additional non-routine national programmes, delivered via the provinces (OIE 2012). The provinces are responsible for policy, funding and implementation of routine field animal health activities; such as dip-tank and auction inspections, vaccination, awareness campaigns, clinical services in communal areas, disease investigations and testing, issuing of livestock movement permits, auditing meat hygiene/inspection and compartmentalization in the commercial sector (OIE 2012). Each provincial VS supervises some State Veterinary Offices (around 95 in total) and each State Veterinary Office supervises some Animal Health Technician (AHT) sub-offices (around 300 in total) (OIE 2012).

Veterinary services staffing comprises registered veterinarians at national, provincial, and district levels. At state levels, typically one or two state veterinarians working in a state office will supervise a control (head) animal health technician, who in turn manages a team of animal health technicians who deliver field activities, some from small satellite offices (OIE 2012).

According to OIE evaluation tool of the Performances of Veterinary Services (OIE 2012), the VS suffer from a lack of veterinarians in regular contact with farms and animals in the field. The veterinary presence in the field is mainly comprised of Animal Health Technicians and private veterinarians (without official delegation). Lack of veterinarians in the field may hamper the quality and timeliness of passive surveillance and early detection. Veterinarians generally provide no on-site or direct field supervision of veterinary para-professionals activities in the public sector. It was also observed during the veterinary services' evaluation conducted by OIE that in many areas some VS veterinarians and many AHT did not have vehicles, cell phones, or computers.

The lack of veterinarians is emphasized especially in areas with extensive animal production systems and with small farmers or livestock owners (OIE 2012). Although often identified at field level by AHTs, most of small and communal farmers are not included in the registry of farmers at state or provincial level (OIE 2012). These farmers are therefore not fully integrated to national relevant disease prevention and control programmes. Therefore, these farmers are under-represented and suffer from a lack of dedicated communication tools from the VS.

The provision of veterinary clinical services in South Africa is undertaken via a dual system. Private veterinarians service the commercial sector with little government interaction and state animal health technicians provide limited services to the emerging or communal sector (OIE 2012).

The fact that the functions and responsibilities of the VS are divided between the national and provincial levels constitutes a break in the chain of command that can lead to a loss of information and can delay the reactions of the VS (OIE 2012). This also limits data collation, analysis and reporting at central level and causes variable implementation of surveillance programmes according to the provinces.

As regards importations, livestock imports from neighbouring countries are allowed from Botswana, Lesotho, Swaziland and Namibia but not from Zimbabwe and Mozambique, which are FMD infected (OIE 2012). Any livestock import must come along a veterinary certificate/import permit. Most borders of South Africa are fenced. However, in several areas the border fences are not in good repair and require a higher level of regular surveillance and maintenance (OIE 2012). The most challenging areas to control are areas where fencing is inadequate, where illegal immigrants access the country, where local and neighbouring populations sought access to water sources, and where flooding is regularly destroying parts of fences (OIE 2012).

In summary, South Africa appears to be at risk for peste des petits ruminants mainly for the following reasons:

- PPR is spreading southwards, with DRC, Angola and Zambia being recently infected,
- South Africa hosts large sheep and goat populations.
- the country shares with six countries 4,862 km of land border, which is considered to be porous due to inadequate manpower and subject to corruption at border posts (SAPS 2014)
- the importance of informal market and stock theft makes small ruminants movements hardly traceable, enhancing the risk of uncontrolled spread of PPR if it comes to be introduced

Therefore, there is a need to assess the most suitable areas for PPR spread in case of potential viral incursion in order to better prepare control and surveillance activities and thus limit the damages to animal health and livestock production sector. To this aim, we used in this study a spatial multi-criteria decision analysis (MCDA) to highlight the most suitable areas for PPR spread in South Africa.

2. THE INTEREST OF THE MCDA APPROACH

A challenge in public health decision making is to determine the best locations for targeting prevention and control measures, with often limited resources (Hongoh et al. 2011). The analysis of the spatial distribution of disease risk and its visual presentation through risk maps allows competent authorities to prioritize areas and thus implement more cost-effective strategies (Eisen, Eisen 2011).

Traditionally, disease risk maps are developed as an extension of a statistical modeling process in which geographically explicit predictor variables are used to estimate the probability of disease occurrence (Ortiz-Pelaez et al. 2010; Haque et al. 2010; Clements et al. 2007). This approach is called "data-driven" risk mapping. This approach is only achievable in areas where surveillance activities have effective coverage, or where epidemiological studies provide appropriate data to describe the distribution of a disease. This is not the case in South Africa for PPR; since the country is free of the disease, we have no quantitative data available on the disease distribution or pattern in South Africa.

In developing countries or in disease-free countries, appropriate data are often scarce or unavailable. However, there is still a need to make the most effective use of limited resources and target priority zones for disease surveillance. To produce risk maps in data-poor environments, "knowledge-driven" methods have been developed.

Spatial multi-criteria evaluation (MCE) and multi-criteria decision analysis (MCDA) are relatively rapid and pragmatic "knowledge-driven" methods for mapping disease risk in the absence of large epidemiological datasets. These processes, based on Geographic Information System (GIS), are processes that transform and combine geographical data and value judgements (expert and bibliographic knowledge, including uncertainties, subjective and qualitative information) to obtain valuable information for guiding decision making (Malczewski 2006) in a risk map format.

In clear, the spatial MCDA approach incorporates what is already known about the disease, along with spatial arrangement of animal distribution, trade, land use, etc. to predict suitability of a geographic area for disease occurrence and/or introduction and/or spread.

The main strength of spatial MCDA for disease risk mapping is its ability to create suitability maps in the absence of field-based disease surveillance data. While dealing with subjective data, MCDA approach provides spatial decision support for early detection and priority setting.

The spatial MCDA method has already been used to identify risk areas for Rift Valley Fever in Africa (Tran et al. 2016; Clements, Pfeiffer, Martin 2006) and in Europe (Tran et al. 2013; Sánchez-Vizcaíno, Martínez-López, Sánchez-Vizcaíno 2013), for HPAI H5N1 in Asia (Stevens 2013; Paul et al. 2016), for African Swine Fever in Africa (De Glanville et al. 2014) or even for vector control programmes (Symeonakis, Robinson, Drake 2007; Rakotomanana et al. 2007).

As regards peste des petits ruminants disease, a spatial MCDA approach has been developed at the African continent scale (Waret-Szkuta 2011) and another one at a regional scale in Eastern Africa (Tran 2013).

MCDA procedure includes the following general steps (adapted from (Hongoh et al. 2011; Store, Kangas 2001)):

- Definition of the problem: are we assessing the risk of disease introduction or risk of spread?
- Identification of risk factors from bibliographic review
- Raw data collection
- Expert opinion, determining the importance (= weight) of the identified risk factors and how they affect the suitability
- Geo-processing of the data into appropriate GIS layers
- Generation of standardized geographical layers for each risk factor
- Generation of weights for each risk factor
- Combination of the risk factors and creation of suitability maps

This study aimed at applying this methodology to identify suitable areas in South Africa for PPR spread. The output of this study is a suitability map, that displays areas where spread of PPR is the most likely and so where control activities should be prioritized in order to avoid the further spread of the disease.

CHAPTER 2: MATERIALS AND METHODS

1. DEFINITION OF THE PROBLEM

To define what risk we are aiming to assess, there is a need for epidemiological definitions (Tran 2013):

Introduction is defined as the transportation and entrance of a pathogen to a free area; the transportation vessel can be either alive or inanimate. After introduction, and under suitable conditions, the pathogen may be locally transmitted to its host, then from second host to several new hosts, and so on: this is the amplification step. Spread is defined as the transportation of the pathogen from the primary outbreak to secondary foci. Similar to introduction, spread can occur either by alive or inanimate vessels. However, in the particular case of PPRV and given its low resistance outside the host, we will consider here only alive vessels.

In this study, we focus on the risk of PPR spread. The risk map we created is showing suitable areas for PPRV spread within the country once PPRV would be introduced. Suitability is defined as the ability of a habitat to support either the introduction, amplification or the spread of PPR virus (Stevens 2013).

2. IDENTIFICATION OF RISK FACTORS

We first identified the risk factors reported in the literature through a bibliographic review. Articles related to risk factors of PPR were searched through ISI Web of Science and PubMed databases, published from 1980 to 2017. We used the key words “peste des petits ruminants” AND (separately) “spatial”, “model”, “analysis” and “risk factors”, using the “all fields” option to find all the articles in which the search terms appeared in the titles, abstracts, or keywords. We read a total of 60 articles, and updated the table of risk factors already produced (Waret-Szkuta 2011; Tran 2013) in table 3. We included only the articles in which there was a statistical analysis of the risk factors (odd ratios, and/or statistically significant difference between two factors (for instance male *vs*. female)).

Table 2: Risk factors for PPR identified in the literature published until May 2017. Updated from (Waret-Szkuta 2011; Tran 2013)

	Risk Factor	Location of observations	References
Individual level	Species	Africa, Turkey, India, Pakistan, Kenya, Algeria, Tanzania, Ethiopia	(Abraham et al. 2005; Muhammad Abubakar et al. 2011; Awa 2002; Diallo 2000; FAO 1999; Lefèvre, Diallo 1990; Ozkul et al. 2002; Roeder et al. 1994; Singh et al. 2004; Sow et al. 2008; Taylor, Ali 2005)(Kihu et al. 2015; Aziz-ul-Rahman et al. 2016; Swai et al. 2009; Kardjadj et al. 2015; Zahur et al. 2011; Waret-Szkuta et al. 2008) (Khan 2008; Khan et al. 2008; Torsson et al. 2017)
	Breed	Iran, Nigeria, Kazakhstan, Bangladesh	(Bazarghani 2006; Lundervold 2004; Odo 2003; Rony et al. 2017)
	Age	Pakistan, Mali, Burkina Faso, Bangladesh, Ethiopia, India, Algeria	(Abubakar et al. 2009; Sow et al. 2008; Tounkara et al. 1996; Rony et al. 2017; Waret-Szkuta et al. 2008; Zahur et al. 2011; Mahajan et al. 2012; Kardjadj et al. 2015; Torsson et al. 2017)
	Sex	Pakistan, Tanzania, India, Ethiopia, Kenya	(Abubakar et al. 2009)(Swai et al. 2009; Mahajan et al. 2012)(Waret-Szkuta et al. 2008; Kihu et al. 2015; Aziz-ul-Rahman et al. 2016; Megersa et al. 2011; Khan 2008)
Production systems	Pastoralism, nomadic pastoralism	Pakistan, India, Kenya, Ethiopia	(Abubakar et al. 2009; Muhammad Abubakar, Khan, et al. 2011; Bett et al. 2009; Nanda 1996; Shankar 1998; Singh et al. 2004; Megersa et al. 2011; Mahajan et al. 2012)
	Large herds, high ruminant densities	Jordan, Pakistan, Turkey, Algeria	(Al-Majali et al. 2008; Khan et al. 2008; Ozkul et al. 2002; Kardjadj et al. 2015)
	Introduction of animals purchased at the market	Pakistan, India, Tanzania	(Abubakar et al. 2009; Muhammad Abubakar, Khan, et al. 2011; Singh et al. 2004; Mbyuzi et al. 2014)
	Mixed herds (sheep and goats)	Jordan, Africa, Algeria	(Al-Majali et al. 2008; Anderson, McKay 1994; Kardjadj et al. 2015)

	Presence of wild ruminants (*bovidae*)	Saudi Arabia, Central Africa, West Africa	(Elzein et al. 2004; Banyard et al. 2010; Couacy-Hymann et al. 2005; Furley, Taylor, Obi 1987; Kinne et al. 2010; Anderson 1995)
	Sharing watering or grazing points	Regions between 40°N and 40°S, Tanzania	(Lefèvre 2003; Mbyuzi et al. 2014)
Markets/Trade/Theft	Importation of live small ruminants (legal or illegal trade)	Saudia Arabia, Turkey	(Al-Dubaib 2009; Al-Naeem 2000; Ozkul et al. 2002; Almeshay et al. 2017)
	Animal movements between neighbouring countries	Sudan, Turkey, India, China	(Osman 2009; Ozkul et al. 2002; Singh et al. 2004; Wang et al. 2009)
	Visiting live animal markets	Sudan, India, Cameroon	(Al-Majali et al. 2008; Shankar 1998; Martrenchar 1995)
	Festival periods	Ghana	(Bonniwell 1980)
	Traditional and commercial practices	Iran	(Bazarghani 2006)
	Livestock theft	Kenya	(Bett et al. 2009)
Climate	Season	Pakistan, India, Africa, Bangladesh	(Abubakar et al. 2009; Diallo 2003b; Gopilo 2005; Odo 2003; Singh et al. 2004; Taylor 1984; Rony et al. 2017; Mondal 2014)
Veterinary Services	Inefficient quarantine, limited availability and access to veterinary services, lack of surveillance systems	Iran, Jordan, Kenya	(Al-Majali et al. 2008; Bazarghani 2006; Bett et al. 2009)

However, these risk factors were identified in various parts of the world, and may not be all relevant for South Africa's context. After checking with several members of the Veterinary Services, we excluded or adjusted some risk factors from the previous table. Pastoralism and nomadic pastoralism are production systems that are not found in South Africa. They were therefore removed from the study. However, it seemed interesting to make the distinction between commercial and communal farming as they are different in many points. Commercial farmers generally keep larger herds and have greater inflow and outflow within their flocks. They are quite well serviced by private veterinarians. Communal farmers have been associated in the literature with higher rates of stock theft, poor access to veterinary services. Communal farmers have less access to markets and therefore are assumed to have a lesser inflow and outflow, except for traditional practices that are mostly practiced in communal areas. Small ruminants living in communal areas are allowed to roam freely and are able to share watering and grazing areas with other flocks.

Finally, we excluded the following individual risk factors as only poor data is available on the distribution of small ruminants according to their sex, age and breed.

In previous MCDA study on PPR in Eastern Africa, camel and cattle densities were included (TRAN 2013) as risk factors for PPR occurrence. As there are few if any camels in South Africa, finding areas where camels and small ruminants have close contact is unlikely; hence we did not include camel density as a risk factor. On the other side, cattle do range freely with small ruminants in communal areas in South Africa. However, as cattle have never shown clinical signs from a natural outbreak, and as we still do not know if they are able to shed the virus, we decided to not take cattle density into account.

Although not explicitly considered as a risk factor in the literature, presence of wild ruminants may be worth taken into account when thinking about PPR transmission. Given the abundance of national parks and wild ungulates in South Africa, if we eventually find out that wild ruminants play a significant role in the epidemiology of PPR, we would miss a significant part of the puzzle if we exclude this factor. Therefore, we decided that wildlife/livestock interfaces should be considered as areas suitable for PPR transmission and thus should be included as a risk factor in our study.

We gathered in table 3 the adjusted risk factors that we decided to keep in our study for their relevance for South Africa, and the correspondent hypothesis. Only factors that could be mapped were selected for the risk mapping process. We were unable to collect meaningful geographical data on communal small ruminant farming and livestock theft (as 70% of the cases are not reported). Festival periods were also difficult to map. As PPR does not display a clear seasonal pattern itself, and as we have to select a limited number of risk factors to produce the map, season was finally not included in the study.

Table 3: Risk factors associated with spread of PPR in small ruminant populations, selected for South Africa and associated hypothesis for PPR. Risk factors for which geographical data was available are highlighted in blue. *A proxy is a variable assumed to resemble the risk factor.

	Risk factor	Hypothesis
Production systems	Goat density as proxy* for communal farming	Increasing goats' density is expected to be associated with a higher contact rate between susceptible and infected goats, and therefore a greater risk of spread. At the national scale, goats are mainly kept in communal farming (DAFF 2015). Communal farming is expected to be of higher risk of PPR spread as animals kept in communal areas roam freely, may have uncontrolled contacts with other animals, share grazing areas. Communal areas are also more likely to host traditional practices and have lesser access to veterinary services.
	Sheep density as proxy* for commercial farming	As for goats, if sheep density increases, the contact rate between susceptible and infected animals is higher, and thus the risk of PPR spread increases. At the national scale, sheep are mainly kept in commercial farming (DAFF 2015). Commercial farming is expected to be of higher risk of spread as flocks are generally larger, with higher inflow and outflow of animals. Sheep are also more prone to stock theft than goats (DAFF, personal statement).
	Communal farming as proxy* for traditional practices, shared grazing areas, uncontrolled movements of animals	Areas where communal farming is practiced are expected to be areas where traditional practices are common and where small ruminant flocks are more likely to share pastures and range freely or at least have uncontrolled movements. Traditional practices such as sacrifices imply increased goat trade and movements. Communal farming areas are thus expected to be areas of increased small ruminants' movements and close contacts, and thus of higher risk of spread.
	Wildlife national parks, as proxy* for wild ruminant densities	Proximity to wildlife national parks may be associated with increased risk of spread of PPR as small ruminants may share grazing areas and water points with wild *bovidae* (although there is no published evidence of the role of wildlife in PPR spread)
	Rivers	Sheep and goats in communal areas extend their roaming area to find food and can gather to rivers to drink and graze. Proximity to rivers is expected to be associated with increased risk of PPR spread through close contact among animals sharing watering points.
Markets and Trade	Small ruminants' markets Taxi ranks as proxy* of small ruminants' informal markets	The flocks gathered on markets have different serological status. Proximity to small ruminants' markets is expected to be associated to more regular visits from the farmers and more likelihood of buying animals from the market. Therefore, proximity to markets (both formal and informal) is expected to be associated with increasing risk of spread of PPR.

	Livestock theft	Increasing livestock theft density is expected to be linked to increasing movements of animals and thus higher risk of PPR spread.
	Roads as proxy for animal trade (legal/illegal)	Proximity to National (e.g N12), Provincial (e.g. R36) and Regional (e.g. R312) roads is expected to be associated to easier access to transport and thus increasing movements of small ruminants for trade, leading to a higher risk of spread of the disease.
	Festival periods	Festival periods (Christmas, Pass Over) are linked to higher small ruminants' importation and trade, and thus are periods of higher risk for PPR spread.
Climate	Season	Risk of transmission of PPR is expected to be greater during the rainy season (because of close confinement of animals, implying higher concentration and stressful conditions favouring virus transmission) and during the dry season (because of the decreased availability of food and water resources, small ruminants share these resources and come in close contact).
	Veterinary Services	Increasing distance to veterinary services offices is expected to be associated with higher risk of PPR spread as awareness and surveillance activities from the animal health technicians and vets may be more difficult to implement.

3. DATA COLLECTION

We collected the digital spatial data available online, mainly browsing South African official websites, but some datasets were not available as it is (they are displayed with a * in table 4). Spatial dataset of state vet offices and AHT sub-offices was not available online nor upon request. Therefore, physical addresses of each state vet office were found on the provincial DAFF websites, and the corresponding locations were saved on Google Earth. The final resulting dataset (in .kml format) gathered all the state vet offices locations in South Africa. We proceeded in the same way for the location of formal small ruminant auctions. Indeed, there is no complete national database of all the sheep and goat markets. Generally, livestock auctions are held on specific days at venues where there are auction facilities all over the country, and production auctions of commercial studs are generally advertised in weekly magazines (National Wool Growers Association, personal statement). Therefore, we had to collect all the locations of venues advertised in magazines in a year. We verified that the same venues were used the year before. The physical addresses were pinned on Google Earth.

As for the informal markets, since we were told that it takes place mostly at taxi ranks, we used a spatial dataset gathering the main taxi ranks of the country and merged the two datasets.

As for the risk factor "proximity to roads", we selected the national, provincial, regional and district roads of South Africa, as these 4 types are the most used for animal transport in the country. Railways are not used for small ruminant transport in South Africa (DAFF, personal statement). As concerns the risk factor "proximity to national parks and game reserves": we only selected national parks, game parks and game reserves that could be able to host substantial population of wild *bovidae*. An arbitrary threshold was made to select all the areas of more than 1000 ha (Jacques O'Dell, personal statement). Among the national parks, we excluded Sodwana Bay National Park and Table Mountain National Park & Cape Floral for their association to very low density of antelopes (SANPARKS mammal lists) and their physical location (on the coastal shore and enclaved by Cape Town urban area, respectively).

Table 4: Geographical datasets collected and the associated sources

Risk Factor	Data Set	Format	Source
Goat density	Goat density	raster	Gridded livestock of the World FAO 2.01 (2014)
Sheep density	Sheep density		
Distance to Veterinary services*	Location of the vet services offices	Vector (points)	DAFF provincial websites www.daff.gov.za
Proximity to rivers	Rivers shapefile	Vector (lines)	Department of Water Affairs (www.dwaf.gov.za) 16/04/2012
Proximity to roads	Roads shapefile	Vector (lines)	OpenStreetMap Roads layer 02.03.2017
Proximity to national parks and game reserves	South Africa Protected Areas Shapefile	Vector (polygons)	Department of Environmental Affairs (https://egis.environment.gov.za) 22/03/2017
Proximity to markets*	Location of formal auctions	kml	Weekly magazines (Landbouweekblad and Farmers Weekly)
	Locations of taxi ranks	kml	OpenStreetMap Transport layer 02.03.2017
Administrative boundaries	Country boundaries	Vector (polygon)	Global Administrative Areas (www.gadm.org) version 2.8 November 2015

4. GEO-PROCESSING OF PPR RISK FACTOR LAYERS

Geographic data were visualized and manipulated using ARCGIS (version 10.5; ESRI Redlands, CA) and QGIS (version 2.18.9, Las Palmas) softwares. We used the projection WGS84/ UTM zone 35S as South Africa is located in the South hemisphere between 24degE and 30degE.

We chose to display our final risk map in a raster format. Therefore, all the risk factor layers had to be transformed into a raster format and at the same resolution to be later able to combine them.

The sheep and goat density layers were already available at the raster format at 1-km^2 scale; they were clipped at the national scale and projected according to WGS84/UTM 35S. These datasets were generated as part of the FAO's Gridded Livestock of the World project in 2005, later updated with more recent census numbers in 2014. As concerns South Africa, the datasets we used were based on the census numbers per province released in 2011 by the Ministry of Agriculture, Forestry and Fisheries of South Africa.

The remaining risk factors, in a vector format, were first individually geo-processed using the "Euclidean Distance" tool of ARCGIS, which generated a raster layer where each pixel of the output layer had the value of the distance to the input layer (either roads, rivers, parks, vet services or markets). The cell size of the output raster was specified to be 1 km^2.

The risk factor layers, namely goat density ("goat_dens"), sheep density ("sheep_dens"), distance to vet offices ("dist_vet"), proximity to rivers ("dist_rivers"), proximity to parks and reserves ("dist_parks"), proximity to roads ("dist_roads"), proximity to markets ("dist_market") were finally all generated in the same raster format, with the same extent and the same resolution (1kmx1km) to be able to be combined together. They are available in Appendix 1.

5. EXPERT OPINION SURVEY

Experts were defined as being persons with relevant experience or knowledge on PPR disease and/or epidemiology and/or small ruminant market chain value in South Africa. A total of 16 experts were contacted. We selected 2 researchers (CIRAD), 2 South African epidemiologists (UP), 5 foreign academics having worked on PPR in Africa, 1 staff of a local non-governmental organization (GAP KZN), 5 provincial vets of the veterinary services (DAFF) and 1 member of an international organization OIE). Eight (50%) of them returned the completed questionnaire.

The questionnaire was developed on Microsoft Word and sent by email to each selected expert. The questionnaire is available in Appendix 2, and contains two parts which are characterization of the relationship between the risk factor and the risk of PPR spread, and weighting of the risk factors.

- Step 1: Relationships definition

First, we asked the experts to define which relationship fitted the best between each selected factor and the risk of PPR spread. Indeed, the same risk may not increase in the same way for each risk factor. For example, risk of spread may increase with road density, since we assume that areas well-equipped with roads are more likely to host animal trade and movements. However, where road density is higher than a given threshold, the area is in fact an urban area, and thus is no longer considered as a suitable area for livestock trading.

Experts had to choose the most suitable membership function linking each risk factor to the risk of PPR spread. Four types of membership functions were suggested in the questionnaire (figure 18). Examples were random and just aimed at illustrating the link between risk and risk factor.

Relationship 1: Linear monotically (increasing or decreasing) relationship. The risk is proportionately increasing with the risk factor or inversely proportional.

Relationship 2: Sigmoidal relationship: risk increases from a specific threshold up to a second threshold, and then stay constant.
Example:
The risk of spread is minimal (=0) if the sheep density is below 20/km^2 ("a"). The risk is maximal (=1) if density is > 100/km^2 ("b"). Between these 2 thresholds, the risk is increasing following a sigmoidal function. Beyond the threshold "b", the risk remains constant (=1).

Relationship 3: Quadratic relationship: highest risk is associated with a specific threshold.
Example:
The risk of PPR spread is minimal when density is <20 goats/km^2 and is increasing up to a threshold "a" where density is 100 goats/km^2. Beyond this threshold, the risk is decreasing until reaching 0 when density is > 1000 goats/km^2. This may be explained by the type of farming (for example, we can think that very large farms have a high level of biosecurity and therefore are a less risky type of farming)

Relationship 4: Linear bi-directional relationship: the risk increases in a linear way until a first threshold then stay constant and finally decreases linearly after a second threshold
Example:
The risk is minimal if the sheep density is below 20/km^2 (threshold "a"). The risk is maximal (=1) if density is between 100 and 400 sheep/km^2 (thresholds "b" and "c"). Beyond 400 sheep/km^2, the risk is decreasing until reaching 0 (minimal risk) when density is > 1000 sheep/km^2 (threshold "d"). Again, this may be explained by the type of farming, among other possibilities.

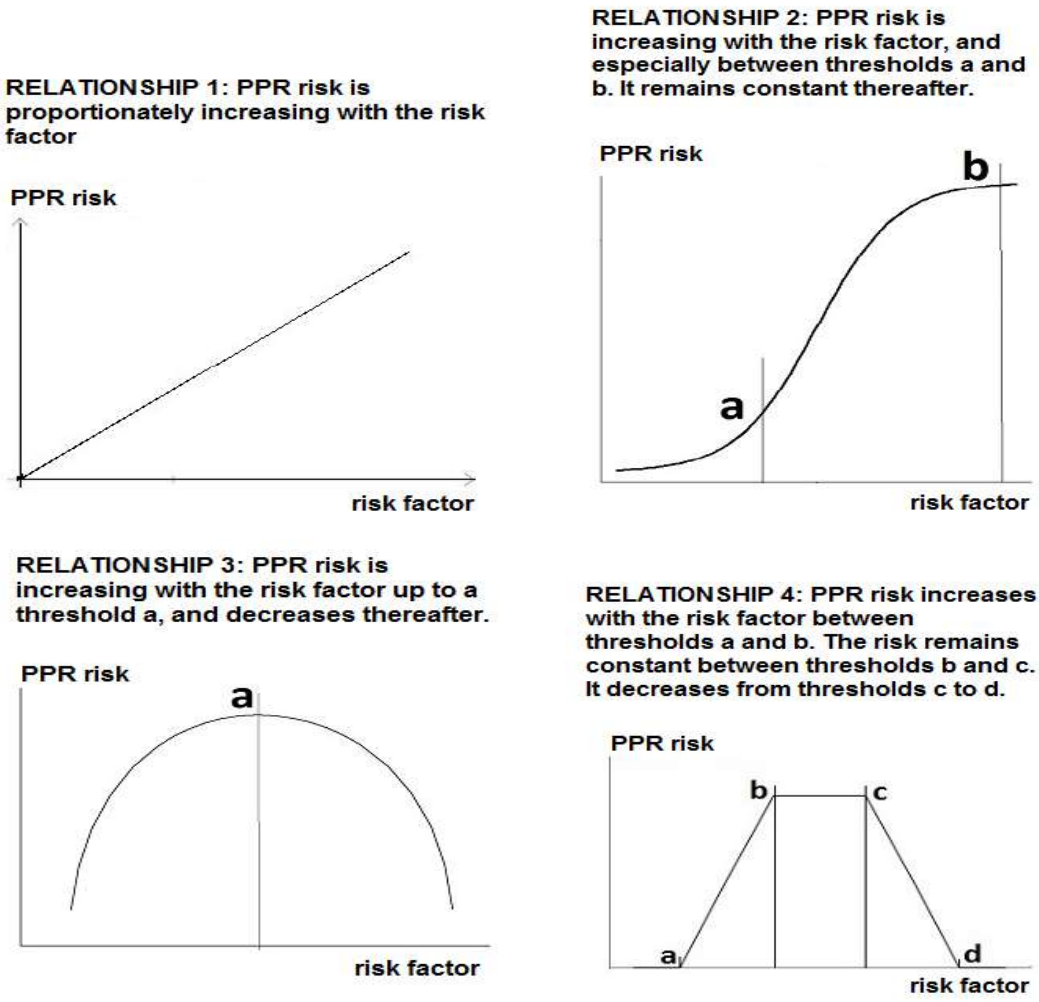

Figure 18: Membership functions used in the expert opinion survey

Examples given in the questionnaire to illustrate the membership functions were not given for PPR risk of spread but for malaria risk of spread, in order to not influence the decisions of the experts.

When experts selected relationships 2, 3, and 4, they were asked to define the value of the correspondent thresholds a and b (and c and d for relation 4). If they were unable to set a value for the thresholds, they had to select the relationship 1 (figure 19).

	Best-fitted Relationship	Threshold a	Threshold b	Threshold c	Threshold d
Density of goats (heads/km2)	Relationship 1	0	max		
Density of sheep (heads/km2)	Relationship 1	0	max		
Distance to vet services (kilometers)	Relationship 2	0	50 km		
Proximity to rivers (meters)	Relationship 2	0	50 km		
Proximity to national parks and game reserves (meters)	Relationship 2	0	100 km		
Proximity to roads (meters)	Relationship 2	0	50 km		
Proximity to markets (kilometers)	Relationship 2	0	50 km		

Figure 19: Best-fitted membership functions and the choice of thresholds (example)

- Step 2: Risk factors weighting

As not all the risk factors are equally important; the weight is a way to establish their relative importance. The method of weighting we used in this study is the pair-wise comparison, adapted from the analytical hierarchy process (Saaty 1980): the question is decomposed into a hierarchy of sub-problems; risk factors are compared two at a time, and a numerical weight is derived for each element of the hierarchy. The advantage of this method is the easy comparison, since only two criteria are compared at the same time. The disadvantage is that if the number of criteria increases, the number of comparisons is very large and therefore the risk of having inconsistencies is higher. Therefore, in the second part of the questionnaire, experts were asked to fill-in the pair-wise comparison matrix (figure 20), where each factor is compared with the others, relative to its importance. Experts had to choose between 9 expressions ranging from "extremely less important", through "equivalent" to "extremely more important" on the Saaty scale (figure 21).

	Density of goats (heads/km²)	Density of sheep (heads/km²)	Distance to vet services (km)	Proximity to rivers (m)	Proximity to national parks/ game reserves (m)	Proximity to roads (m)	Proximity to markets (km)
Density of goats (heads/km²)		moderately more important	moderately more important	very strongly more important	strongly more important	strongly more important	strongly more important
Density of sheep (heads/km²)	moderately less important		equivalent to	very strongly more important	strongly more important	moderately more important	moderately more important
Distance to vet services (km)	moderately less important	equivalent to		very strongly more important	strongly more important	moderately more important	moderately more important
Proximity to rivers (m)	very strongly less important	very strongly less important	very strongly less important		moderately more important	moderately less important	strongly less important
Proximity to national parks/ game reserves (m)	strongly less important	strongly less important	strongly less important	moderately less important		moderately less important	strongly less important
Proximity to roads (m)	strongly less important	moderately less important	moderately less important	moderately more important	moderately more important		equivalent to
Proximity to markets (km)	strongly less important	moderately less important	moderately less important	strongly more important	strongly more important	equivalent to	

Figure 20: Example of a filled-in pair-wise comparison matrix

More important								*Less important*
Extremely	Very strongly	Strongly	Moderately	Equivalent	Moderately	Strongly	Very strongly	Extremely
9	7	5	3	1	1/3	1/5	1/7	1/9

Figure 21: Simplified Saaty Scale used for comparing risk factors in the analytical hierarchy process (Saaty 1980).

6. FACTOR STANDARDIZATION

All the selected risk factors do not have the same scale; for example, sheep and goat density are expressed in head/km^2, proximity to markets in kilometers, proximity to rivers in meters, etc. Therefore, to make comparisons between risk factors possible, and eventually combine them into a final suitability map, we needed to standardize them to a common continuous scale.

In the spatial MCDA method, two ways of standardization are possible. There is the crisp approach that transforms the factor layer into discrete data: for each factor in a given pixel, the risk is either equal to 0 (unsuitable) or 1 (suitable). Contrastingly, the fuzzy approach transforms the factor layer into continuous data: for each factor in a given pixel, the risk (or suitability) ranges between 0 (completely unsuitable) and 1 (completely suitable).

In this study, we chose the fuzzy approach. For each map unit (i.e. pixel), the transformation of each factor into a suitability value was made by applying the membership function identified by the experts.

$$F(x) = y$$

with x= risk factor values, and y= suitability values

This standardization was made using RStudio software (version 1.1.383) with R scripts courtesy of Dr Mathilde Paul and available in Appendix 3. We computed the script for the results of one expert at a time. For example, for expert 1, we ran the standardization script on the 7 risk factor layers according to the membership functions expert 1 has selected in his questionnaire. Therefore, for each of the 4 consistent experts, we had 7 standardized risk factors rasters where each pixel had a value ranging from 0 to 1.

7. GENERATION OF WEIGHTS FOR EACH RISK FACTOR

To calculate the final weight of each risk factor according to each expert, we converted the completed pair-wise comparison matrix into a numerical matrix, using the Saaty scale (figure 22). In the following example of HPAI H5N1 risk of spread (figure 22), an expert assessed that waterfowl density was moderately less important than population density; the corresponding value is 1/3, according to the Saaty scale.

Factor 2 / Factor 1	WfowDen	PopDen	ProxRoads
WfowDen	Equally important	Moderately less important	Strongly more important
PopDen		Equally important	Extremely more important
ProxRoads			Equally important

→

Factor 2 / Factor 1	WfowDen	PopDen	ProxRoads
WfowDen	1	1/3	5
PopDen	3	1	9
ProxRoads	1/5	1/9	1

Figure 22: Conversion of the pair-wise comparison matrix into a numerical matrix (example for HPAI H5N1).

Once all the comparisons converted into numerical weights, the total weight of each risk factor was calculated using the lambda max (λmax) method (mean of normalized values), for each matrix (and therefore, for each expert) (figure 23). The grey boxes have the value of 1, since a given risk factor (in row) is logically equivalent to the same risk factor (in column).

Risk factor	*goatdens*	*sheepdens*	*distvet*	*proxrivers*	*proxparks*	*proxroads*	*proxmarkets*	*Weight*
goatdens		3,00	3,00	7,00	5,00	5,00	5,00	*0,367*
sheepdens	0,33		1,00	7,00	5,00	3,00	3,00	*0,190*
distvet	0,33	1,00		7,00	5,00	3,00	3,00	*0,190*
proxriver	0,14	0,14	0,14		3,00	0,33	0,20	*0,041*
proxparks	0,20	0,20	0,20	0,33		0,33	0,20	*0,034*
proxroads	0,20	0,33	0,33	3,00	3,00		1,00	*0,079*
proxmarkets	0,20	0,33	0,33	5,00	5,00	1,00		*0,099*
Sum	*2,41*	*6,01*	*6,01*	*30,33*	*27,00*	*13,67*	*13,40*	
sum*weight	0,883055513	1,141207309	1,142396607	1,258001392	0,914226243	1,077448314	1,324440514	

Figure 23: Example of a numerical matrix filled-in by an expert, with risk factors' weights for HPAI H5N1 risk of spread.

For example, if we look at the risk factor "goatdens", the total weight is:

$$\text{mean}\left(\frac{1}{2{,}41}+\frac{3}{6{,}01}+\frac{3}{6{,}01}+\frac{7}{30{,}33}+\frac{5}{27}+\frac{5}{13{,}67}+\frac{5}{13{,}40}\right)= 0{,}367$$

Each elicited expert filled in one pair-wise comparison matrix in the questionnaire. To prevent comparison matrices that could be considered inconsistent, we assessed the overall consistency of each comparison matrix by calculating a consistency ratio (CR). Indeed, if the expert gives a weight of 2 to A compared to B, and a weight of 4 to B compared to C, then the weight given to A compared to C should be 2*4=8. The consistency ratio (CR) is defined as the distance from the consistency, and is calculated with the following formula:

$$\text{CR} = \frac{CI}{RI}$$

Where CI (consistency index) = $\frac{(\lambda\text{max n})}{(\text{n}-1)}$ with λmax = Σ (sum*weight) and n: number of risk factors (7 in our study)

And where RI = Random Index, determined from a look-up table (which depends on n). Here with n= 7 risk factors, RI=1.32.

If CR was <0.13, we considered the expert as consistent. Non-consistent experts were removed from the study.

8. COMBINATION OF THE RISK FACTORS INTO SUITABILITY MAPS

The final suitability of areas is calculated for each raster cell (map unit). For each unit, the standardized risk factor value and its corresponding weight are combined using a weighted linear combination (WLC) (Malczewski 2000):

$$A = \sum_{i=1}^{n} w_i . x_i$$

with A: output
xi: standardized suitability value of risk factor i
wi: weight of risk factor (criteria) i
n: number of risk factors

The WLC consists in multiplying the weight assigned to each factor by the standardized value for this risk factor in that pixel. Then, the products calculated for each factor are summed, giving a final value for each raster cell. This output is called the suitability index (SI). The SI in each pixel varies from 0 to 1; a high score indicating a high suitability for PPR spread. Below is an illustration of a combination of 4 risk factors weighted by their corresponding weight for a given risk in Europe. The final suitability map (output) is the sum of the 4 weighted and standardized risk factors (figure 24).

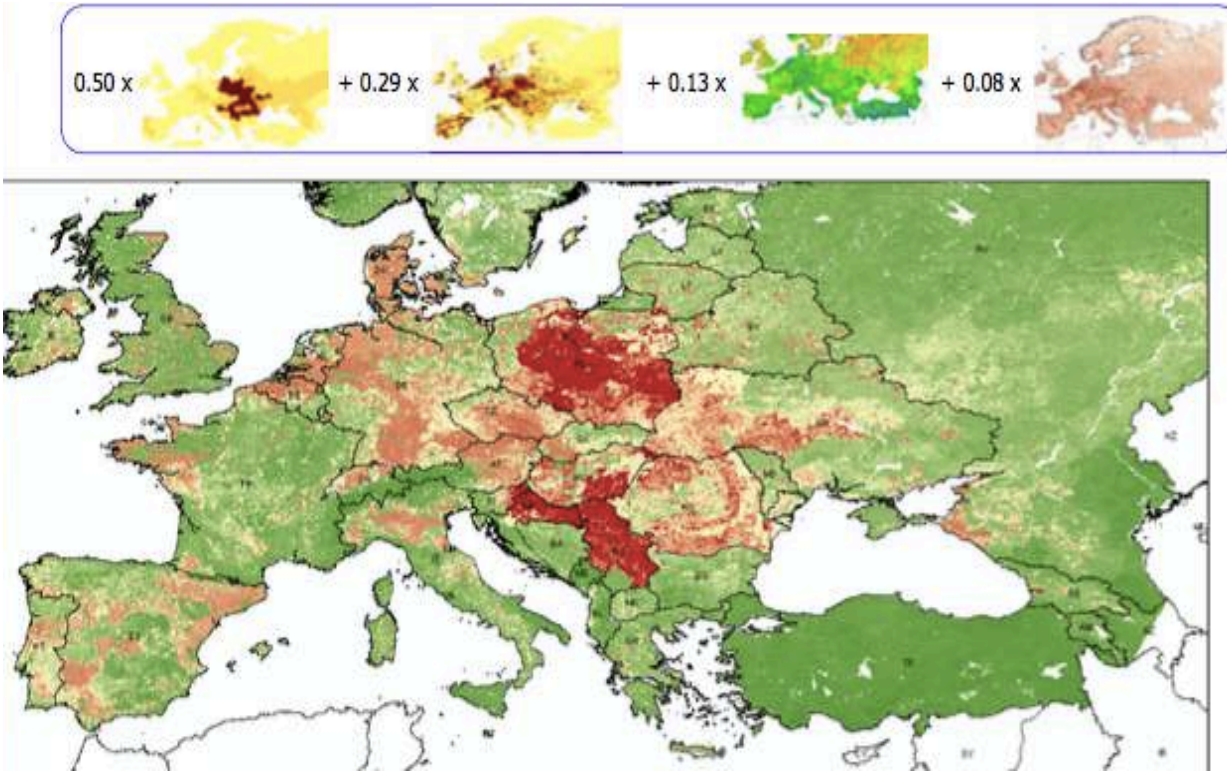

Figure 24: Output suitability map for a given risk in Europe, obtained by the WLC method (Tran 2017)

In our study, we applied the weighted linear combination four times (one for each consistent expert) to get one map. For example, for expert 1, we multiplied each standardized risk factor by its corresponding weight (that we had calculated from his or her comparison matrix). These weighted layers were then added, in order to get one final map per expert. Then, to produce the ultimate suitability map (the final output of our study) we calculated the mean of the 4 final expert maps.

These calculations on raster layers (WLC and mean) were made on RSTUDIO software (version 1.1.383).

9. PRODUCTION OF TWO ADDITIONAL SUITABILITY MAPS AT PROVINCIAL SCALE

In addition to the suitability map at the country scale, we produced a suitability map for two provinces (Northern Cape and Western Cape) for which sheep and goat census data were available at the Veterinary Services. Indeed, these two provinces provided census data with GPS points. Therefore, it was possible to project these points using ARCGIS. Each GPS point was corresponding to a location of census, with the number of animals recorded, species, use, handling facilities, etc. We calculated sheep and goat density by adding the value of the census points located in each settlement and dividing by the area of each settlement (table 5). Then, we converted these four shapefiles (goatdensNC, goatdensWC, sheepdensNC, sheepdensWC) into raster formats of 1km^2 resolution, in order to be able to combine them to the 5 remaining risk factors. They are available in Appendix 4. Those five remaining factors, initially at the national scale, were clipped using the 'Clip' tool in ARCGIS to fit their extent to the extent of Northern Cape and Western Cape provinces. Finally, all with the same resolution and extent, they were able to be combined following the same methodology that the one for the national map.

Table 5: Geographical datasets collected for the provincial maps

Dataset	Format	Source
Sheep and Goat Census	Excel files	Courtesy of DAFF Northern Cape and DAFF Western Cape
Settlement typology	Shapefile (vector)	CSIR (Council for Scientific and Industrial Research) (sources: Department of Environmental Affairs, 2011, Demarcation Board, 2012, CSIR Built Environment, Geospatial Analysis Platform 2012 (http://www.gap.csir.co.za), Surveyor General, 2012, Statistics South Africa, 2012)

CHAPTER 3: RESULTS

1. WEIGHTS ATTRIBUTED BY EXPERTS

After the elimination of inconsistent responses, data from 4 experts were retained. The experts attributed the greatest weight to goat density. Next in terms of influence, the experts ranked proximity to market, sheep density and distance to vet services. Proximity to roads, parks and rivers only came in last positions (Table 5).

Table 6: Weights attributed by the experts. Minimum and Maximum values are indicated in brackets.

Rank	Risk Factor	Final Weight
1	Goat density	0.335 [0.2672 ; 0.3718]
2	Proximity to market	0.174 [0.0776 ; 0.2941]
3	Sheep density	0.169 [0.0476 ; 0.2672]
4	Distance to vet services	0.137 [0.0773 ; 0.190]
5	Proximity to roads	0.088 [0.0690 ; 0.1048]
6	Proximity to parks	0.053 [0.034 ; 0.0756]
7	Proximity to rivers	0.045 [0.0219 ; 0.0690]

2. OUTPUT OF THE SUITABILITY MAPS

The resulting maps of areas suitable for PPR spread are presented in figure 25, 26 and 27 for the national map, the Northern Cape map and the Western Cape map, respectively. The outputs of the model were coloured to indicate very low and low suitability for PPR spread in green, medium suitability in yellow and high and very high suitability in red. The suitability for Northern Cape province ranges from 0.10 to 0.71 (with a mean at 0.22). The suitability for Western Cape province ranges from 0.11 to 0.66 (with a mean at 0.25). The suitability for the national map ranges from 0.12 to 0.89 (with a mean of 0.27).

At the national scale, the most suitable areas for PPR spread appear to be the eastern half of the territory, with emphasis in Eastern Cape, Free State and Mpumalanga provinces. Western Cape and Northern Cape provinces appear to be less suitable for PPR spread. The red area in the Northern Cape is due to the Gridded Livestock of the World and should not be taken in consideration. For Western Cape and Northern Cape provinces it is advised to look at the provincial maps for better accuracy. It is important to note that some highly suitable hotspots appear only on provincial maps but not on the national map, showing the importance of collecting locally-sourced data.

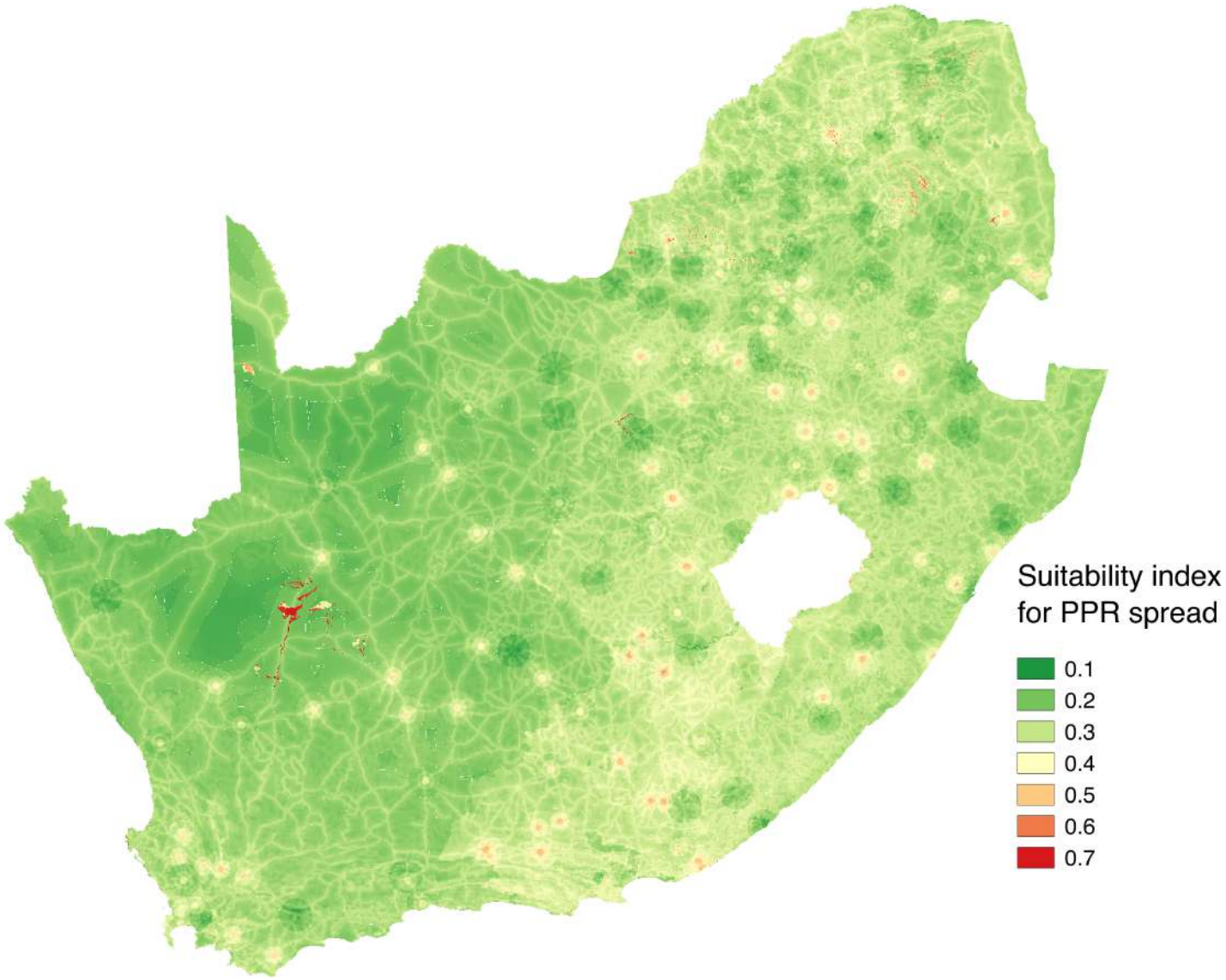

Figure 25: Suitability map at the national scale

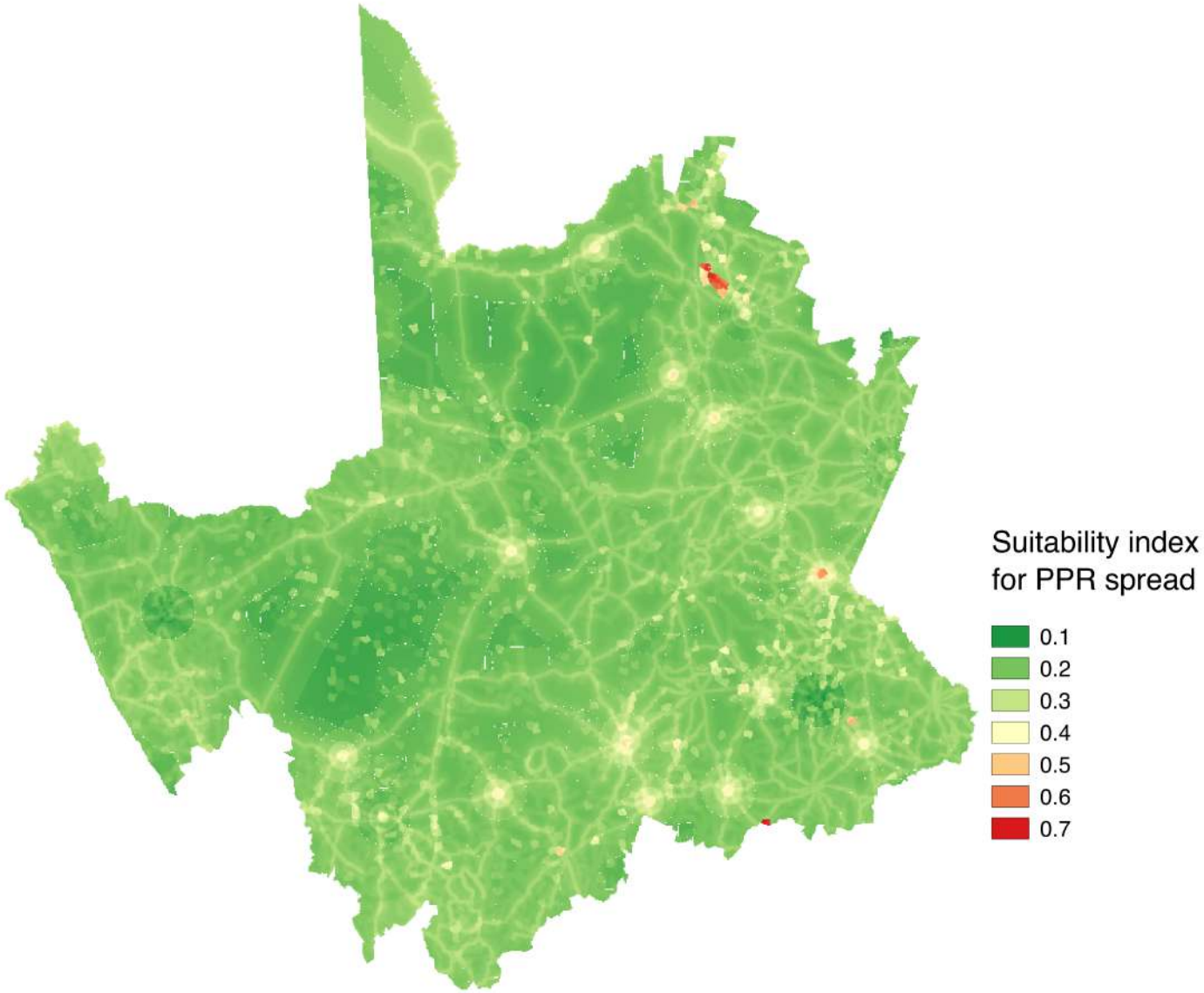

Figure 26: Suitability map for Northern Cape Province

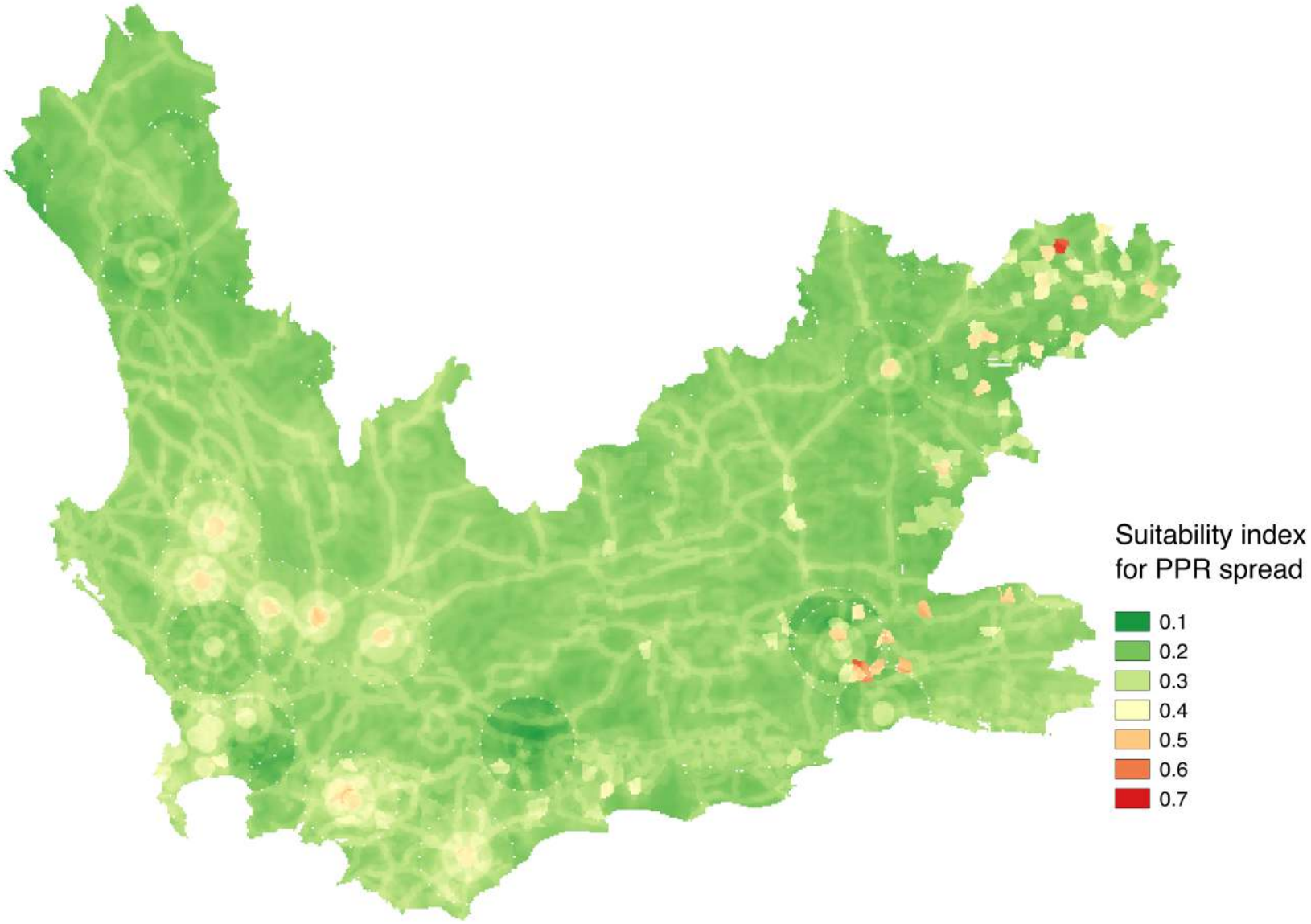

Figure 27: Suitability map for Western Cape Province

CHAPTER 4: DISCUSSION

The objective of the study was to develop a geographic knowledge-based method to map areas suitable for PPR spread in South Africa. The cut-off of 0.5 for suitability index to distinguish suitable and unsuitable areas of the output is rather arbitrary but has been commonly used in similar works (Liu et al. 2005; De Glanville et al. 2014; Paul et al. 2016).

In Northern Cape Province, the mean suitability index of 0.22 indicates that most of the province can be considered as unsuitable for PPR spread. However, the detailed examination of the suitability map points out some high suitability spots, that correspond mainly to small ruminant formal auctions. This correspondence can be easily understood given the important weight allocated to this risk factor by experts (0.174). The area of Kuruman (the hot spot located at the North-East of the province) is particularly suitable for PPR spread as the auction is located close to areas of high small ruminant density. Other locations such as Britstown, Hopetown and in a lesser extent Victoria West, Van Zylrus, Carnarvon and Williston can be considered as areas particularly suitable for PPR spread. Contrastingly, Calvinia and Upington areas have auctions but appear unsuitable for disease spread given the low density of small ruminants. The presence of veterinary services offices in Kuruman and De Aar would help conduction of efficient veterinary surveillance activities.

The Western Cape Province can be considered as unsuitable for PPR spread in the major part of its territory, with a mean suitability index of 0.25. The Eastern tip of the province (around Murraysburg) hosts high density of animals and appear to be suitable (SI > 0.5) for PPR spread. The area around Oudtshoorn at the South East of the province also appears to be suitable. Veterinary services are present in Beaufort West and Oudtshoorn, thus facilitating the implementation of surveillance activities. As for the hotspots west of the province, they correspond to the presence of small ruminant auctions and taxi ranks, more or less associated to high animal density. Indeed, these areas appear to be suitable but in a lesser extent than the Eastern areas of the province, despite their high densities of sheep. This can be explained by the low goat numbers in these areas. Goat density and proximity to markets seem to drive the final output of the model.

At the national scale, the various hotspots spread throughout the territory correspond either to formal auctions or to taxi ranks. The mean suitability index (0.27) is slightly higher than those of Northern Cape and Western Cape provinces. A difference in suitability can be visually distinguished between the western half of the country (Northern Cape and Western Cape) and the eastern half. Three provinces appear more suitable for PPR spread: Limpopo, Free State and Eastern Cape and this can be understood by the large number of small ruminants hosted in these provinces. The fact that Limpopo province is one of the most suitable areas for PPR spread should be particularly taken into consideration given that the province shares borders with Mozambique, Zimbabwe and Botswana. If the virus is eventually introduced through these borders, the spread of the disease would be facilitated as the habitat is suitable.

South-west of Eastern Cape province and north of Limpopo province are suitable areas that are far from veterinary services offices. Therefore, efficiency of surveillance and awareness activities in these areas are threatened. PPR coordination programmes have been implemented by DAFF in areas considered critical, such as in Mpumalanga province. As part of the programme, serological surveys are conducted to verify the absence of PPRV.

When looking at the maps, stakeholders must bear in mind that lots of small ruminants (and especially goats) may spread the disease in an unpredicted way as their movements are difficult to trace. For example, Kwazulu Natal (KZN) province hosts large numbers of goats in communal areas and hosts populations with many religious beliefs and celebrations using small ruminant sacrifices. However, our map did not highlight KZN as a highly suitable area, potentially due to inaccurate data on ruminant census. Indeed, it appeared to us during the study that small ruminant numbers in South Africa were hardly traceable and countable. As said earlier, there is an important informal market – especially for goats – that unable the competent authorities to trace animal movements and numbers efficiently.

Factors weights

In our study we selected seven risk factors, a number that appears to be in line with those of other studies (Paul et al. 2016; Arsevska et al. 2016; Clements, Pfeiffer, Martin 2006). However, for similar studies on PPR risk mapping using MCDA (Waret-Szkuta 2011; Tran 2013), 10 risk factors were used. The challenge in selecting numerous risk factors is the consistent completion of the comparison matrix by the experts.

Our risk factors weights and the consecutive rank among risk factors can be compared to those of previous studies on PPR risk assessment in Africa (Table 7).

Table 7: Comparison of the weights and rank of the risk factors used in PPR risk mapping using MCDA approach.

Rank	Our study	(Tran 2013)	(Waret-Szkuta 2011)
1	Goat density (0.335)	Goat density (0.249)	Goat density
2	proximity to market (0.174)	Sheep density (0.220)	Sheep density
3	sheep density (0.169)	Distance to dry and semi-dry areas (0.105)	Distance to veterinary services
4	distance to veterinary services (0.137)	Camel (0.092)	Proximity to navigable waters
5	proximity to roads (0.088)	Road density (0.098)	Distance to roads = camel density

6	proximity to national parks (0.053)	Proximity to rivers and wetlands (0.067)	Distance to arid/semi-arid zones
7	proximity to rivers (0.045)	Proximity to markets (0.064)	Distance to cities
8		Proximity to wildlife national parks (0.041)	Distance to protected areas
9		Density of railways (0.040)	Proximity to railways

For the study for Eastern Africa (Tran 2013), the risk factor weighting was based on the own expertise of the authors; experts were not solicited. For the study at the continental scale (Waret-Szkuta 2011), the resulting weights were not available. We can note that goat density has been ranked as the most important factor in all the studies. Contrastingly, proximity to market was not considered as important as in our study since it was ranked 7/9 or not selected at all. Distance to veterinary services appears one of the most important risk factor that is not linked to animal densities. As in our study, proximity to water sources and parks are among the least important risk factors for PPR spread.

Goat and Sheep Density

In our study, we first aimed at collecting livestock census data per local municipality (the third administrative level). The area of local municipality ranges from 545 km2 (Mandeni Local Municipality in KwaZulu Natal) to 44,231 km2 (Dawid Kruiper Local Municipality in Northern Cape). This is way more than the mean area of the third administrative level in Thaïland (70 km2) and Cambodia (112 km2) (Paul et al. 2016). Therefore, our study site implies automatically a coarser resolution. However, in South Africa, only few provinces were able to provide us with the requested data in the time schedule of the project. By the time of the study, some provinces had completed only census of 30% of their approximate small ruminant numbers.

Therefore, for the national map, we finally had to source sheep and goat density data from the FAO's project Gridded Livestock of the World. Indeed, FAO developed standardised global, sub-national maps of the major livestock species. To produce density maps, official census and survey data are combined to various parameters assessing habitat suitability for livestock keeping (such as elevation, urban areas, protected areas, etc.). The map values are modelled livestock densities at 1 km2 scale. The GLW model has been used in other animal health risk mapping projects using MCDA (Tran 2013; De Glanville et al. 2014). For South Africa, sheep and goat numbers used in this model were sourced from official data issued per province (first administrative level). This certainly impacted the accuracy of the output GLW model.

As a matter of fact, in Uganda, researchers and staff of the veterinary services in a field mission pointed out some discrepancies between the GLW maps and national agricultural statistics recorded at district level (Tran 2013). For example, a region covering areas with the greatest concentrations of cattle in the country (called the "cattle-corridor) do not appear in the GLW-modelled maps. Therefore, the output maps of our study should be interpreted with caution. For the PPR suitability maps of Northern Cape and Western Cape provinces, sheep and goat census data were provided by the veterinary services where each census was corresponding to a GPS point on the map, enabling us to get a thinner resolution than the data per local municipality. This made it possible to produce more accurate maps, and we hope these will illustrate the need of locally-sourced data to the veterinary services and will encourage the participation of the other non-respondent provinces.

Even if the census data available per GPS point is the most accurate and would be ideal, it is more realistic to ask for collection of data available at the local municipality scale (smaller administrative unit). An interesting improvement would be the collection of official census data at the local municipality level, to which would be applied the methodology of the GLW model, to precise accuracy of sheep and goat density maps in a near future. Moreover, the South Africa land cover data is available in a raster format with a pixel size of 30m x 30m and could bring a better resolution of the density map if it comes to be incorporated to the GLW model for the country.

Distance to veterinary services

It is understandable that the spread of the disease from a primary spot depends on the detection delay, therefore on the farmers' awareness and the veterinary services efficiency. To map the lack of access to veterinary services, we chose to map the Euclidean distance from each recorded veterinary office in each province. However Euclidean distance can be considered as the distance as the crow flies and as such, does not take transport availability into account. Indeed, distance should not be taken into consideration as such, but should be studied according the type of road and its accessibility; some farms may be closer from the veterinary services office when considering Euclidean distance but in reality can be more difficult to access (no road or poor road such as gravelled road). To calculate actual distance (i.e. using roads network), we could have run a "cost distance analysis" in ArcMap. Alternatively, some spatial MCDA risk mapping projects used "travel time" analysis (raster describing travel time in hours) (De Glanville et al. 2014) which could appear more pertinent. This remark is also worth for other criteria in our study that consider distance or proximity.

At first, we requested the provincial veterinary services to provide locations of the veterinary and AHT offices in their various districts. However, since only few provinces were able to provide such data, we collected the location of the veterinary services offices browsing official DAFF databases in which the Animal Health Technician's office did not appear. Given the fact that most of the field activities, especially in communal areas, are completed by the AHTs, we can assume that our dataset is missing an important part of the puzzle. This point could be addressed by the participation of the veterinary services in the collection of data.

Furthermore, some areas can be accessible to veterinary services but unvisited because of insecurity; for example, areas close to borders, or areas where relationships between authorities and farmers are conflictual for various reasons. Such areas would worth being mapped. Another way to map the lack of veterinary services could be the number of veterinarians and animal health technicians per area or per animal. Indeed, it seems obvious that the less numerous the staff is, the busier are the veterinary services and the less available they are to conduct their surveillance and awareness activities. However, such data was not available by the time of our study.

Proximity to roads

In our study, we considered only roads as an effective mean of transport for livestock, based on local stakeholders' opinion. Contrastingly, in other studies mapping PPR risk in Eastern Africa, railways (Tran 2013) and navigable rivers (Waret-Szkuta 2011) were included. However, the situation in South Africa is different as small livestock is transported essentially using road network and there is no formal navigable river in the country. In the study targeting Eastern Africa (Tran 2013), criterion was not "proximity to" roads but "density of" roads, as a proxy for trade. In our study, we considered that the closer a farm was from a national, regional, provincial route, the easier it was for the farmer to trade his livestock, formally or informally. Choosing "Proximity to" rather than "density of" was also aiming at facilitating the selection of thresholds for experts when characterizing the relationship between the risk factor and PPR spread.

Proximity to rivers

Proximity to perennial and non-perennial rivers was expected to be associated with higher risk of spread through close contact among animal at watering places. In our study, this risk factor was considered as the least important. This may be explained by the fact that in commercial farming animals are less likely to share watering points with other flocks. In communal farming, animals also drink at dams and puddles from rain, or even in buckets brought by the farmer in areas where there is no standing water (Goat Agribusiness Project, KZN, personal statement).

Proximity to national parks and reserves

The weight given to the factor "proximity to national parks and reserves" (0.053, rank 6/7) did not appear to be a key factor for the experts, suggesting that the potential role of wild ruminants as reservoir for PPRV is not as important as small ruminant densities and markets. Proximity to wildlife national parks was also used as a risk factor in a similar PPR risk mapping project in Eastern Africa (Tran 2013) as a proxy for wild ruminant densities. The use of this criteria can be questioned as we have no evidence of wildlife ability to transmit the virus to other species. However, to date too little is known on this topic to be able to exclude this hypothesis. We regret the lack of census data of wild ruminants in each park or reserve, which would have helped the inclusion or exclusion of the different areas in our geographical layer. Indeed, parks and reserves of more than 1000 ha have been included.

This arbitrary threshold issued from a specialist of South African wildlife, would however worth being replaced rather by a wildlife ruminant density calculated for each park or reserve. It is possible that in our study we included areas of more than 1000 ha that host very small numbers of wild ruminants, as it is possible that we excluded small areas with higher densities.

Proximity to markets

The location of the different formal and informal markets for small ruminants was asked to the provincial veterinary services through a questionnaire. As it was the case for animal densities and locations of vet and AHT offices, only few provinces were able to provide such data. There is no comprehensive database of small ruminant auctions in South Africa. For informal markets, as it is informal it is very difficult for the veterinary services to spot where are the trading locations. Therefore, we tried to be the most comprehensive possible browsing farming magazines available online for the past two years, upon recommendation of a member of the National Wool Growers Association. As for the location of informal markets, we used the OpenStreetMap database that gathers the main taxi ranks in the country. In some provinces where informal market is particularly important (such as Limpopo, Mpumalanga and KwaZulu Natal), we could add pension pay points since they are believed to be also places where communal goats are traded. Some studies used human population densities as a proxy for the location of markets; in Eastern Africa, cities with densities > 1000 inhabitants/km2 were selected as markets, based on an analysis of the locations of markets in Ethiopia, Uganda and Kenya (Tran 2013). If such analysis come to be available for South Africa and provides a specific and realistic threshold, this proxy could be used for the risk factor "proximity to markets".

The importance of informal market of small ruminants is very dependent on the province considered. South Africa has the particularity to display important socio-economic variations among provinces.

In addition, in our study we tried to associate goat density to communal farming and sheep density to commercial farming, based on DAFF reports (DAFF 2015c, 2015d). This was an arbitrary choice based on a rough estimate and that could be discussed. Indeed, sheep in KZN can be mostly kept in commercial farming but can be kept mostly in communal farming in Western Cape. Again, variations between provinces certainly impact accuracy of our maps. Therefore, it is advised that when collecting census data, information on whether animals are kept commercially or communally should be reported in the census to be able to use such risk factor in a near future.

Given the important provinces particularities, we understand the interest of producing provincial suitability maps. In our study, we used the same risk factors and the same weights than those applied for the national map, but we can easily imagine risk factors being selected differently based on which province is under study, and even the weights of the different risk factors could vary among provinces. Furthermore, we created maps were sheep density and goat density were both risk factors in the same model. It could be interesting to create one map assessing PPR spread suitability within goat populations, and another map within sheep populations. Indeed, all risk factors may not impact the two species in the same extent. For instance, proximity to auctions may impact more sheep populations and proximity to taxi ranks (which would become a proper risk factor) could impact more goat population.

Ecological factors (such as climate, landscape, water availability, etc.) have been considered risk factors in similar risk mapping approaches mostly for vector-borne diseases (Sánchez-Vizcaíno, Martínez-López, Sánchez-Vizcaíno 2013; Clements et al. 2007; Tran et al. 2013). As for PPR, no article reported ecological factors as risk factors for disease transmission, except climatic factor (rain season in some articles, dry season in others) and always without statistical significance. In a similar study on PPR but for Eastern Africa (Tran 2013), the authors included seasonality in their MCDA model, taking into account climatic (rain season) and socio-cultural events (Eid-al-Kabeer). For South Africa situation, given the wide climatic and socio-economic variations among provinces, a potential inclusion of season as a risk factor should be considered for suitability maps at provincial levels only. Indeed, all the provinces are not affected by drought (and rain) in the same extent, and provinces can be very different in terms of traditional practices implying small ruminant movements. Moreover, all South Africans implied in such practices do not share the same religion, and if areas hosting a large proportion of Muslims may be considered for Eid-al-Kabeer, some areas host large proportions of Christians, where sheep and goat movements are linked to Christmas and Pass-over for example. Many tribes in various provinces are responsible for small ruminant trade year-round for funerals and weddings. Therefore, the seasonality should be considered with caution and most of all applied to each province's specificity.

The spatial MCDA methodology comes with various degrees of subjectivity in every step of the process, eventually leading to limitations.

Identifying and weighting risk factors for PPR transmission

Two main methods for risk factor identification and weighting have been reported; the bibliographical review and the expert elicitation. The identification of risk factors through literature review has been extensively used in other studies (De Glanville et al. 2014; Waret-Szkuta 2011). In our study, we mixed both methods: we identified risk factors through bibliographic review, and referred to experts for their weighting.

As for the bibliographic method, risk factors can be weighted according to their frequency in the articles (Guillaume 2015; Clements, Pfeiffer, Martin 2006; Sánchez-Vizcaíno, Martínez-López, Sánchez-Vizcaíno 2013) but they can also be weighted based on their statistical significance. In a study on HPAI H5N1, risk factors were indeed weighted according to their odd ratio and the result of their pvalue (<0.1, <0.05 and <0.01) (Roulleau 2014).

Some studies also compared the outputs of the bibliographic method to those of the expert elicitation method, where experts have to identify risk factors among a list (Roulleau 2014; Guillaume 2015). It is interesting to note that when comparing these two methods, the maps produced by expert's opinion resulted in significantly higher predictive ability than the bibliographic-based model (Paul et al. 2016).

In our study, we selected a set of risk factors identified in the literature for which obtaining correspondent geographical data was achievable. Therefore, we automatically introduced a bias using only risk factors that could be mapped, although other factors (such as traditional practices for instance) may contribute at least ass the other factors used in our study.

We did not take statistical significance into consideration, despite the fact that some articles provide poor statistical analysis on the mentioned risk factors. We chose to rely on expert opinion to weight the risk factors, but it could be interesting to combine risk factor weights issued from statistical significance in bibliography with the weight allocated by the experts.

Choice of experts

There is no consensus on the method to choose the experts. In our study, we chose to elicit mainly local stakeholders (members of the veterinary services, epidemiologists) but also researchers having worked on PPR in Africa. This choice of local experts was also made in a spatial MCDA risk mapping of leptospirosis with the selection of local veterinarians and doctors in the experts panel (Guillaume 2015). Contrastingly, in other studies, experts were selected based on their participation in at least 2 publications on PPR risk factors (Waret-Szkuta 2011). In a study on African Swine Fever, experts were authors of publications about ASF risk factors, without a minimum number of publications (De Glanville et al. 2014). Caution should be taken when selecting authors of publications as experts as their opinion can be biased by the results of their own studies. Anyway, opinion of experts may vary depending on their experience and the type of organization they belong to.

There is no consensus neither on the number of experts to participate but it seems that the number of experts we selected is in line with sample sizes previoulsy reported (Paul et al. 2016). In our study, we contacted 16 experts; of which 8 (50%) returned the completed questionnaire but the results of only 4 (50% of the respondents) were considered consistent and retained. In a similar study on PPR in Africa, 22 experts were identified and 14 (63%) had returned the opinion survey (Waret-Szkuta 2011). In a study on leptospirosis in New Caledonia, 100 experts were sollicitated, 17 (17%) returned the survey and the results of 7 (41% of the respondents) were retained for their consistency (Guillaume 2015). A study on HPAI H5N1 in Thailand and Cambodia (Paul et al. 2016; Roulleau 2014) contacted 14 and 11 experts, respectively. 7 (50%) experts in Thailand and 5 (45%) in Cambodia were retained, the remaining experts having provided inconsistent, incomplete or no answers. Our statistics are less than the above mentioned study: we worked with the results of 25% of our elicited experts. A larger number of participating and consistent experts would have logically improved the robustness of our model.

The collection of expert opinion in our study was made using an electronic questionnaire with individual expert elicitation. This collection method was used in other studies (Guillaume 2015; Roulleau 2014). However, we notice that among our 4 consistent experts, 2 of them were experts we met in person and were explained the design of our questionnaire. In addition, it is important to note that we had previously met 6 of the 8 experts who sent back the filled-in questionnaire. This may mean that experts' opinion collection could be more efficient at a meeting than by sending emails. However, the gathering of a large number of experts in a meeting requires some time and budget; if more accurate data (census data in particular) comes to be available, organization of a meeting will need to be foreseen.

Pairwise comparison matrix and consistency ratio

Pairwise comparison is a method that has been applied various times to assess the relative importance of one factor to another in a decision making process (Boroushaki, Malczewski 2008; Vaidya, Kumar 2006) and has been used many times for disease mapping using spatial MCDA (De Glanville et al. 2014; Hongoh et al. 2011; Stevens, Pfeiffer 2011). The fact of ranking factors one compared to another using qualitative criteria rather than quantitative ones automatically introduces uncertainty and subjectivity in the weights (Chen, Yu, Khan 2013). Therefore, the main challenge with such matrices is their frequent inconsistency (Bozóki, Rapcsák 2007). To tackle such inconsistency, the cut-off of 0.1 for the consistency ratio has been suggested (Saaty 1980) and is used in various studies in animal health mapping (Guillaume 2015; Tran 2013).

In our study, we had two experts of CR<0.1 and two more experts of CR<0.13. Therefore, in order to be able to use the results of 4 experts, we slightly enlarged the cut-off to 0.13.

Contrastingly, we could have weighted our different experts based on their consistency ratio, and thus kept the results of inconsistent experts but weighted by the smallest weight. This would have enable the inclusion of more experts results and therefore our final maps would have been issued from more expert maps. Such expert weighting based on their consistency ratio has already been done in similar approaches for HPAI H5N1 (Roulleau 2014) and leptospirosis (Guillaume 2015).

We can note that the validity of this cut-off has been questioned (Koczkodaj 1993; Kwiesielewicz, Van Uden 2004) and a study showed that a matrix passing the consistency test successfully may still be contracditory. Alternatively to the 0.1 cut-off suggested by Saaty, a study on spatial MCDA for african swive fever in Africa (De Glanville et al. 2014), introduced stochasticity to assess the consistency of the pairwise comparison matrices.

Validation

Validation consists in assessing the ability of the output maps to predict the most suitable areas for PPR spread. This step of the process is essential prior the interpretation of the results, but in our case, since South Africa is still free of PPR, there is no disease data (outbreak) to use for validation. The results of our study should therefore be interpreted with caution. Due to lack of disease surveillance data, validation is often limited to a visual comparison (Pfeiffer et al. 2008). However, in contexts where disease outbreaks data are available, quantitative assessments have been developed (De Glanville et al. 2014; Paul et al. 2016; Stevens 2013) calculating the Area Under the Curve from the ROC (Receiver Operating Characteristic Curve) analysis. A model with good predicting ability has an AUC close to 1, but an AUC close to 0.5 shows a lack of predicting ability of the model, i.e. it cannot predict better than if it was random.

Such assessment was conducted for the PPR risk mapping in Eastern Africa and revealed a high (AUC >0.9) predicting ability (Tran 2013).

In disease-free countries, such maps are interesting to avoid the risk to happen; therefore, we should find a way to validate them prior the apparition of disease outbreaks. This is the challenge we shall face in the case of South Africa for PPR. A solution to our situation would be to create a map for several Southern African countries including PPR-affected countries (i.e. with outbreaks data). For example, if we apply our model to Mozambique and Tanzania to create a regional suitability map, we could proceed to map validation using PPR outbreaks of Tanzania.

Sensitivity analysis

The sensitivity analysis aims at assessing the robustness and reliability of our results. Indeed, we would need to confirm that our maps are not too dependent on the choices made by the experts. This analysis could also identify which risk factor impacts the most the output. If a risk factor impacts more than others, then we should think about improving the quality and accuracy of the corresponding geographic data, in order to improve the quality of our maps. Several studies have already assessed the sensitivity of their suitability maps (Paul et al. 2016; Tran et al. 2016).

In our case, since no sensitivity analysis has been performed, we did not checked the absence of correlation between factors; therefore, it is possible that our model includes double counting. A sensitivity analysis should therefore be considered as a prerequisite before making use of our output maps.

As we can see, our maps can be discussed in several ways. This discussion aimed at bringing some means of improvements to our model in a near future. To date, there is no consensus on which method to apply for risk factor weighting, characterization and aggregation.

An advantage of the spatial MCDA approach is that the data unavailable at the time of the modelling can be incorporated later on when available. That means that this model could be improved as soon as more accurate data would be provided by the competent authorities, as for the livestock census data for example. In addition, we could allocate weights to experts according their consistency ratio. This is an important interest of the approach: its flexibility to modify the risk factors, weights, add more experts, more risk factors, change the methodology to improve accuracy of the model. The method also allows identifying key parameters that have significant impact on the output maps, and identifying the main knowledge gaps. In our study, the main gaps concern geographic data accuracy and resolution. More consistent experts' opinions could also be incorporated to our model in a near future, but the most challenging part will certainly be the collection of accurate geographical data with fine resolution.

As every knowledge-driven method, the spatial MCDA model has the inconvenient to rely on subjective data and is also limited by the quality, accuracy and spatial resolution of selected geographic data. To tackle this subjectivity, quantitative assessments must be performed before map interpretation and decision-making. However, the expert-based model developed in a study had a greater predictive capacity than previously published statistical model (Paul et al. 2016). It confirms the potential of GIS-based MCDA methods for disease risk mapping, provided map validation and sensitivity analysis are conducted.

CHAPTER 5: CONCLUSION

To our knowledge, this is the first attempt to predict the suitability for Peste des petits ruminants (PPR) spread in South Africa. The spread of PPR towards Southern Africa will certainly raise questions about sheep and goat stocks management and animal health surveillance efficiency within South Africa. The country has to cope with an important informal market chain value that limits the efficiency of their sanitary measures. South Africa is officially recognized by the OIE as a PPR-free country. This status is threatened by the highly contagious nature of the virus and by the anarchic movements of small ruminants throughout Southern Africa and beyond borders.

Yet, the loss of this status would have important consequences on the country's economy. With an area of more than 1.2 million km^2, there is a need to draw potential spatial patterns of the disease in order to target where to implement animal health activities in priority. The spatial MCDA model enables the construction of maps to assess the suitability of areas for PPR spread and provides support to decide where to focus financial and human resources. The main asset of this method is its application in areas where epidemiological data are scarce, and in that way South Africa is a good candidate for the spatial MCDA model.

Our model synthetized scientific knowledge and expert opinions to create maps that revealed spatial heterogeneity of PPR suitable areas in South Africa. South Africa appears to be relatively not suitable for PPR spread (with a mean suitability index of 0.27). However, some high suitability spots are found around small livestock formal and informal markets and where goat and sheep densities are high. The high suitability in Limpopo province that shares borders with at-risk countries should raise concerns and call for a suitability map specifically applied to the Limpopo province.

Such hotspots could be targeted for implementation or enforcement of surveillance activities (such as the PPR coordination programmes implemented by the DAFF). The outputs could also be used as a communication tool between animal health stakeholders, decision-makers and scientific experts. Indeed, maps are often an effective means of communication that gives an instinctive visualization of where are the important areas.

It is important that such outputs are interpreted in the light of the methodology adopted, which remains highly subjective and combines data sources of variable quality, most of which originated from internet-based data repositories. We incorporated only risk factors that can be mapped. In a context where small ruminant (and goats in particular) numbers and movements are hard to trace, it is possible that we missed an important piece of the puzzle. Furthermore, absence of map validation and sensitivity analysis limit the interpretation of our maps.

The update of our maps with more accurate and locally-sourced data is the way to go if we want to use our maps as an accurate decision support tool. Several ways of improvements were discussed above, but it seemed important to us to note that our model could be improved in priority with collection of GPS locations of formal and informal markets and census data by local municipality, ideally with distinction between communal and commercial farming. While we are aware that such data is difficult to collect, we think that the main weakness of our maps is the lack of locally-sourced data.

Furthermore, we note that the 4 provinces that replied to our data collection enquiry where those for which we met a DAFF veterinarian in person at a meeting. Therefore, it is advisable to meet the local stakeholders in person in the future (rather than using emails) in order to get a better participation rate. Organizing a meeting with veterinarians from all the provinces will however require time and budget, that were hard to meet in our study. That said, local stakeholders with ground-proof knowledge and experience such as veterinarians and animal health technicians shall certainly play an important role in the modelling process and, in that way, will determine the use we should make of these suitability maps.

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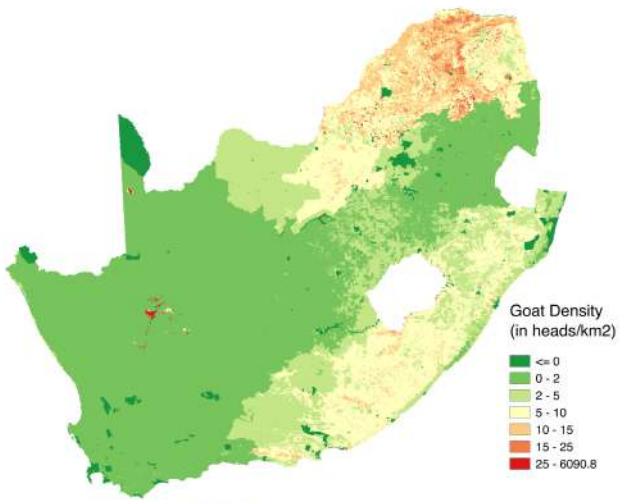
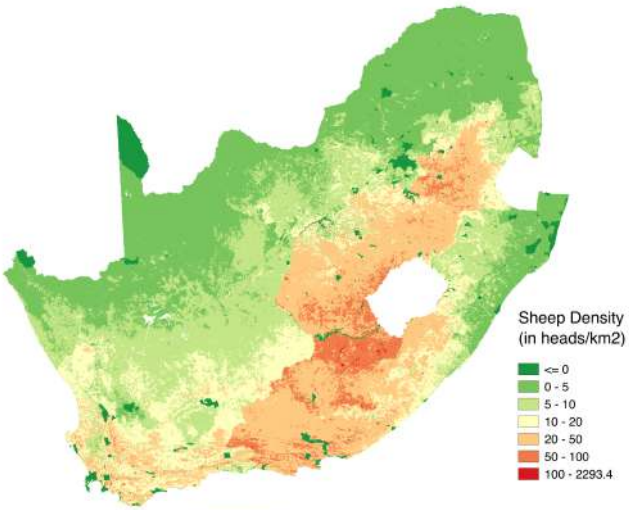
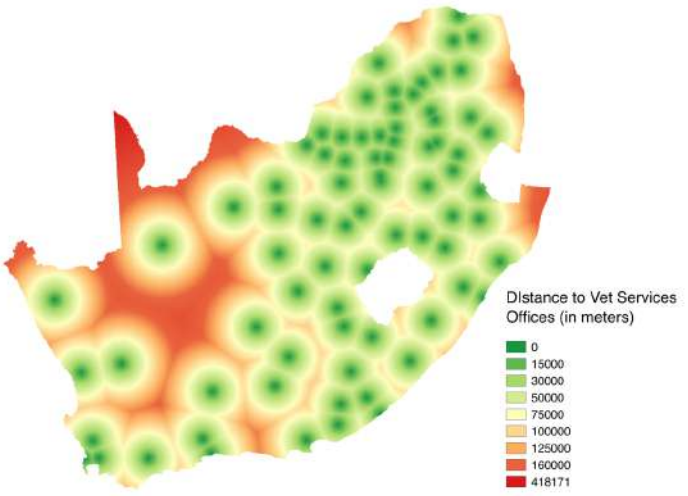
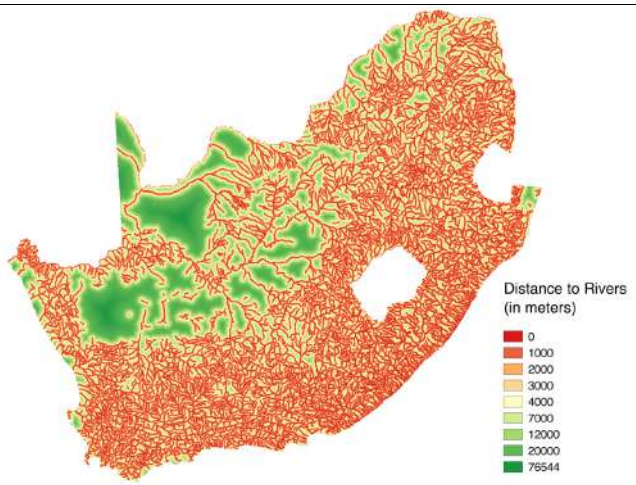
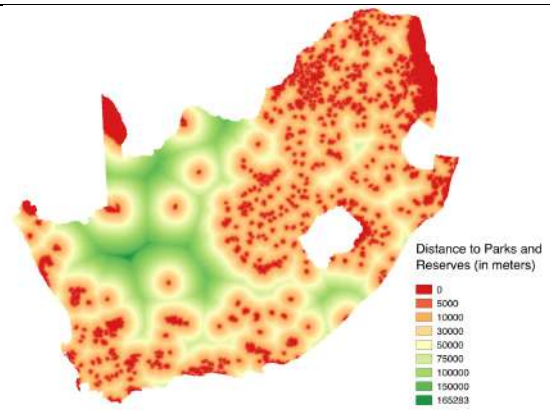
Appendix 1: Risk factor datasets

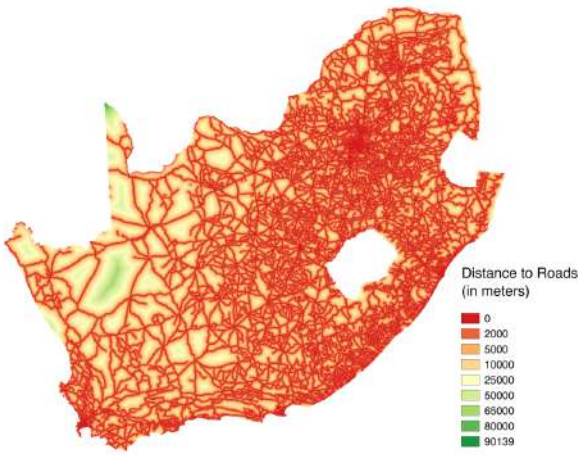
Filename of dataset	goat_dens.tif
Data type	Risk factor layer in a raster format
Author	Alexia Rondeau
Country	South Africa
Summary	Increasing goats' density is expected to be associated with a higher contact rate between susceptible and infected goats, and therefore a greater risk of spread. At the national scale, goats are mainly kept in communal farming (DAFF 2015). Communal farming is expected to be of higher risk of PPR spread as animals kept in communal areas roam freely, may have uncontrolled contacts with other animals, share grazing areas. Communal areas are also more likely to host traditional practices and have lesser access to veterinary services.
Content	Goat density (in heads/km^2)
Original data source	Goat density data: Gridded Livestock of the World 2.01 (2014) Geographic data: Global Administrative Areas (Nov 2015)
Software Version	ArcGis 10.5, QGis 2.18.6
Raw data shapefiles	- AF_Goats1km_AD_2010_v2_1.tif - countryadmin_UTM35S.shp
Processing steps	In ArcGis 10.5: clip the raster "AF_Goats1km_AD_2010_v2_1.tif" to the extent of "countryadmin_UTM35S.shp" and project it to create the raster "goat_dens.tif".
Projection System	WGS 84/ UTM zone 35S
Quicklook	

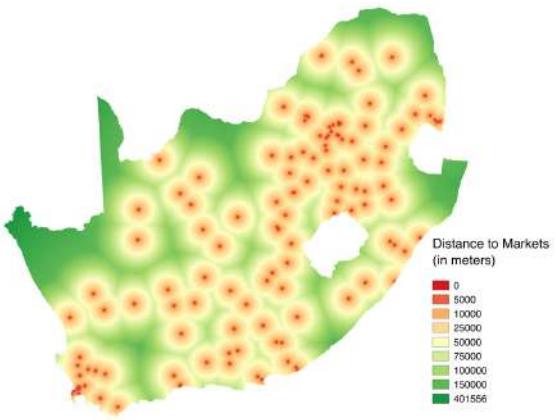
Filename of dataset	sheep_dens.tif
Data type	Risk factor layer in a raster format
Author	Alexia Rondeau
Country	South Africa
Summary	If sheep density increases, the contact rate between susceptible and infected animals is higher, and thus the risk of PPR spread increases. At the national scale, sheep are mainly kept in commercial farming (DAFF 2015). Commercial farming is expected to be of higher risk of spread as flocks are generally larger, with higher inflow and outflow of animals. Sheep are also more prone to stock theft than goats (DAFF, personal statement).
Content	Sheep density (in heads/km^2)
Original data source	Sheep density data: Gridded Livestock of the World 2.01 (2014) Geographic data: Global Administrative Areas (Nov 2015)
Software Version	ArcGis 10.5, QGis 2.18.6
Raw data shapefiles	- AF_Sheep1km_AD_2010_v2_1.tif - countryadmin_UTM35S.shp
Processing steps	In ArcGis 10.5: clip the raster "AF_Sheep1km_AD_2010_v2_1.tif" to the extent of "countryadmin_UTM35S.shp" and project it to create the raster "sheep_dens.tif".
Projection System	WGS 84/ UTM zone 35S
Quicklook	

Filename of dataset	dist_vet.tif
Data type	Risk factor layer in a raster format
Author	Alexia Rondeau
Country	South Africa
Summary	Increasing distance to veterinary services offices is expected to be associated with higher risk of PPR spread as awareness and surveillance activities from the animal health technicians and vets may be more difficult to implement.
Content	Distance to vet services provincial offices (in meters)
Original data source	Vet offices data: Provincial DAFF websites Geographic data: Global Administrative Areas (Nov 2015)
Software Version	ArcGis 10.5, QGis 2.18.6
Raw data shapefiles	- Vet Services.kml - countryadmin_UTM35S.shp
Processing steps	In QGIS: Import "Vet Services.kml" and convert it and project it into a new shapefile "vetoffices_UTM35S.shp". Apply "Euclidean distance" tool to this shapefile to create "dist_vet.tif". Extent: "countryadmin_UTM35S.shp" Resolution: 1000m x 1000m
Projection System	WGS 84/ UTM zone 35S
Quicklook	

Filename of dataset	dist_rivers.tif
Data type	Risk factor layer in a raster format
Author	Alexia Rondeau
Country	South Africa
Summary	Sheep and goats in communal areas extend their roaming area to find food and can gather to rivers to drink and graze. Proximity to rivers is expected to be associated with increased risk of PPR spread through close contact among animals sharing watering points.
Content	Distance to rivers (in meters)
Original data source	Rivers data: Department of Water Affairs (Apr 2012) Geographic data: Global Administrative Areas (Nov 2015)
Software Version	ArcGis 10.5, QGis 2.18.6
Raw data shapefiles	- allrivers_repaired_UTM35S.shp - nondryrivers_AF_UTM35S.shp - countryadmin_UTM35S.shp
Processing steps	In ArcGis 10.5: In "allrivers_repaired_UTM35S.shp": selection by attributes in the field "CLASS": "dry", invert selection and save as "nondryrivers_UTM35S.shp", clip that vector to fit the extent of "countryadmin_UTM35S.shp". Apply the "Euclidean distance" tool to "nondryrivers_AF_UTM35S.shp" to create the raster "dist_rivers.tif". Extent: "countryadmin_UTM35S.shp" Resolution: 1000m x 1000m
Projection System	WGS 84/ UTM zone 35S
Quicklook	

Filename of dataset	dist_parks.tif
Data type	Risk factor layer in a raster format
Author	Alexia Rondeau
Country	South Africa
Summary	Proximity to wildlife national parks may be associated with increased risk of spread of PPR as small ruminants may share grazing areas and water points with wild *bovidae* (although there is no published evidence of the role of wildlife in PPR spread)
Content	Distance to national parks, nature reserves and game parks and reserves of more than 1000 ha (in meters)
Original data source	Protected areas data: Department of Environmental Affairs (March 2017), Geographic data: Global Administrative Areas
Software Version	ArcGis 10.5, QGis 2.18.6
Raw data shapefiles	- protectedareas_UTM35S.shp - countryadmin_UTM35S.shp
Processing steps	In ArcGis: select by attribute in the field "GIS_AREA": all the polygons > 1000ha: "protectedareas1000_UTM35S.shp". In this layer, select by attribute in the field "SITE_TYPE": "national park", "nature reserve" (removing the marine reserves) and apply the expression "game" as filter in the field "CUR_NAME" of "protectedareas1000_TM35S.shp" to select all game parks/reserves/farms. In "SITE_TYPE"="World Heritage Site", select !Simangaliso Wetland Park and Ukhahlamba Drakensberg Park. "Merge": nationalparks1000_UTM35S.shp, terrestrialNR1000_UTM35S.shp, allgame1000_UTM35S.shp, WHS_UTM35S.shp into : "game_parks_reserves_UTM35S.shp". Apply Euclidean distance to "game_parks_reserves_UTM35S.shp" to create "dist_parks.tif". Extent: "countryadmin_UTM35S.shp". Resolution: 1kmx1km
Projection System	WGS 84/ UTM zone 35S
Quicklook	

Filename of dataset	dist_roads.tif
Data type	Risk factor layer in a raster format
Author	Alexia Rondeau
Country	South Africa
Summary	Proximity to National (e.g N12), Provincial (e.g. R36) and Regional (e.g. R312) roads is expected to be associated to easier access to transport and thus increasing movements of small ruminants for trade, leading to a higher risk of spread of the disease.
Content	Distance to roads (in meters)
Original data source	Roads data: OpenStreetMap (March 2017) Geographic data: Global Administrative Areas (Nov 2015)
Software Version	ArcGis 10.5, QGis 2.18.6
Raw data shapefiles	- countryadmin_UTM35S.shp - gis.osm_roads_free_1.shp - roads_UTM35S.shp
Processing steps	In ArcGis 10.5: In "gis.osm_roads_free_1.shp": selection by attribute in the "fclass" field : "primary", "secondary", "tertiary", "trunk" and "motorway" roads. Merge of these 5 classes to create "roads_UTM35S.shp". Apply "Euclidean distance" tool to "roads_UTM35S.shp" to create "dist_roads.tif". Extent: "countryadmin_UTM35S.shp", Resolution: 1000m x 1000m
Projection System	WGS 84/ UTM zone 35S
Quicklook	

Filename of dataset	dist_market.tif
Data type	Risk factor layer in a raster format
Author	Alexia Rondeau
Country	South Africa
Summary	The flocks gathered on markets have different serological status. Proximity to small ruminants' markets is expected to be associated to more regular visits from the farmers and more likelihood of buying animals from the market. Therefore, proximity to markets (both formal and informal) is expected to be associated with increasing risk of spread of PPR.
Content	Distance to markets (in meters)
Original data source	Formal markets data: Auction venues.kml (advertisements in Weekly magazines) Informal markets data: OpenStreetMap (March 2017) Geographic data: Global Administrative Areas (Nov 2015)
Software Version	ArcGis 10.5, QGis 2.18.6
Raw data shapefiles	- countryadmin_UTM35S.shp - Auction venues.kml - gis.osm_transport_a_free_1.shp
Processing steps	Import the kml file in QGIS and convert it and project it into a new shapefile "auctions_UTM35S.shp". In "gis.osm_transport_a_free_1.shp", selection by attribute in the field "fclass": "taxi_rank" and create a new shapefile "taxiranks.shp" with the selection. Merge these two shapefiles to create "formal_informal_markets_UTM35S.shp". Apply "Euclidean distance" tool to this shapefile to create "dist_market.tif". Extent: "countryadmin_UTM35S.shp", Resolution: 1000m x 1000m
Projection System	WGS 84/ UTM zone 35S
Quicklook	

Appendix 2: Expert opinion survey

PESTE DES PETITS RUMINANTS (PPR): SPATIAL RISK ANALYSIS (MCDA) IN SOUTH AFRICA: Risk factors Relationships and Weighting

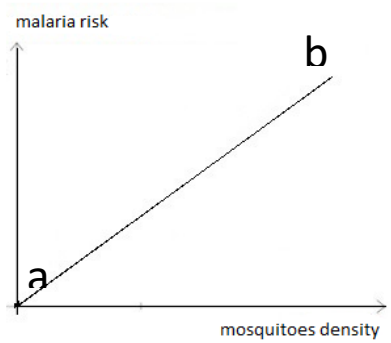
First of all, thank you for your participation. In our study, we are geographically assessing the risk of PPR spread in RSA in the case where PPR would have been introduced in the country. After identification in the literature and collection of the correspondent geographical data, we selected a final set of risk factors, which are listed below. However, all these risk factors may not have the same influence on the risk of PPR spread. Therefore, we need your expertise to define the right relationship that links each risk factor to the risk of PPR spread (step 1), and define their respective weight (=importance) (step 2). One table for each of these two steps should be filled-in. Thereafter is a reminder of the selected risk factors and their associated hypothesis in our study:

Risk factor (unit)	Associated hypothesis
Density of goats as a *proxy* for communal farming (heads/km^2)	Increasing goats' density is expected to be associated with a higher contact rate between susceptible and infected goats, and therefore a greater risk of spread. At the national scale, goats are mainly kept in communal farming (DAFF 2015). Communal farming is expected to be of higher risk of PPR spread as animals kept in communal areas roam freely, may have uncontrolled contacts with other animals, share grazing areas. Communal areas are also more likely to host traditional practices and have lesser access to veterinary services.
Density of sheep as a *proxy* for commercial farming (heads/km^2)	As for goats, if sheep density increases, the contact rate between susceptible and infected animals is higher, and thus the risk of PPR spread increases. At the national scale, sheep are mainly kept in commercial farming (DAFF 2015). Commercial farming is expected to be of higher risk of spread as flocks are generally larger, with higher inflow and outflow of animals. Sheep are also more prone to stock theft than goats (DAFF, personal statement).
Distance to vet services (kilometers)	Increasing distance to veterinary services offices is expected to be associated with higher risk of PPR spread as awareness and surveillance activities from the animal health technicians and vets may be more difficult to implement.
Proximity to rivers (meters)	Sheep and goats in communal areas extend their roaming area to find food and can gather to rivers to drink and graze. Proximity to rivers is expected to be associated with increased risk of PPR spread through close contact among animals sharing watering points.
Proximity to national parks and game reserves (meters)	Proximity to wildlife national parks and game reserves may be associated with increased risk of spread of PPR as small ruminants may share grazing areas and water points with wild *bovidae*.
Proximity to roads as a *proxy* for trade (meters)	Proximity to National (e.g N12), Provincial (e.g. R36) and Regional (e.g. R312) roads is expected to be associated to easier access to transport and thus increasing movements of small ruminants for trade, leading to a higher risk of spread of the disease.
Proximity to markets (kilometers)	The flocks gathered on markets have different serological status. Proximity to small ruminants' markets is expected to be associated to more regular visits from the farmers and more likelihood of buying animals from the market. Therefore, proximity to markets (both formal and informal) is expected to be associated with increasing risk of spread.

Step 1: Select the relationship between each risk factor and the risk of PPR spread in South Africa

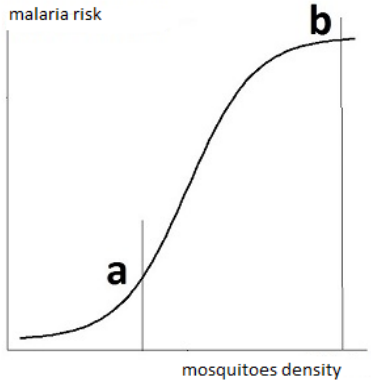
Let's take the example of the risk of malaria spread and its relationship with the risk factor "density of Anopheles mosquitoes". Anopheles being a vessel for malaria transmission, experts may say that the risk increases with the density of Anopheles (mosquitoes/km2), but four different relationships between the risk factor and malaria risk are possible (relationships 1, 2, 3 and 4). They are illustrated hereafter. The value of the risk ranges from 0 (the risk is minimal) to 1 (the risk is maximal). The different values of thresholds have only been chosen randomly to illustrate the explanations.

RELATIONSHIP 1: malaria risk is proportionately increasing with density of Anopheles mosquitoes



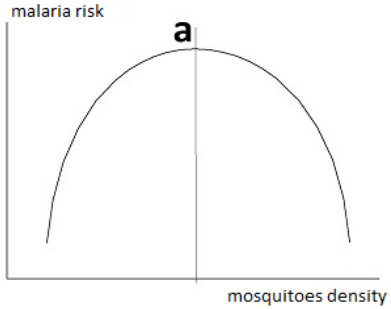
The risk of spread is minimal (=0) if the mosquitoes' density is below 20/km2 (threshold "a"). The risk is maximal (=1) if density is > 100/km2 (threshold "b"). Between these 2 thresholds, the risk is increasing proportionately (linear function).

RELATIONSHIP 2: malaria risk is increasing with density of Anopheles mosquitoes, and especially between threshold "a" (example: very low density) and threshold "b" (example: very high density). It remains constant thereafter



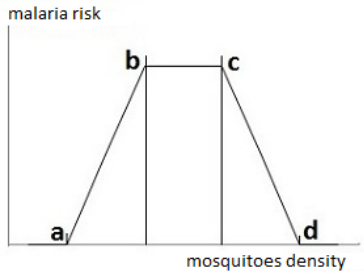
The risk of spread is minimal (=0) if the mosquitoes' density is below 20/km2 ("a"). The risk is maximal (=1) if density is > 100/km2 ("b"). Between these 2 thresholds, the risk is increasing following a sigmoidal function. Beyond the threshold "b", the risk remains constant (=1).

RELATIONSHIP 3: malaria risk is increasing with density of Anopheles mosquitoes up to a threshold "a", and decreases thereafter



The risk of malaria spread is minimal when density is <20 mosquitoes/km2 and is increasing up to a threshold "a" where density is 100 mosquitoes/km2. Beyond this threshold, the risk is decreasing until reaching 0 when density is > 2000 mosquitoes/km2. This may be explained by the biology of Anopheles, (a greater density may imply competition/changes in feeding habits, etc.)

RELATIONSHIP 4: malaria risk increases with density of mosquitoes between thresholds "a" and "b". The risk remains constant between thresholds "b" and "c". It decreases from thresholds "c" to "d".



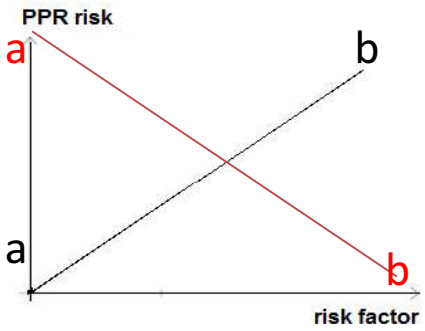
The risk is minimal if the mosquitoes' density is below 20/km2 (threshold "a"). The risk is maximal (=1) if density is between 100 and 1000 mosquitoes/km2 (thresholds "b" and "c"). Beyond 1000 mosquitoes/km2, the risk is decreasing until reaching 0 (minimal risk) when density is > 5000 mosquitoes/km2 (threshold "d"). Again, this may be explained by the biology of Anopheles.

Based on this example, and according to your experience about epidemiology/small ruminants/PPR, select the most accurate relationship between each risk factor and the risk of PPR spread in South Africa on the drop-down lists. Select the best-fitted threshold(s) a, b, c and d for each risk factor on the drop-down list(s). If you can't choose a threshold, select the linear function (relationship 1).

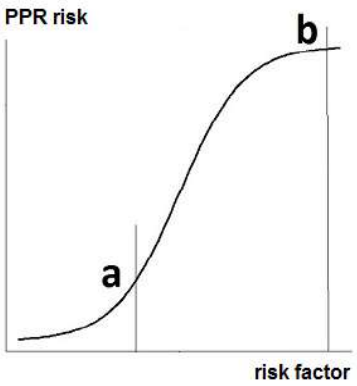
	Best-fitted Relationship	Threshold a	Threshold b	Threshold c	Threshold d
Density of goats (heads/km2)	Select a relationship				
Density of sheep (heads/km2)	Select a relationship				
Distance to vet services (kilometers)	Select a relationship				
Proximity to rivers (meters)	Select a relationship				
Proximity to national parks and game reserves (meters)	Select a relationship				
Proximity to roads (meters)	Select a relationship				
Proximity to markets (kilometers)	Select a relationship				

PLEASE NOTE: In our example with Malaria, all the relationship functions were increasing with the risk factor. However, in our study we have risk factors named "proximity", where the closer to rivers/national parks/roads/markets we are, the riskier it is, and contrastingly the further we are the less risky it is. For example, for Relationships 1 and 2, the value of the threshold "b" may be smaller than the value of the threshold "a".

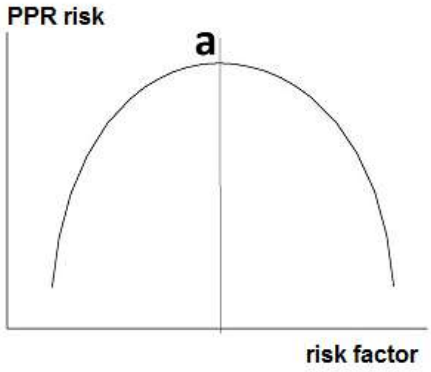
RELATIONSHIP 1: PPR risk is proportionately increasing with the risk factor



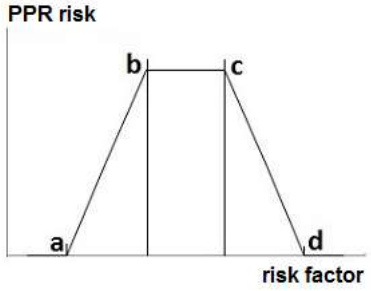
RELATIONSHIP 2: PPR risk is increasing with the risk factor, and especially between thresholds a and b. It remains constant thereafter.



RELATIONSHIP 3: PPR risk is increasing with the risk factor up to a threshold a, and decreases thereafter.



RELATIONSHIP 4: PPR risk increases with the risk factor between thresholds a and b. The risk remains constant between thresholds b and c. It decreases from thresholds c to d.



Step 2: Pair-wise comparison between risk factors

In our example of Malaria, the study considers three risk factors for malaria spread: "proximity to open water areas", "proportion of people suffering from malnutrition", and "density of Anopheles mosquitoes". However, they may not have the same influence on the risk of malaria spread. Indeed, one expert may think that mosquitoes' density is more important for the malaria transmission than the proximity to open water areas. Therefore, nine different options are possible (based on the Saaty scale), ranging from "extremely more important" to "extremely less important" to compare the risk factors between each other.

More important								*Less important*
Extremely	Very strongly	Strongly	Moderately	Equivalent	Moderately	Strongly	Very strongly	Extremely
9	7	5	3	1	1/3	1/5	1/7	1/9

Below is an example of comparison matrix filled by an expert. Here, according to the expert opinion, the "proximity to open water area" is considered to be "strongly less important" than "density of Anopheles mosquitoes" for the risk of malaria, and compared to the "proportion of people…" its influence is considered equivalent. All the risk factors are compared pair-wise. Experts select one option per box, and all the boxes must be filled-in one after another. The table should be read and filled-in "row by row": the variable of the row 1 is compared to the variable of the Column 1, then to Column 2, then to Column 3. Then the variable of Row 2 is compared to the values of C1, C2, then C3, etc. The table must be read as follows: "proximity to open water" (R1) is equivalent to "proportion of people" (C2), and "proximity to open water" is strongly less important than "density of Anopheles". Grey boxes should not be filled-in.

	Proximity to open water areas C1	**Proportion of people suffering from malnutrition C2**	**Density of Anopheles mosquitoes C3**
Proximity to open water areas R1		equivalent to	strongly less important
Proportion of people suffering from malnutrition R2	moderately less important		very strongly more important
Density of Anopheles mosquitoes R3	strongly more important	strongly less important	

Now, select an option in each drop-down list according to the influence that each risk factor has on the risk of PPR spread compared to one other.

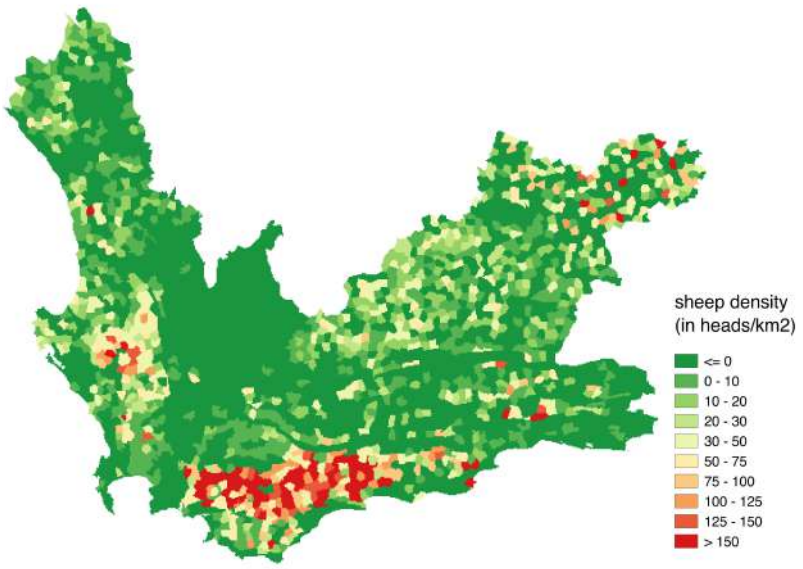
	Density of goats (heads/km^2)	Density of sheep (heads/km^2)	Distance to vet services (km)	Proximity to rivers (m)	Proximity to national parks/ game reserves (m)	Proximity to roads (m)	Proximity to markets (km)
Density of goats (heads/km^2)		Select a weight.	Select a weight	Select a weight.	Select a weight.	Select a weight	Select a weight.
Density of sheep (heads/km^2)	Select a weight.		Select a weight.	Select a weight.	Select a weight.	Select a weight.	Select a weight.
Distance to vet services (km)	Select a weight.	Select a weight.		Select a weight.	Select a weight.	Select a weight.	Select a weight.
Proximity to rivers (m)	Select a weight.	Select a weight.	Select a weight.		Select a weight.	Select a weight.	Select a weight.
Proximity to national parks/ game reserves (m)	Select a weight.	Select a weight.	Select a weight.	Select a weight.		Select a weight.	Select a weight.
Proximity to roads (m)	Select a weight.	Select a weight.	Select a weight.	Select a weight.	Select a weight.		Select a weight.
Proximity to markets (km)	Select a weight.	Select a weight.	Select a weight.	Select a weight.	Select a weight.	Select a weight.	

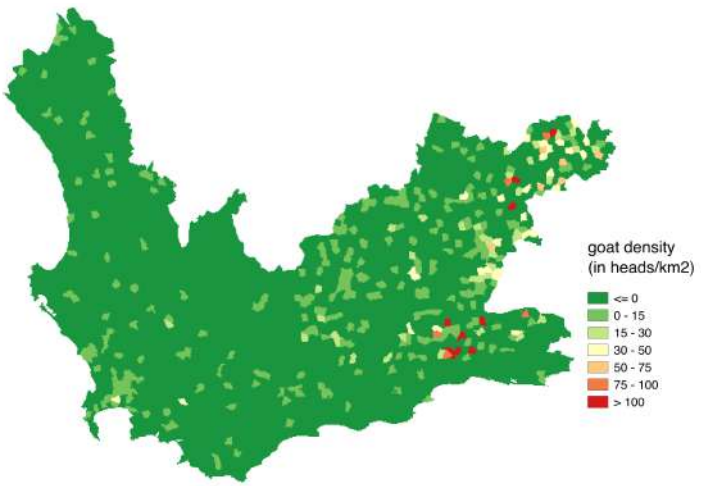
Appendix 3: Scripts for standardization in R

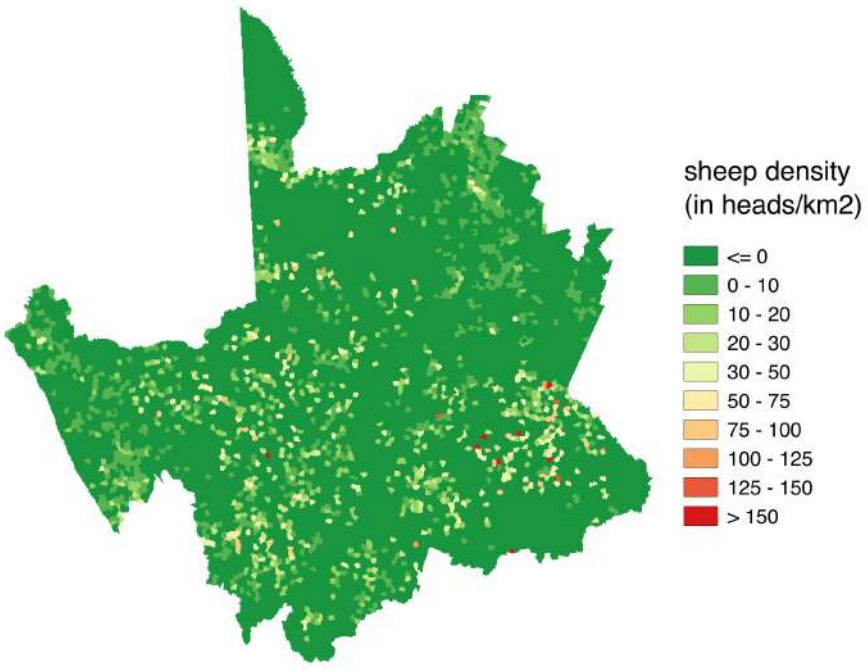
```
# ------------------------------------------------------------------------------------------
# SPATIAL MULTI CRITERIA EVALUATION
# FACTORS STANDARDIZATION - RASTER DATA
# Scripts used for the MCDA training held in Toulouse, in March 2017 by Dr Mathilde Paul
# ------------------------------------------------------------------------------------------
#-----------------------------------------------------
# Install and call packages
# -----------------------------------------------------
library(raster)
library(rgdal)
# -----------------------------------------------------
# Read the raster data
x1 <-
 raster("D:/docs_mpaul/MCDA_Training_Toulouse/Weerapong_training/Data/RasterData/distobat
 ")
x2 <-
 raster("D:/docs_mpaul/MCDA_Training_Toulouse/Weerapong_training/Data/RasterData/distoorc
 hard")
x3 <-
 raster("D:/docs_mpaul/MCDA_Training_Toulouse/Weerapong_training/Data/RasterData/pigden")
# -----------------------------------------------------
# plot raster data
plot(x1)
plot(x2)
plot(x3)
# -----------------------------------------------------
###Making layer stack
x = stack(x1, x2, x3)
plot(x)
# -----------------------------------------------------
# Standardize pig density using membership functions
# -----------------------------------------------------

# Fuzz1: monotonically increasing between a and b
# -----------------------------------------------------
# Set values for a and b
f1 <- x3
a <- 500
b <- 1000
# Define the membership function
f1[f1 <= a] <- 0
f1[f1 > a & f1 <=b] <- (f1[f1 > a & f1 <=b]-a)/(b-a)
f1[f1 > b] <- 1
# display the result
plot(f1)

# Fuzz2: monotonically decreasing between a and b
# -----------------------------------------------------
# Set values for a and b
a <- 500
b <- 1000
f2 <- x3
# Define the membership function
f2[f2 <= a] <- 1
f2[f2 > a & f2 <=b] <- (f2[f2 > a & f2 <=b]-b)/(a-b)
f2[f2 > b] <- 0
# display the result
plot(f2)

# Fuzz3: Linear bi-directional (trapezoidal)
# -----------------------------------------------------
# Set values for a, b, c and d
a <- 300
```

```
b <- 600
c <- 1000
d <- 1500
f3 <- x3
# Define the membership function
f3[f3 <= a] <- 0
f3[f3 > a & f3 <=b] <- (f3[f3 > a & f3 <=b]-a)/(b-a)
f3[f3 > b & f3 <=c] <- 1
f3[f3 > c & f3 <=d] <- (f3[f3 > c & f3 <=d]-d)/(c-d)
f3[f3 > d] <- 0
plot(f3)

# Fuzz4: S-shaped
# ------------------------------------------------------
# Set values for a and b
a <- 500
b <- 1000
f4 <- x3
# Define the membership function
f4[f4 <= a] <- 0
f4[f4 > a & f4 <=b] <- 1/(1+exp(-5/a*(f4[f4 > a & f4 <=b]-(b+a)/2)))
f4[f4 > b] <- 1
plot(f4)
# visualize the function
plot(x3,f4, col="blue")


# Fuzz5: sigmoidal decreasing
# ------------------------------------------------------
# Set values for a and b
a <- 500
b <- 1000
f5 <- x3
# Define the membership function
f5[f5 <= a] <- 1
f5[f5 > a & f5 <=b] <- 1/(1+exp(5/a*(f5[f5 > a & f5 <=b]-(b+a)/2)))
f5[f5 > b] <- 0
plot(f5)
# visualize the function
plot(x3,f5, col="blue"
```

Appendix 4: Provincial small ruminant density datasets

Filename of dataset	sheepdensWC.tif
Data type	Risk factor layer in a raster format
Author	Alexia Rondeau
Country	South Africa
Summary	If sheep density increases, the contact rate between susceptible and infected animals is higher, and thus the risk of PPR spread increases. At the national scale, sheep are mainly kept in commercial farming (DAFF 2015). Commercial farming is expected to be of higher risk of spread as flocks are generally larger, with higher inflow and outflow of animals. Sheep are also more prone to stock theft than goats (DAFF, personal statement).
Content	Sheep density (in heads/km^2)
Original data source	Sheep census data: DAFF Western Cape (Qry_WesterneCape_PPRstudy.xlsx) Geographic data: CSIR
Software Version	ArcGis 10.5, QGis 2.18.6
Raw data shapefiles	- sheepdensWC_UTM35S.shp (points shapefile) - settlementsWC_UTM35S.shp (polygon shapefile)
Processing steps	In QGIS, spatial join tool to join each census point to the settlement (polygon) they belong to, adding a new column "sum" in the resume so that we can see the sum of the animal numbers per polygon. In the attribute table: new field "areakm2" to calculate the area of each polygon. New field "goatdens" = "sumcensus"/"areakm^2". "Rasterize tool" based on the field "goatdens".
Projection System	WGS 84/ UTM zone 35S
Quicklook	

Filename of dataset	goatdensWC.tif
Data type	Risk factor layer in a raster format
Author	Alexia Rondeau
Country	South Africa
Summary	Increasing goats' density is expected to be associated with a higher contact rate between susceptible and infected goats, and therefore a greater risk of spread. At the national scale, goats are mainly kept in communal farming (DAFF 2015). Communal farming is expected to be of higher risk of PPR spread as animals kept in communal areas roam freely, may have uncontrolled contacts with other animals, share grazing areas. Communal areas are also more likely to host traditional practices and have lesser access to veterinary services.
Content	Goat density (in heads/km^2)
Original data source	Goat census data: DAFF Western Cape (Qry_WesterneCape_PPRstudy.xlsx) Geographic data: CSIR
Software Version	ArcGis 10.5, QGis 2.18.6
Raw data shapefiles	- goatdensWC_UTM35S.shp (points shapefile) - settlements WC_UTM35S.shp (polygon shapefile)
Processing steps	In QGIS, spatial join tool to join each census point to the settlement (polygon) they belong to, adding a new column "sum" in the resume so that we can see the sum of the animal numbers per polygon. In the attribute table: new field "areakm2" to calculate the area of each polygon. New field "goatdens" = "sumcensus"/"areakm^2". "Rasterize tool" based on the field "goatdens".
Projection System	WGS 84/ UTM zone 35S
Quicklook	

Filename of dataset	sheepdensNC.tif
Data type	Risk factor layer in a raster format
Author	Alexia Rondeau
Country	South Africa
Summary	If sheep density increases, the contact rate between susceptible and infected animals is higher, and thus the risk of PPR spread increases. At the national scale, sheep are mainly kept in commercial farming (DAFF 2015). Commercial farming is expected to be of higher risk of spread as flocks are generally larger, with higher inflow and outflow of animals. Sheep are also more prone to stock theft than goats (DAFF, personal statement).
Content	Sheep density (in heads/km^2)
Original data source	Sheep census data: DAFF Northern Cape (Census Ovine Jan2015Des2016.xls) Geographic data: CSIR
Software Version	ArcGis 10.5, QGis 2.18.6
Raw data shapefiles	- sheepNC_UTM35S.shp (points shapefile) - settlementsNC_UTM35S.shp (polygon shapefile)
Processing steps	In QGIS, spatial join tool to join each census point to the settlement (polygon) they belong to, adding a new column "sum" in the resume so that we can see the sum of the animal numbers per polygon. In the attribute table: new field "areakm2" to calculate the area of each polygon. New field "goatdens" = "sumcensus"/"areakm^2". "Rasterize tool" based on the field "goatdens".
Projection System	WGS 84/ UTM zone 35S
Quicklook	

Filename of dataset	goatdensNC.tif
Data type	Risk factor layer in a raster format
Author	Alexia Rondeau
Country	South Africa
Summary	Increasing goats' density is expected to be associated with a higher contact rate between susceptible and infected goats, and therefore a greater risk of spread. At the national scale, goats are mainly kept in communal farming (DAFF 2015). Communal farming is expected to be of higher risk of PPR spread as animals kept in communal areas roam freely, may have uncontrolled contacts with other animals, share grazing areas. Communal areas are also more likely to host traditional practices and have lesser access to veterinary services.
Content	Goat density (in heads/km^2)
Original data source	Goat census data: DAFF Northern Cape (Census CaprineJan2015Des2016.xls) Geographic data: CSIR
Software Version	ArcGis 10.5, QGis 2.18.6
Raw data shapefiles	- goatNC_UTM35S.shp (points shapefile) - settlements NC_UTM35S.shp (polygon shapefile)
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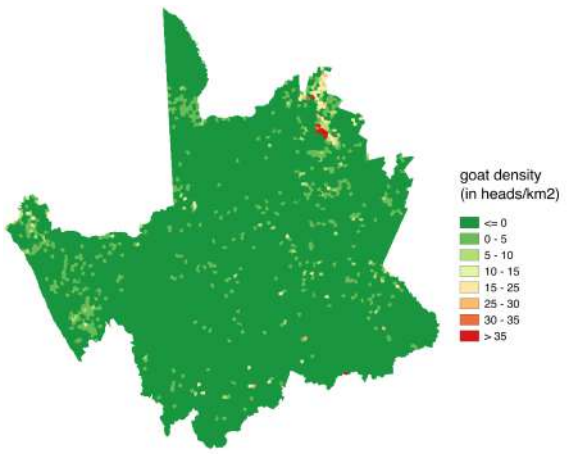
Projection System	WGS 84/ UTM zone 35S
Quicklook	

ECOLE NATIONALE VETERINAIRE TOULOUSE

UNIVERSITÉ TOULOUSE III PAUL SABATIER

AGREMENT SCIENTIFIQUE

En vue de l'obtention du permis d'imprimer de la thèse de doctorat vétérinaire

Je soussignée, **Mathilde PAUL**, Enseignant-chercheur, de l'Ecole Nationale Vétérinaire de Toulouse, directeur de thèse, certifie avoir examiné la thèse de **Alexia RONDEAU** intitulée **«Assessment of the risk of peste des petits ruminants in South Africa through the use of multi-criteria decision analysis »** et que cette dernière peut être imprimée en vue de sa soutenance.

Fait à Toulouse, le 27 octobre 2017
Docteur Mathilde PAUL
Maître de Conférences
de l'Ecole Nationale Vétérinaire de Toulouse

Vu :
La Directrice de l'Ecole Nationale Vétérinaire de Toulouse
Isabelle CHMITELIN

ECOLE NATIONALE VETERINAIRE DE TOULOUSE

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La Vice-Présidente de la CFVU
Régine ANDRE-OBRECHT

Mlle Alexia RONDEAU
a été admis(e) sur concours en : 2012
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a validé son année d'approfondissement le : 02/11/2017
n'a plus aucun stage, ni enseignement optionnel à valider.

Université de Toulouse

Toulouse 2017

NOM : RONDEAU **PRENOM :** Alexia

TITRE : Evaluation du risque de dissémination de la peste des petits ruminants en Afrique du Sud à l'aide de la méthode d'analyse décisionnelle multicritère spatialisée.

RESUME : La peste des petits ruminants est une maladie virale hautement contagieuse des petits ruminants, aujourd'hui présente en Afrique, Asie et au Moyen-Orient. La maladie s'étant récemment propagée vers l'Afrique australe, l'Afrique du Sud est à risque. Dans un pays indemne de PPR et donc où des données sur la PPR sont absentes, l'analyse de risque peut être réalisée par la méthode d'analyse décisionnelle multicritère spatialisée. Nous avons utilisé cette méthode associant connaissances scientifiques et avis d'experts pour produire des cartes de probabilité. Elles illustrent les zones les plus à risque pour la transmission de la PPR sur le territoire dans le cas où le virus aurait été introduit. Ce travail a pour but d'apporter un support pour cibler les activités sanitaires. Les biais dus à la méthode pourraient être limités par l'ajout de données géographiques plus précises, permettant ainsi d'améliorer la précision de nos cartes de probabilité dans un futur proche.

MOTS CLES : épidémiologie / modélisation spatiale / Afrique du Sud / petits ruminants / SIG

TITLE: Assessment of the risk of spread of peste des petits ruminants in South Africa through use of spatial multi-criteria decision analysis.

ABSTRACT: Peste des petits ruminants is a highly contagious viral disease of small ruminants, today spread throughout Africa, Asia and Middle-East. With recent spread of the disease towards Southern Africa, South Africa is put at risk. In a PPR-free country so where data is unavailable, risk analysis can be performed by spatial Multi Criteria Decision Analysis. We applied this method combining scientific knowledge and expert opinion to produce suitability maps. These maps highlight the most suitable areas for PPR spread within the territory in the case where the virus would have been introduced. The output of our work aims at providing support to decide where to target control and surveillance activities. However, our model has numerous bias due to its reliance on subjective decisions. These could be limited with the incorporation of more precise geographical data when later available; letting the opportunity to improve accuracy of suitability maps in a near future.

KEYWORDS: epidemiology / spatial modelling / South Africa / small ruminants / GIS-based