Ecology of wild and domestic suids in relation to the epidemiology of African swine fever in northern KwaZulu-Natal

by

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SUMMARY

Ecology of wild and domestic suids in relation to the epidemiology of African swine fever in northern KwaZulu-Natal

by

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Keywords: African swine fever virus, bushpigs, domestic pigs, warthogs, sylvatic cycle, movements

African swine fever (ASF) affect wild and domestic stock and can cause extensive socio-economic damage. The main objective of this study was to understand the role of Ndumo Game Reserve (NGR) and its surroundings in the ecology and epidemiology of the two diseases as well as the implications of pig husbandry practices in disease transmission. This study area was chosen because the game reserve shares its northern boundary with Mozambique where ASF is endemic. The study area, which lies within an ASF control zone, also shares its western boundary with eSwatini, which is ASF free. It is therefore to be expected that the NGR and surroundings is a high-risk area for the aforementioned diseases, making regular assessments pertinent.

Line transect counts revealed a warthog density of 3-5 individuals/km^2, with a total population of 400-500 warthogs in the study area. Most of the bushpig recorded on camera traps (0.515 animals/camera day) were found in habitats close to water. Warthogs (0.536 animals/camera day) on the other hand, were found in sandy environments. Fence survey results indicated that wild suids regularly cross the fence into the neighbouring farming community, particularly during the dry season. This was corroborated by 11 farmers who indicated that they had seen wild suids in the area. Questionnaire surveys, from the 254 domestic pig farmers, determined that most of the farmers free-ranged their animals outside of the cropping season. This finding, coupled with the observation that pigs periodically breach the game fence, is significant for disease management as it points to the potential existence of domestic-domestic and wild-domestic interactions which can facilitate disease introduction and spread. The risk of disease introduction is further heightened as some farmers purchase pigs outside the study area, particularly from Mozambique and eSwatini, and these movements are not reported. Social network analysis showed substantial movements (through buying and selling) between pig farmers connecting all villages in the study area. These movements can exacerbate the risk of disease introduction and spread.

Even though the location of the study area suggests the potential presence of the diseases, burrow surveys (n=35) did not provide evidence of *Ornithodoros* tick infestation, implying that a sylvatic ASF cycle is currently unlikely to be present in the area, suggesting that ASF is unlikely to be present in NGR. Furthermore, blood samples of domestic pigs (n=67) tested negative for both ASF. This view is supported by the fact that the farmers reported no clinical signs or sudden deaths of pigs due to ASF in past years. Although no evidence of the presence of the two diseases was found in the study area, the area remains a high risk area for these diseases and ongoing disease surveillance is recommended. It is also recommended that farmers be educated on the best pig husbandry methods in order to reduce the risk of disease introduction and transmission.

RESEARCH OUTPUTS

Journal articles

Submitted:

Mapendere C., Jori F., Etter E.M.C. and Ferguson J.W.H (2020). Do wild suids from Ndumo Game Reserve, South Africa, play a role in the maintenance and transmission of African swine fever to domestic pigs?

Mapendere C., Ferguson J.W.H, Jori F., Etter E.M.C (2020). Pig value chain network analysis to assess the effectiveness of the zoning policy: A case study of African swine fever control in South Africa.

Conference presentations

Oral presentations

Etter EM, Mushagaluza Ciza A, **Mapendere C**, Ferguson W, Jori F and Penrith M (2019). Understanding ASF dynamics in South Africa: from spatio-temporal analysis at national level to fine special network analysis. GeoVet Conference 2019. Novel spatio-temporal approaches in the era of Big Data, Davis, United States, 8 Oct - 10 Oct, 2019.

LIST OF ABBREVIATIONS AND ACRONYMS

AAU	Association for African Universities
ANOVA	Analysis of variance
ASF	African swine fever
ASFV	African swine fever virus
ASM	American Society for Mammologists
ARC-OVR	Agricultural Research Council-Onderstepoort Veterinary Research
BTC	Belgian Technical Cooperation
EKZNW	Ezemvelo KwaZulu-Natal Wildlife
GPS	Global Positioning System
KNP	Kruger National Park
NGR	Ndumo Game Reserve
NKZN	Northern KwaZulu-Natal
NRF	National Research Foundation
PAs	Protected areas
SA	South Africa
SAT	Southern African Territories
SEM	Standard Error of Mean
SNA	Social Network Analysis
TAD	Transboundary animal disease
TFCAs	Transfrontier Conservation Areas
TUT	Tshwane University of Technology

DECLARATION

I, Cynthia Mapendere, hereby declare that this dissertation, "*Ecology of wild and domestic suids in relation to the epidemiology of African swine fever in northern KwaZulu-Natal"* which I hereby submit for the degree MSc Environmental Ecology at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution. All sources cited or quoted in this research paper are indicated and acknowledged with a comprehensive list of references.

ETHICS STATEMENT

The author, whose name appears on the title page of this dissertation/thesis, has obtained, for the research described in this work, the applicable research ethics approval.

The author declares that she has observed the ethical standards required in terms of the University of Pretoria's Code of Ethics for Researchers and the Policy guidelines for responsible research.

SIGNATURE: 

STUDENT NAME: Cynthia Mapendere

DATE: December 2020

DEDICATION

I dedicate this research to my parents, Morgan (my late father) and Maggie Mapendere, my siblings, Tongai and Sinothabo, and my husband Tendai.

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LANGUAGE EDITING

I acknowledge that this thesis was edited for integrity, logical progression as well as text and language by Dr Abeda Dawood.

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CHAPTER 1: GENERAL INTRODUCTION

1.1 BACKGROUND AND SCOPE

Africa is characterised by a variety of ecosystems and habitats suitable for wildlife conservation. Indeed, a considerable mass of land has been set aside for wildlife conservation across Africa and the world at large. The aim was that by 2020, protected areas (PAs) will cover 17 percent of the world's terrestrial area (Western *et al.*, 2015). Although this target has not been met, it illustrates the importance given to conserving wildlife by countries across the world. This is probably because PAs are now viewed as a valuable tool for conserving wildlife, habitats and nations' cultural heritages, but in addition, as a viable tool to derive economic value from land not utilised for agriculture (Rotherham, 2015).

Humans value wildlife, and their contribution to economic progress and cultural heritage preservation. However, wildlife also adversely affects the well-being of human societies in some areas. The conservation literature includes many examples detailing the negative impacts of wildlife on society and vice versa. This phenomenon is known as human-wildlife conflict (HWC) (Mekonen, 2020). Human-wildlife conflict is a broad subject but one emerging aspect of HWC gaining prominence is the transmission of diseases from wild populations to humans and their livestock.

Several factors have caused an increase in contact between humans, their livestock and wildlife, making it a concern for governments and conservation practitioners. The main factor is the ballooning human population that has resulted in humans settling at the boundaries of PAs (Stoldt *et al.*, 2020). In addition, changing climate characterised by an increase in the occurrence and severity of drought has negatively impacted resource availability within PAs forcing wildlife to make forays into human inhabited areas (Munthali *et al.*, 2018). This increased contact is how diseases are transmitted between these two systems (Cowled and Garner, 2008).

In recent years, there has been increasing concerns about emerging diseases at the livestock–wildlife interface (Cunningham, 2005). Wild animals are likely to become the source of infectious diseases that put at risk the health of human beings and livestock (Gortázar *et al.*, 2007). For example, in the Baltic states and Belgium where African swine fever (ASF) virus is maintained in wild boar populations, and occasionally, causes outbreaks of the disease among domestic pigs (Vergne *et al.*, 2020).

In the South Africa, several diseases can be transmitted from wild species to humans and/or their livestock. Bovine tuberculosis, brucellosis, Rift Valley Fever and theileriosis circulate at the interface between communal lands and protected areas in southern Africa (De Garine-Wichatitsky *et al.*, 2013). One of the most problematic diseases is ASF.

A viral haemorrhagic fever, ASF is a serious disease affecting pigs and is considered a major threat to pig industries worldwide (Penrith *et al.*, 2019). The socio-economic ramifications of ASF can be much greater due to high morbidity and mortality. This is because pigs are a cheap source of protein and a livelihood for some poor people around the world (Cupido, 2020). The consequences of an outbreak may differ. For example, locally, stock movements can be forbidden, and some culling could occur in disease free zones while nationally it could result in a ban in the international of trade of live animals and animals products (Jori & Etter, 2016).

Bushpigs (*Potamochoerus larvatus*) and warthogs (*Phacochoerus africanus*) play an important role in maintaining and transmitting ASF (Bora *et al.*, 2020). African swine fever has a sylvatic cycle which plays a role in the maintenance of the virus (Jori & Bastos, 2009). In this cycle, African swine fever virus (ASFV) is maintained by *Ornithodoros moubata* soft ticks and warthogs in the wild (Dixon & Chapman, 2008). Ticks play an important role in this cycle as they act as vectors facilitating the transmission of ASFV. Although ASFV is detected in adult warthog, viremia is usually low, limiting the chances of direct transmission between adult warthogs. However, adult warthogs can be infected if bitten by ASFV infected ticks. Once the bushpigs or warthogs are infected, experimental studies suggest that they can transmit the ASFV through direct contact with susceptible domestic pigs (Anderson *et al.*, 1998).

Due to the socio-economic impacts of ASF, it is in the best interest of authorities to reduce the risk of outbreaks. One way of achieving this is by eliminating or reducing the interactions between domestic and wild suids. Fences have been used to demarcate wildlife areas from those inhabited by humans and their livestock (Jakes *et al.*, 2018). The effectiveness of wildlife fences depends on the target animal and the nature of the fence. Fences have been successful, to some extent, in reducing the interactions between humans and wildlife in countries such as Kenya and South Africa (Pekor *et al.*, 2019). However, some species have proven difficult to control with fences. These include bushpigs and warthogs, as they can breach a fence. Therefore, wildlife authorities cannot rely exclusively on fences.

Since complete freedom from disease is difficult to attain at a local, national or regional scale, authorities also employ zoning to promote animal health and trade benefits (Mogotsi *et al.*, 2016). This involves demarcating geographical areas according to the risk of disease transmission. The areas closest to the potential source of diseases represent the highest risk areas and animal movements beyond these areas are controlled by veterinary authorities. If strictly implemented and supported by research findings, this strategy can reduce outbreaks on a broad scale (DAFF, 2014).

1.2 PROJECT RATIONALE

Key to evaluating whether the control measures are working, is understanding the rate at which control zone boundaries are breached, the prevalence of diseases in human communities, records of diseased wildlife in human populated areas, and the movement of susceptible animals beyond the control zones.

Several methods can be used to understand the factors relevant to disease ecology. In order to identify the species involved and the rate at which fences are breached, periodic fence patrols can be carried out. In order to understand the prevalence of the diseases of interest in communities, blood can be collected from livestock and serological tests conducted to detect disease causing agents. Questionnaires can be used to determine if wildlife was seen in human inhabited areas and the possible movements of susceptible livestock from the control zones. Social network analysis (SNA) is a method used to determine the extent to which livestock movement occurs within and out of a control zone. Also, important to understanding disease ecology is determining the densities of susceptible animals within a wildlife area.

This study was conducted in Ndumo Game Reserve (NGR) in KwaZulu-Natal and its surrounding communities (total population: 18072; area: 686 km^2; households: 3555). Villages in the community are typical of South African communal areas where subsistence farming is the major economic activity. The inhabitants of the area grow mainly maize and keep livestock which include cattle, goats, pigs and chickens. The reserve was proclaimed a PA in 1924. The previous inhabitants of NGR resettled along the periphery of the game reserve where they guaranteed allegiance to local chiefs, built new houses and prepared new fields. At present, there are two Traditional Authorities (TAs), the Mathenjwa TA on the southern and western side of the reserve and the Tembe TA in the narrow stretch of land in the east between Ndumo Game Reserve's eastern fence and Tembe Elephant Park's western fence.

For this study, NGR is of particular interest as it is home to warthogs and bushpigs, which are important in the ecology and epidemiology of ASF. In addition, the reserve shares its border with Mozambique, a country where ASF is endemic and outbreaks have been reported within a 100 km radius of the study site. It is also near to eSwatini.

1.3 AIM AND OBJECTIVES

The overall aim of the study was to understand the role of Ndumo Game Reserve in the ecology and epidemiology of ASF as well as the implications of pig husbandry practices in disease transmission. Specifically, the study aims to achieve this by:

1. providing quantitative information on the wild and domestic suid population sizes and distributions in the study area,
2. assessing the movements of wild and domestic suids between NGR and the neighbouring community,
3. investigating the potential existence of a sylvatic cycle of ASF, and
4. understanding pig husbandry practices and their potential implications on disease transmission.

1.4 ORGANIZATION OF REPORT

1) Chapter 1: Introduction

   Chapter 1 outlines the broad perspective of the study. It discusses some of the pertinent issues regarding the epidemiology of ASF.

2) Chapter 2: Do wild suids from Ndumo Game Reserve, South Africa play a role in the maintenance and transmission of African swine fever to domestic pigs?

   This chapter includes the quantification of wild population sizes and their distribution. It describes the movements of wild suids into the neighbouring community and assesses the potential existence of the sylvatic cycle of ASF

3) Chapter 3: Pig value chain network analysis to assess the effectiveness of the zoning policy: A case study of African swine fever control in South Africa

   Chapter 3 quantifies domestic suid population sizes and maps the movements of pigs within the study area. Furthermore, pig husbandry practices and their implications are explored.

4) Chapter 4: Conclusion and recommendations.

Chapter 4 discusses the implications of the study and recommends further research that is required.

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CHAPTER 2: DO WILD SUIDS FROM NDUMO GAME RESERVE, SOUTH AFRICA, PLAY A ROLE IN THE MAINTANANCE AND TRANSMISSION OF AFRICAN SWINE FEVER TO PIGS?

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2.1 ABSTRACT

In southern Africa, the African swine fever (ASF) sylvatic cycle presents a permanent threat to the development of the pig farming industry. Warthogs (*Phacochoerus africanus)* and bushpigs (*Potamochoerus larvatus*), wild reservoirs of ASF, are present in Ndumo Game Reserve (NGR), located in the northern KwaZulu-Natal province, South Africa. This is within 30 km of the locations of ASF outbreaks in Mozambique, where the disease is endemic and where sylvatic disease transmission has been implicated. In order to assess if wild suids represent a risk of ASF virus spillover to domestic pigs in the neighbouring community, transect counts and fence patrols were conducted and camera traps deployed in NGR to estimate wild suid abundance and incursions outside NGR boundaries. *Ornithodoros* ticks were searched for in 35 warthog burrows distributed across different NGR areas. Pig farmers (n=254) in the surrounding Mathenjwa Community were interviewed to gather information on interactions between domestic and wild suids and the occurrence of ASF. It was concluded that NGR has established populations of bushpigs and warthogs, estimated at 5 and 3-5 individuals/km^2, respectively. Both species move out of the reserve regularly (15.4 warthogs/day and 6.35 bushpigs/day), with a significant increase in movements during the dry season. Some farmers observed warthogs and bushpigs as far as 8 and 19 km from the reserve, respectively, but no direct wild-domestic suids interactions, nor any ASF outbreaks were reported. In addition, no soft ticks were found among the 35 warthog burrows. The absence of ticks in warthog burrows from the NGR and the absence of reported outbreaks and familiarity with ASF in the surrounding farming area, suggests that a sylvatic cycle of ASF is at present unlikely in NGR. However, further research should be undertaken to confirm this by surveying a larger number of warthog burrows and monitoring potential antibodies in warthogs from NGR and domestic pigs in the neighbouring community.

Key words: African swine fever, bushpigs, domestic pigs, warthogs, sylvatic cycle, South Africa

2.2 INTRODUCTION

In southern Africa, warthogs (*Phacochoerus africanus*) and bushpigs (*Potamochoerus larvatus)* are considered potential wild reservoirs of African swine fever (ASF). Warthog is found in open savannah habitats in most of sub-Saharan Africa and their densities range from 1–10 individuals/km^2 in protected areas (Cumming, 1975). The bushpig is mainly distributed in forested areas of eastern, southern and western central Africa with densities ranging from 1–10 individuals/km^2 in protected areas (Venter *et al.*, 2016). African swine fever is a highly infectious and haemorrhagic disease affecting exclusively domestic and wild suids, a significant threat to the pig industry worldwide (Costard *et al.*, 2013). In Africa, the virus is maintained in two epidemiological cycles: the sylvatic cycle, involving warthogs, bushpigs and ticks, and the domestic cycle, involving domestic pigs. The disease can be transmitted by direct contact with an infected animal, its body parts or its secretions, or indirectly through fomites or contaminated food (Chenais *et al.*, 2018). Warthogs are resistant to the disease and do not become viraemic, apart from a brief period as young warthog piglets, and thus do not transmit the disease directly (Plowright, 1981,Thomson, 1985). Warthogs transmit ASF through soft tick bites, from the complex *Ornithodoros moubata* acting as a vector of the disease within warthog populations, but also between warthogs and other suid species, particularly domestic pigs. These ticks are the natural reservoir maintaining the disease (Pereira De Oliveira *et al.*, 2019). In the absence of *Ornithodoros* ticks, warthogs do not excrete sufficient amounts of virus to transmit the disease horizontally to domestic pigs, therefore, the presence of warthogs is not enough to maintain a permanent source of the virus in the environment (Jori and Bastos, 2009). The bushpig has been shown to be naturally resistant through experimental infection (Oura *et al.*, 1998). Previous studies suggest that bushpigs could have a potential role in the epidemiology of ASF (Okoth *et al.*, 2013) because they have occasionally been found carrying the virus in different parts of Africa. Their capacity to transmit the virus through direct contact to susceptible domestic pigs has been proven in captivity (Anderson *et al.*, 1998). However, their potential to maintain ASFV in its natural habitat and its transmission to domestic pigs has not been proven (Ravaomanana *et al.*, 2011, Ståhl *et al.*, 2014).

In southern and East Africa, the maintenance of ASF in a sylvatic cycle linked to the presence and maintenance of ASF virus in *Ornithodoros* ticks living in warthog burrows, represents a challenge for the development of pig farming in rural areas due to a constant risk of ASF spill over to domestic pigs (Quembo *et al.*, 2016). This can occur through direct physical or indirect contact between wild and domestic suids through the sharing of environmental resources such as soil, forage and water facilitating disease transmission (Kock, 2005). African swine fever is a disease of global concern, as it has the capacity to spread worldwide and can lead to severe negative socio-economic impacts, both in areas where it is newly introduced and where it is endemic (Chenais *et al.*, 2019). In South Africa ASF is a notifiable disease with a disease-free area and a control area defined in 1935 where ASF has been reported as endemic (Van Rensburg *et al.*, 2020). The spread of ASF outside of the control area should be notified internationally to the OIE and could result in an international ban of pigs and pork trade involving the disease-free area (OIE, 2011).

ASF is endemic in Mozambique, a country immediately north of NGR. The first laboratory-confirmed outbreak of ASF in Mozambique was reported in 1960 (Quembo *et al.*, 2018). Several outbreaks have since been observed around the country, including in the region south of Maputo, within 30 km of NGR. Though movements of domestic pigs from one province to the other in Mozambique played a role in disease transmission and spread, the sylvatic cycle was considered equally important particularly in the vicinity of conservation areas where warthogs and bushpigs are common (Penrith *et al.*, 2007).

The complexity in the eco-epidemiology of this multi-host pathogen disease makes it hard to respond to outbreaks by implementing disease mitigation strategies. Among other factors, farming practices in neighbouring communities, the distance from the neighbouring community to a protected area (PA), the availability of resources in PAs, and the nature of the fence (surrounding PAs) stimulate wildlife-livestock interactions that promote the introduction and spread of diseases (Kukielka *et al.*, 2016). Cowled and Garner (2008) argued that behaviour, animal density, distribution, contact rate and habitat connectivity of both the vector and susceptible species, are important for understanding how diseases are transmitted between wildlife and livestock. For ASF, the higher the wild suid density within a PA the greater the chances that some suids will get into contact, directly or indirectly, with domestic pigs. Also, the further wild suids move from the PA into farmland, the greater the risk of disease transmission. Pech and Mcilroy (1990) argued that the movements of pigs increase the likelihood of contact between infected and uninfected pigs, and thus the spatial extent and velocity of spread of a disease.

Fencing has a long history in wildlife conservation and in many cases has proven to be an effective tool for keeping wildlife out of specific areas, as well as controlling animal movements and disease outbreaks (Durant *et al.*, 2015). Fences are often deleterious to wildlife, preventing access to food and water as well as natural migration, but also protect wildlife from human threats (Pirie *et al.*, 2017). However, given that they undergo changes, fences probably do not work in the same way and with the same efficiency in all cases. Floods, breaks due to wildlife movement and damage due to theft, are factors increasing fence permeability. Therefore, a fence requires regular inspection and maintenance (Jori *et al.*, 2011).

Ndumo Game Reserve is home to warthogs and bushpigs which play a role in maintaining and transmitting livestock diseases (Costard *et al.*, 2009b). It is located adjacent to a communal area with a substantial number of farmed pigs, generating a wildlife-livestock interface. In addition, the reserve is within the boundaries of the ASF control zone in South Africa. That means the area is suspected to host a sylvatic cycle in which *Ornithodoro*s tick populations colonize warthog burrows, representing a permanent source of ASF. The reserve shares its borders with Mozambique, where ASF is considered to be endemic. This study aimed to provide quantitative information about the potential presence of a sylvatic cycle at the wildlife livestock interface of NGR, which is part of the Lebombo Transfrontier Conservation Area, a transboundary conservation initiative including protected areas from South Africa, ESwatini and Mozambique. Understanding the extent to which wild suids from NGR interact with surrounding domestic pigs close to NGR is critical for surveillance and control of ASF, especially as the study area has been declared an ASF control area since 1935. Therefore, the specific objectives of the study were: i) to estimate the population size of warthog and bushpigs in NGR; ii) to assess the presence of ticks in warthog burrows from NGR; iii) to study the movements of wild suids between NGR and the adjoining farming areas and their potential interactions with domestic pigs.

2.3 MATERIALS AND METHODS

2.3.1 Study area

Ndumo Game Reserve is a 10 117 ha wildlife reserve which shares its border with the Mathenjwa community in the northern KwaZulu-Natal province, South Africa, and also Mozambique (Figure 1). The boundary of the reserve is fenced except on its northern side, where the seasonal Usuthu River separates South Africa and Mozambique. There are two seasons: wet (October-March) and dry (April-September) with an average annual rainfall of 638 mm. The mean annual temperature is 21.9 °C with dry season temperatures often above 40 °C. Villages surrounding the eastern, western and southern boundaries of the reserve are typical of South African communal areas where subsistence farming is the major economic activity. The inhabitants of the area grow mainly maize and keep livestock which include cattle, goats, pigs and chickens. Dipping, the driving of cattle through a specially constructed concrete tank with water and an acaricide to control ticks on cattle, is a regular activity in these villages.

The reserve is home to a variety of mammals representative of southern Africa, including different species of antelopes, black and white rhinos, hippos, crocodiles and both species of wild suids (bushpigs- *Potamochoerus larvatus* and warthogs-*Phacochoerus africanus*). The Usuthu and Pongola Rivers feed a number of pans, namely the Nyamithi, Banzi, Shokwe, Usuthu and Pongola pans. Within the game reserve, fence and reserve patrols are a daily activity for field rangers to combat poaching.

The reserve has seven major vegetation types: Western Maputaland Clay Bushveld, Makatini Clay Thicket, Lowveld Riverine Forest, Western Maputaland Sandy Bushveld, Sand Forest, Subtropical Alluvial Vegetation and Subtropical Salt Pans (Mucina *et al.*, 2006). In order to facilitate interpretation and analysis of the results, vegetation types with similar plant communities were grouped together. A vegetation map for the area was uploaded on Arcmap V10.6, and vegetation types were merged e.g. those near water areas (Figure 1). Consequently, only four major vegetation types were used in the analysis: Bushveld, Thicket, Sandveld and Water**.**

2.3.2 Abundance estimation

2.3.2.1 Warthog counts derived from annual transect counts

Ndumo Game Reserve has eight permanent line transects used for annual game counts, ranging from 1.5 km to 8 km with a combined length of 50.915 km. The transects cut across the four vegetation types. ArcGIS 10.6 (ESRI, Redmont, California, USA) was used to measure the lengths of transects based on their position within different vegetation types (Table 1). These transects were used to conduct annual warthog counts and bushpig track counts. To maximise the accuracy of estimates, the eight transects in NGR were walked 16 times annually, during the dry seasons (April-September) of 2017 and 2018, using distance sampling methodology. The researcher, together with NGR game scouts and students from Tshwane University of Technology (TUT), conducted counts in the morning (5 to 8 am) to maximise chances of detecting warthogs as they are difficult to detect later in the day when they rest in the shade. Two observers, each focusing on one side of the transect, counted warthogs observed, and, for each encounter, recorded GPS coordinates of the observer, distance from observer to animal (r), group size (n) and angle of the animal from the transect (Ɵ). In addition, transect count data from 2013 to 2016 were provided for analysis by Ezemvelo KwaZulu-Natal Wildlife (EKZNW). The number of warthogs in the reserve was estimated using the Distance sampling software (Distance V8) with the negative exponential cosine model as the detection function. This function computes the likelihood contributions for off-transect sightings distances, scaled appropriately, for use as a distance likelihood. Only those years with consistent and reliable count data that fitted statistical models were used. Warthog transect sightings were mapped according to vegetation types using ArcGIS V10.6 (ESRI, Redmont, California, USA) and recorded in Excel (Microsoft Corporation, 2018) as follows: a) year of transect counts, b) transect number, c) vegetation type in which that observation was made, d) length of the transect with that specific habitat, e) number of warthogs seen, and f) the number of warthogs per km of transect. Descriptive analyses and linear mixed effect regression (Pinheiro & Bates, 2006) were conducted. Summary statistics, including mean and standard error of the mean (SEM) were computed.

2.3.2.2 Bushpig relative abundance using the transects

Bushpigs are crepuscular and nocturnal and seldom observed. Therefore, the only realistic method of assessing bushpig abundance is the use of indirect evidence provided by tracks, as well as photographs obtained by static camera traps. Bushpig track transect counts, using the eight transects used for warthogs, were conducted from June 2018 to December 2018. In order to maximise statistical reliability, each transect was walked 21 times recording bushpig tracks encountered. The researcher was assisted by game scouts with experience in animal tracking. Bushpigs tracks, compared to those of warthog, have broader hoofs and their claw mark show clearly on the tracks. The GPS coordinates of observed bushpig tracks, the transect identity, count repetition, the number of tracks, and any evidence of bushpigs (e.g. droppings) were recorded. To avoid the risk of double-counting, tracks were erased using branches. The following were recorded for each observation: date, repetition, transect number, vegetation type, length of that particular vegetation type in a transect, map reference coordinates of where the observation was made, number of tracks and the number of events, i.e. discrete groups of tracks.

The data were entered onto Excel (Microsoft Corporation, 2018). An event indicated a cluster of tracks in a particular transect. Tracks indicated the total count of tracks recorded per event. A linear mixed-effects regression model was executed to predict the mean number of events and tracks based upon habitat (Pinheiro and Bates, 2006). This allowed an assessment of relative bushpig abundance indicators (tracks) in each of the four habitat categories in NGR.

2.3.2.3 Camera trap surveys

A pilot study was conducted from May to July 2017 to fine-tune the camera trap data collection method. Twenty four static camera traps were deployed based on the field rangers' perceptions of areas where bushpigs could be found. During the pilot study, the duration of each camera trap placement was variable because NGR has a history of extensive theft of cameras by poachers. Camera traps were removed immediately after signs of human activity near a camera. After the pilot study, 24 camera trap stations were randomly positioned within the four main vegetation types using ArcGIS V10.6 (Figure 1). Camera trap surveys were conducted from February to December 2018. At each camera trap station, a single camera was tied to a tree or stump at bushpig height (30-50 cm above the ground) or higher (150-200 cm) with a downward pointing inclination, depending on the vegetation. Surrounding vegetation that would promote triggering by wind in front of the camera was cleared. Despite the nocturnal behaviour of the target species, camera traps were set to record photographs 24 hours a day. Trophy Cam ® (Bushnell Outdoor Products, USA) camera traps had continuous triggering of a one-second interval between consecutive images while the ScoutGuard ® traps were set to record 10 s video footage each time a movement was detected within the distance range (15 m). The date and time were shown on each photograph or video. The objective was 60 consecutive day periods of observation but the period was sometimes shortened in the case of poacher activity around the camera traps. All images were downloaded from the cameras after which the date and duration of each observation of suids was entered into Microsoft Excel, each record reflecting an event per specific camera trap station. An event was defined as an observation of at least one suid on the photographs within a single 30-min time interval. The following were recorded: a) camera trap station ID, b) GPS map reference coordinates of the camera, c) habitat in which the camera trap was installed, d) bushpig count (the total number of animals seen for all the pictures taken during one event on a camera trap station), e) duration of each event, and f) time duration since the previous event. Wild suid rate is the number of wild suid individuals (bushpig or warthog) photographed per camera day. Likewise, events are the number of events per camera day. Due to the small sample size of the sand and bushveld habitats, these two vegetation types were merged into a single category. Log transformation of the raw data was performed to obtain a normal-like statistical distribution of abundance values. A 1-way ANOVA was performed for detecting differences in wild suid rate between habitats.

2.3.3 Fence survey

In February 2018, a pilot fence survey was conducted to identify portions of the fence with holes used by wild suids. We term these holes as sites. The fence was divided into four main sections to relate fence crossings by pigs to the localities of farms. Thirty-two sites were identified on the western part of the reserve, 57 on the south-western side, 46 on the south-eastern and six on the eastern side.

Two bouts of fence surveys were conducted to identify wild suid activity at the respective sites: the wet season survey was conducted in 27 consecutive days of February 2018 and the dry season survey was conducted in August 2018 for 30 consecutive days. The number and location of all the sites were the same for both surveys. On each day the sites were each inspected for the presence of bushpig and/or warthog tracks. Once tracks were observed, the researcher, with the help of experienced tracker game scouts, took note of the species responsible, identity of the site, and the number of tracks counted. For each observed set of tracks, the species was identified based on the footprints and (on a few occasions) droppings. Three items were recorded for each site: a) whether tracks indicated wild suids crossing the fence (= a crossing event), b) the species of suid, and c) an estimate of the number of wild suids that had crossed at that point, based on the tracks leading to and from the site. A crossing event refers to an occasion when one or more warthogs/bushpigs crossed the fence at a specific site. The mean number of crossing events/site/day during a survey (f_c) is the total number of crossing events per day for a specific site (Table 1). Similarly, the mean number of wild suids/site/day during a survey (f_p) is the total number of wild suids that crossed at a specific site/number of survey days (Table 1). Since the statistical distribution of the number of crossings was similar to that described by a negative exponential function, analyses were performed on the natural log-transformed values of f_c and f_p. For detecting differences among the four sections of the fence, a 1-way ANOVA was separately performed on f_c as well as on f_p classified by fence section. For detecting differences between the dry and wet seasons, a repeated-measures ANOVA was separately performed on f_c as well as on f_p categorised by season. Standard errors of the estimates (S.E.M.) for the number of wild suids crossing the whole fence each day were generated by performing 1000 bootstrap samples of the observations at each fence site and finding the S.E.M. of the 1000 estimates of the wild suid crossing rate.

The R V3.4.4 (R Core Team, 2018) was used for all statistical analyses and statistical significance was set for P-value lower or equal to 0.05.

2.3.4 Farmers interviews

A structured questionnaire was used to collect data from all smallholder pig farmers within the Mathenjwa community (n=254) from April 2017 to December 2017. The purpose of the interview was to gather information on potential wild-domestic pig interactions observed by the local rural communities and to gather information on prevalent pig diseases in the area. Pig farmers were identified at diptanks, and interviews conducted on their farms. The 45 minute interview comprised 22 questions administered in Zulu by the first author. To ensure that no pig farm was missed, the exhaustive snowball method was used (Etikan *et al.*, 2016). Farmers were asked if they observed wild suids near their farm (Figure 3). Observations were clustered into two groups of distances from their farms: near (0-20 km) and far (>20 km). This clustering represented farmers' opinions on the contact rate of wild and domestic pigs from those that are either very close or very far away from the reserve. If any observation was made, they would then respond to whether they had seen them: a) in direct contact with domestic pigs (physical contact), b) on their farms (close to domestic pigs), c) close to their farms, or d) elsewhere. They were also asked to comment on diseases of their domestic pigs and about potential outbreaks of ASF occurring in the area. Farmers were asked if their pigs got sick or died from any disease. If affirmative they provided symptoms. They were also asked to name diseases prevalent in the study area.

2.3.5 Soft ticks survey

Warthog burrows within NGR were identified with the assistance of game scouts during their regular patrols. When a warthog burrow was encountered, signs of activity (tracks and droppings) were looked for and the GPS coordinates recorded. A 20 litre bucket was used to collect sand from each burrow which was spread in a thin layer across a large, black plastic sheet in the sun. Due to the photophobic nature of soft ticks, the sunlight and warm temperatures encourages *Ornithodoros* tick movement and facilitates tick detection as well as collection. A minimum period of 30 minutes per burrow was allowed, to ensure that tick movement would be elicited and that all visible ticks were collected (Jori *et al.*, 2013).

2.3.6 Ethics

The methods used for collecting data from pig farmers were assessed and approved by the University of Pretoria's Research Ethics Committee (EC 161129-084). Permission to conduct the study within the NGR was obtained from the Ezemvelo Kwazulu-Natal Wildlife authorities. Verbal consent from the local chief was obtained before the project inception. For the interviewees, participation was voluntary, private and confidential, and there was no penalty if they decided not to participate. A written informed consent was obtained from each participant.

2.4 RESULTS

2.4.1 Wild suid counts derived from transect counts

2.4.1.1 Warthog numbers from distance sampling and habitat preference

Using the Distance software, data for the years 2013-2018 were analysed. The estimation of the number of warthogs in NGR were *n*=632, 95% confidence interval=$[490,815]_{95\%}$ and *n*=383, CI=$[271, 541]_{95\%}$, respectively. This would suggest a population ranging between 400 and 500 warthogs, i.e. 3-5 individuals/km^2 in NGR. Table 2 shows the raw counts of warthogs along the transects for each year. Warthogs had a significant preference for Water areas compared to other vegetation types (1-way ANOVA P= 0.002).

2.4.1.2 Bushpig relative abundance and habitat preference using line transect counts

The linear mixed-effects ANOVA indicated that thickets (15.601 tracks/km) had the highest density of bushpig tracks compared to Water areas (5.374 tracks/km) and Sandveld (2.566 tracks/km) (Table 3). The trend was similar for the events data and the tracks data. The Bushveld areas had no bushpig tracks.

2.4.2. Wild suid abundance estimation using camera traps

Forty-eight camera traps were set up in four different vegetation types for a total of 1383 days. Bushpigs (*n*=483) were observed more frequently than warthogs (*n*=304). Similarly, the mean observation rate was higher for bushpigs (0.3518 animals/day) (Table 5) than for warthogs (0.221 animals/day) (Table 4).

2.4.2.1. Warthogs

Although the camera-derived results suggested that warthogs were more common in the Sand vegetation (0.536 animals/camera day; 0.268 events/camera day) (Table 4), the effect was not statistically significant due to the low numbers of warthog recorded.

2.4.2.2 Bushpigs

Even though the camera data suggested that bushpigs preferred water areas to other habitats, this was not statistically significant due to a relatively small sample size of camera days. The findings were consistent with events (0.515 animals/camera day; 0.0855 events/camera day) (Table 4).

2.4.3. Tick presence in warthog burrows

Despite intensive sampling, no soft ticks were recovered from any of the 35 warthog burrows distributed in different areas of the NGR territory (Figure 1).

2.4.4. Movements of wild suids across NGR boundaries

The mean number of bushpigs crossing the fence in the wet season (0.56 pigs/day) (Table 5) was 11 times lower than the mean number observed in the dry season (6.348 pigs/day) (Table 5) and this difference was statistically significant ($P < 0.0001$). Similarly, the mean number of warthogs crossing the fence was significantly lower during the wet season (10.26 pigs/day) (Table 5) compared to the dry season (15.4 pigs/day) (Table 5) ($P = 0.03$).

Bushpigs crossed the reserve fence at a significantly higher rate (0.0592 crossings/site/day) (Table 5) ($P<0.0001$) during the dry season than the wet season (0.0066 crossing/site/day) (Table 5). Warthogs had a similar trend to bushpigs. However, there was no seasonal effect in the number of warthog crossings per site and day. The crossing rate was (0.036 crossings/site/day), during the dry season and (0.028 crossing/site/day) in the wet season (Table 5). Crossings were more common across the western section of the fence compared to other sections and those results were consistent for bushpigs and warthogs. Bushpigs crossed the western section at a significantly higher rate than the south-eastern section in both dry (1.592 pigs/day) ($P<0.0001$) and wet (0.1389 pigs/day) ($P=0.0315$) seasons. In the wet season no bushpigs crossed through the eastern fence. Warthogs showed a similar trend although the differences were not statistically significant (Table 5).

2.4.5. Reports of wild suid presence in surrounding pig farms

Most pig farms were concentrated adjacent to the western (78%) and south-western (13%) sections of the fence. Some were located in proximity of the south-eastern fence section (9%), while the eastern section had no adjacent farms. The highest number of domestic pigs (n=631) was located in proximity to the western section of the fence while a considerably smaller number (n=172) were found on the south-western section of the fence (Figure 1).

Among the 254 pig farmers, eight reported bushpigs near their households (20 km radius) while three reported to have seen warthogs. None of them reported any direct interaction between those wild suid species and their domestic pigs. Bushpig sightings were reported as far as 19 km from the fence while for warthogs the furthest was eight km (Figure 2).

Pig farmers who reported bushpigs near their households were located adjacent to the western, south-western, and south-eastern section of the fence, whereas those who had seen warthogs tended to be more evenly distributed adjacent the western and south-eastern section of the fence (Figure 2). None of the farmers reported disease or disease symptoms compatible with ASF outbreaks.

2.5 DISCUSSION

Warthogs and bushpigs are common in the study area. Annual transect counts in NGR revealed a warthog density of 3-5 individuals/km^2, with a total population of 400-500 warthogs in the area. These estimates are at the lower end of population densities found by Cumming (1975) who reported that, in Africa, warthog densities range from 1-15 individuals/km^2. This could be partly explained by their preference for open savannah (Deribe *et al.*, 2008), instead of the bush thicket common at NGR. The camera trap survey indicated that NGR has a significant bushpig population, which may be similar to warthogs in numbers. This approach was useful in detecting the abundant bushpig population which had not been recorded using the diurnal line transects. Most of the bushpig recorded on camera traps (0.515 animals/camera day) were found in habitats close to water, consistent with the observations of different authors who noted that bushpigs are water dependent (Kingdon, 2014, Seydack, 2017). Warthogs (0.536 animals/camera day) on the other hand, were also found in sandy environments. Therefore, NGR provides a good habitat for both wild suids.

Movements of both wild and domestic suids can facilitate direct or indirect interactions with domestic pigs as well as ASF transmission at the interface of a protected area (Arias *et al.*, 2018). The wild suid species regularly crossed the game fence, moving into adjacent farmland. Standard wire or wire-mesh fencing are not efficient in containing suiform species and warthogs are often reported to escape from other protected areas by digging under fences (Jori *et al.*, 2011; Swanepoel *et al.*, 2016). Therefore, where it is important to contain wild suids in conservation areas, other kinds of barriers such as wild boar proof fences, are recommended (Satheeshkumar *et al.*, 2012, Efsa, 2014).

In the study area, crossings were more common during the dry season for both bushpigs (6.35 bushpigs/day) and warthogs (15.4 warthogs/day). The high number of fence crossings represents a challenge in the management of diseases in domestic pigs. This is because, in the farming area (as in many African rural areas) a considerable population of domestic pigs is left free-ranging, increasing the chances of direct and indirect interactions between wild and domestic suids and disease transmission (Jori *et al.*, 2018). This risk is further exacerbated by the fact that most crossings were observed on the western side of the reserve, where the highest number of pig farms are located. A possible explanation for more crossings on the western section could be that this terrain is mountainous with a moister thicket vegetation, providing a more suitable habitat for a shy species such as the bushpig (Jori and Bastos, 2009, Flamand *et al.*, 1991). This habitat also provides the suids with fruits and bulbs (Nyafu, 2009) particularly during the dry season when resources in the game reserve are scarce. The farms therefore have the potential for high levels of direct or indirect wild-domestic and domestic–domestic pig interactions, facilitating the transmission of shared pathogens, such as ASF. Despite limited veterinary research on the pathogenic burden of wild African pigs in comparison with the Eurasian wild boar (*Sus scrofa*), warthogs and bushpigs are known carriers of ASF as well as other pathogens such as trichinella, bovine tuberculosis and several porcine viruses that could be transmitted to domestic pigs sharing the same environment (Jori *et al.*, 2018).

Similar to previous studies, a limited number of farmers (*n*=11) reported to have seen at least one of the wild suid species outside the reserve (Kukielka *et al.*, 2016), but none were observed interacting with domestic pigs. While, to our knowledge, natural hybridization between domestic pigs and warthogs has never been reported, there are a number of reports of cross-breeding between bushpigs and domestic pigs (Jori and Bastos, 2009, Kingdon, 2015). We assume than while interactions could occur, they are not necessarily observed due to the elusive and nocturnal behaviour of bushpigs (Payne *et al.*, 2018). Incursions of bushpigs in farming areas are likely to occur at night and warthogs may have displayed avoidance behaviour (Kassilly *et al.*, 2008). Therefore, questionnaires alone are not the best method to derive conclusions on potential nocturnal interactions, and other methodologies such as radio-tracking and setting up camera traps near pigsties should be considered.

In many African rural areas, a considerable number of domestic pigs are free-ranging (Nantima *et al.*, 2015, Quembo *et al.*, 2016, Penrith *et al.*, 2013), increasing the chances of direct and indirect interactions between wild and domestic suid interactions and potential pathogen transmission (Jori *et al.*, 2018, Penrith *et al.*, 2013). Even though the sharing of the same habitat and resources represents an ideal situation for the transmission of pathogens between wild suids and domestic pigs (Barth *et al.*, 2018), in the present study there was no evidence suggesting that NGR currently harbours a sylvatic cycle that would allow wild suid species to act as carriers of ASF. Within the sample of surveyed burrows (*n*=35), no evidence of *Ornithodoros* tick infestation was found, suggesting that the tick reservoir is currently unlikely to be present in NGR and a permanent source of ASF virus is not maintained in the reserve, despite the presence of warthogs and bushpigs. These findings on the absence of ASF are similar to those in Mkuze Game Reserve (approximately 100 km south of NGR) where 98 warthog burrows were inspected and ticks collected (Arnot *et al.*, 2009).

The apparent absence of a sylvatic cycle in NGR is consistent with the fact that none of the farmers interviewed were concerned with severe disease outbreaks compatible with regular

ASF outbreak occurrences. Given the importance of the sylvatic cycle in Mozambique and the observations of some ASF outbreaks on the Mozambican side close to NGR (Penrith *et al.*, 2013), further research should be undertaken on a larger number of burrows in order to confirm this. Another aspect that should be further explored is a survey of ASF antibodies in wild pigs and domestic pig populations living at the interface of the NGR. Indeed, an absence of circulating antibodies in these populations would be a good indicator that the ASF virus is not being maintained in this study area.

The combination of an endemic ASF status in Mozambique (at the northern boundary of NGR), the presence of significant numbers of warthog and bushpig within NGR, the regular movements of both species between NGR and the surrounding farmland, suggest that strong veterinary surveillance and management remains necessary to identify potential infectious disease introductions within the local pig population, which can act as a sentinel population.

2.6 CONCLUSION

We investigated the interface between wild and domestic pigs and the potential presence of a sylvatic cycle in an African protected area. Both warthogs and bushpigs are common in NGR and they often move out of the park, sharing home ranges and resources with domestic pigs, particularly in the dry season. Fencing should not be the method of choice to prevent transmission from potentially infected wild suids to neighbouring pig farming areas since they are prolific diggers. Despite the potential occurrence of wild-domestic interactions, the study results suggest that it seems unlikely that the wild suids will transmit ASF to domestic pigs as no ticks were found in warthog burrows and surrounding pig farmers were not familiar with ASF outbreaks in their area. Further research should explore a larger number of warthog burrows to confirm the absence of ticks and potential antibodies against ASF and other diseases should be monitored in pigs and wild suids which are potentially exposed to ASF. An awareness program among smallholder farmers is also encouraged particularly targeting the western and southern sections of the park, which could potentially have a high burden of contact between wild and domestic pigs. Confining pigs during periods of high potential interactions (at night and/or in the dry season) is also recommended since full-time penning is expensive and impractical. Considering the proximity of the Mozambican border, regular surveillance of wild and domestic suids is equally important for monitoring potential incursions of ASF in this area of high risk.

2.7 CONFLICT OF INTEREST

There was no conflict of interest. None of the authors received any funding from Ezemvelo KwaZulu-Natal Wildlife to perform the study.

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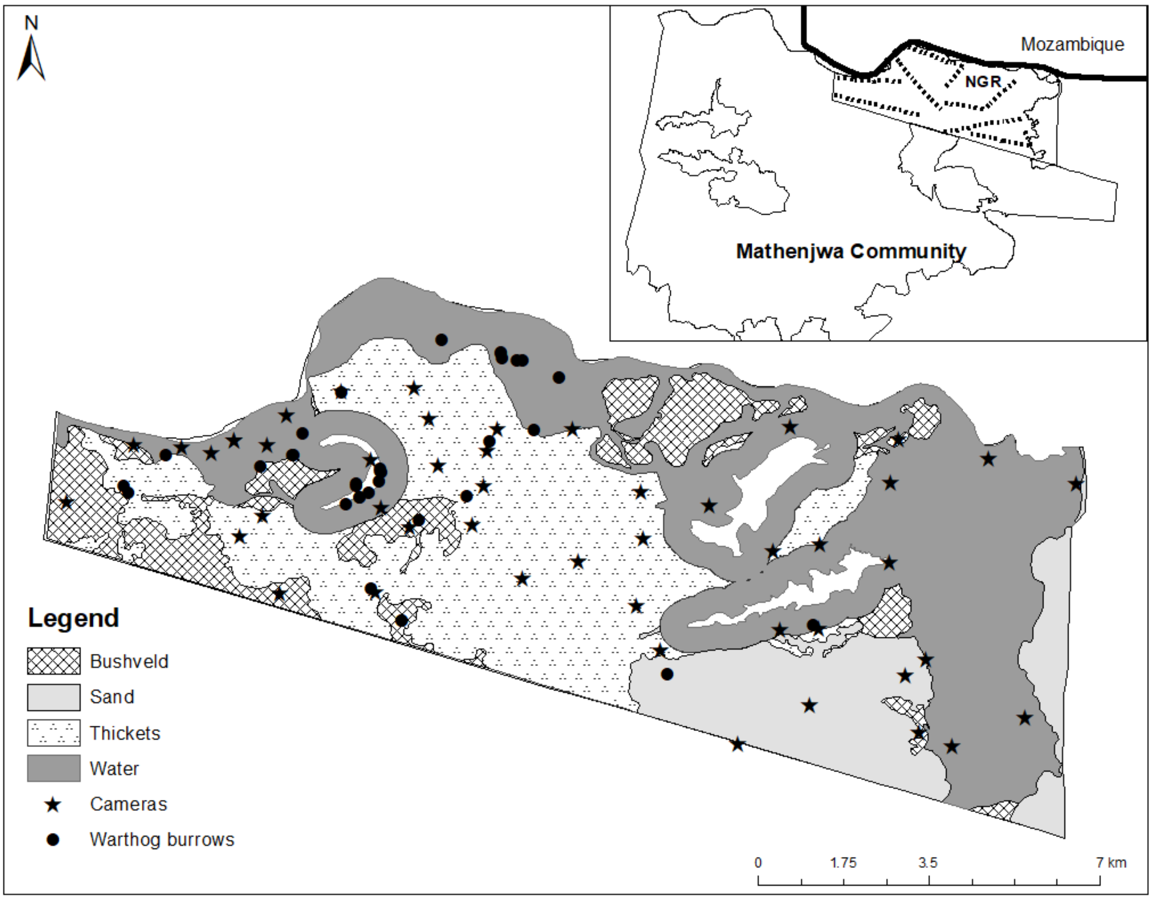

Figure 1. The distribution of four vegetation types present in Ndumo Game Reserve as well as surveyed warthog burrows (black dots) and the location of the static camera traps (black stars). The transects walked (dashed lines on the insert map) during the study are presented as dotted lines within NGR in the figure insert.

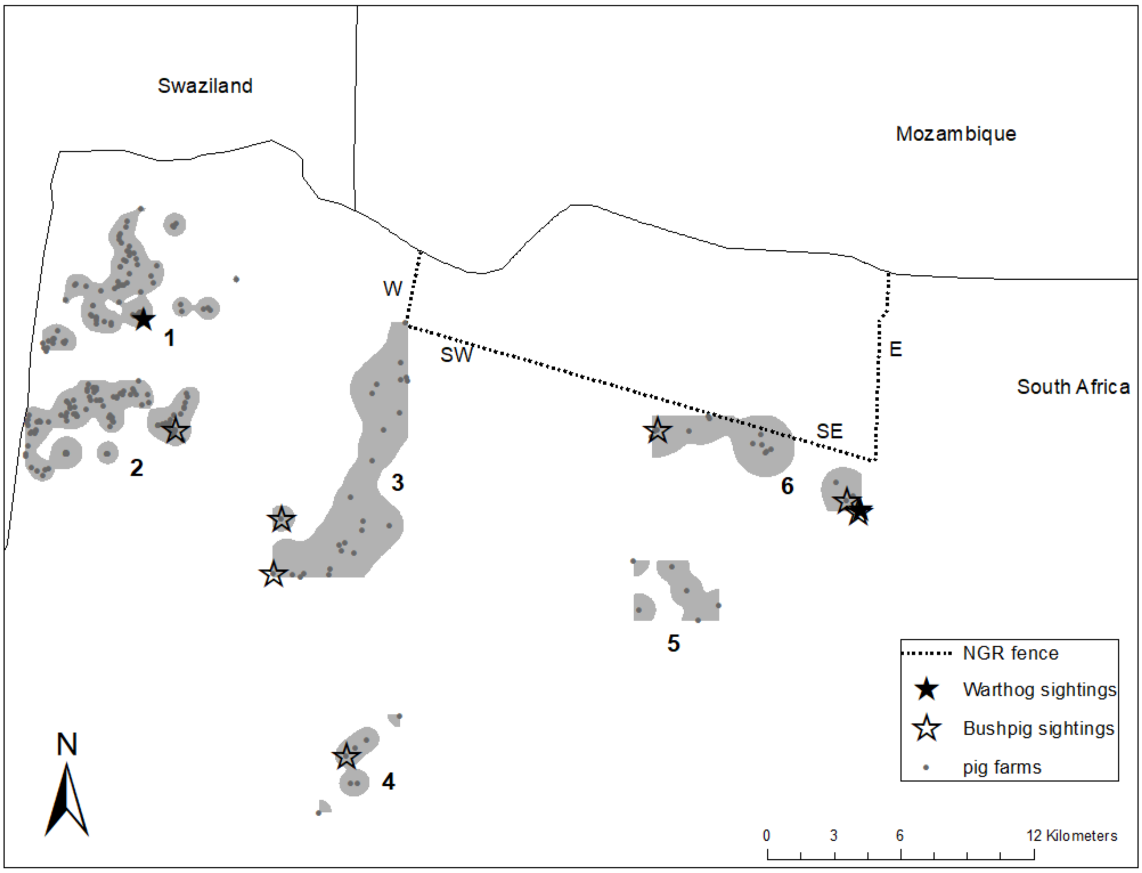

Figure 2. Clustered (in grey shade) distribution of pig farmer households and wild suids sightings as reported by farmers in the Mathenjwa Community surrounding NGR. Numbers indicate cluster identity (i.e. 1 denotes Cluster 1).

Table 1. Transects lengths (km) within different vegetation zones in NGR

Transect ID

Vegetation type	1	2	3	4	5	6	7	8	Total
Bushveld	0.2	1.2	0.02	0.98	4.42	0.62	-	0.9	8.34
Sand	5.4	4.3	-	-	-	-	-	-	9.7
Thicket	-	1.7	4	0.3	3.935	0.51	7.05	-	17.495
Water	1.2	0.02	2.54	0.28	-	5.36	0.2	5.78	15.38
Total	6.8	7.22	6.56	1.56	8.355	6.49	7.25	6.68	50.915

Table 2. Annual warthog counts along transects in the four vegetation types of Ndumo Game Reserve. Habitat length is the length of the respective habitats in different transects. Mean density indicates number of warthogs/km. There is a significant preference for thicket and water (1-way ANOVA p<0.002)

		Habitat				
Year		Bushveld	Sand	Thicket	Water	n
	Length (km)	8.34	9.7	17.5	15.36	
2013	No. warthog	44	33	95	64	236
	Mean density	**5.276**	**3.402**	**5.429**	**4.167**	
2015	No. warthog	15	5	46	184	250
	Mean density	**1.799**	**0.515**	**2.629**	**11.979**	
2016	No. warthog	36	25	20	154	235
	Mean density	**4.317**	**2.577**	**1.143**	**10.026**	
2017	No. warthog	12	28	25	104	169
	Mean density	**1.439**	**2.887**	**1.429**	**6.771**	
2018	No. warthog	13	1	67	60	141
	Mean density	**1.559**	**0.103**	**3.829**	**3.906**	
Overall	No. warthog	120	92	253	566	1031
	Mean density/year	**2.88**	**1.9**	**2.89**	**7.37**	
	SEM	0.7999	0.6646	0.7932	1.5956	

Table 3. Bushpig tracks encounter rates survey results in four vegetation types of the NGR. An event indicates a cluster of tracks in a particular transect. Tracks indicates number of bushpigs inferred from tracks for each event. The t and P-values reflect the outcomes of a repeated-measures linear mixed model using REML, comparing the bushpig encounter rate in the Bushveld with each of the other three habitats. These differences are mostly statistically significant with Thicket having the highest encounter rates.

Events

	Mean	Standard Error	t	P
Sand	1.311	0.457	2.868	P<0.05
Thicket	3.024	0.357	8.458	P<0.001
Water	0.982	0.366	2.681	P<0.05
Bushveld	0	0.429	0	n/a

Tracks

	Mean	Standard Error	t	
Sand	2.566	2.608	0.984	NS
Thicket	15.601	2.039	7.649	P<0.001
Water	5.374	2.09	2.571	P<0.05
Bushveld	0	2.696	0	n/a

Table 4. Warthog and bushpig abundance in the four vegetation types in NGR, inferred from camera traps. The total number of wild suid species and events are shown. The mean number of wild suids species/events indicate the number of wild suid species events per camera day. The numbers in bold type indicate warthog results while the italicised numbers are for bushpigs. P= statistical significance of a 1-way ANOVA on the log-transformed number of images with wild suids, comparing different habitats. Since the total number of camera days is relatively small, differences among habitats are not significant.

Vegetation types	Number of cameras	Camera days	Number of wild suids		Events		Mean number of wild suids		S.E.M. (wild suids)		Mean number of events		S.E.M. (events)		P
Sand (S)	3	97	**52**	*7*	**26**	*2*	**0.536**	*0.072*	**0.418**	*2.330*	**0.268**	*0.021*	**0.241**	*0.660*	
Bushveld (B)	5	170	**4**	*6*	**3**	*5*	**0.024**	*0.035*	**0.015**	*0.063*	**0.018**	*0.029*	**0.011**	*0.064*	
Combined S+B	8	267	**56**	*13*	**29**	*7*	**0.210**	*0.049*	**0.179**	*0.869*	**0.109**	*0.026*	**0.090**	*0.246*	
Thicket	17	514	**77**	*174*	**20**	*27*	**0.150**	*0.338*	**0.249**	*1.007*	**0.039**	*0.052*	**0.069**	*0.087*	**0.903** *0.634*
Water	23	602	**168**	*307*	**36**	*51*	**0.279**	*0.515*	**0.249**	*1.323*	**0.060**	*0.086*	**0.069**	*0.182*	
Overall	48	1383	**301**	*491*	**85**	*85*	**0.218**	*0.355*	**n/a**	*n/a*	**0.061**	*0.061*	**n/a**	*n/a*	

Table 5. Fence survey results for bushpigs and warthogs in NGR for the dry and wet season with two variables: the number of crossings per site per day and the number of pigs per day. Outcomes for a 1-way and repeated measures ANOVA are indicated. The numbers in bold type indicate warthogs results while the italicised type are for bushpigs.

	Fence section:	West	South West	South East	East	Whole fence; Bootstrap	1-way Anova df=137,3
	No. of sites	32	57	46	6	141	
	Wet season						
	No. of surveys †	27	27	27	27	27	
	No. of site-days †	864	1539	1242	162	3807	
	Mean no. crossing events/site/day	_0.0046_	_0.0012_	_0.0008_	_0_	_0.0066_	_F=1.7414 P=0.1614_
		0.0335	**0.0292**	**0.0418**	**0.0062**	**0.1107**	**F=1.1436 P=0.3338**
	Mean no. pigs /day	_0.4074_	_0.0741_	_0.0741_	_0_	_0.56 0.226‡_	_F=3.0318* P=0.0315_
		2.5185	**3.7037**	**3.9629**	**0.0741**	**10.26 0.048‡**	**F=0.9285* P=0.4289**
	Dry Season						
	No. surveys †	30	30	30	30	30	
	No. site-days †	960	1710	1380	180	4230	
	Mean no. crossing events/site/day	_0.0343_	_0.0187_	_0.0007_	_0.0055_	_0.0592_	_F=8.6126 P<0.0001_
		0.0542	**0.0392**	**0.0246**	**0.0277**	**0.1457**	**F=2.2483 P=0.0855**
	Mean no. pigs /day	_3.0333_	_3.1333_	_0.1000_	_0.1000_	_6.367 1.021‡_	_F=9.0643* P<0.0001_
		5.0000	**6.3666**	**3.6666**	**0.4000**	**15.4 0.061‡**	**F=1.4405* P=0.2337**
Effect of season: Repeated-measures ANOVA df=278,1	Mean no. crossing events/site/day						_F=39.100 P<0.0001_
							F=2.0090 P=0.157
	Mean no. pigs /site/day						_F=46.83 P<0.0001_
							F=34.665 P=0.0316

Wild-domestic suids interactions and disease oubreaks

1. Interaction of domestic and wild species

Have you seen any of these species near your farm?

Bush pig Y ☐ No ☐
Warthog Y ☐ No ☐

If yes to any of the above,
Where they in direct (physical) contact with domestic pigs on your farm? Y ☐ No ☐

Near your farm or, Y ☐ No ☐
Elsewhere…………?

How far away were observations made from your farm? Near (0-20km away) ☐ far (>20km way) ☐

2. Outbreaks and response

Has any of your livestock ever been affected (sick or died) by any disease? Yes ☐ No ☐

Do you know what disease it was?
……………………………………………………………………………………………

What were the symptoms?
……………………………………………………………………………………………………

Which diseases are prevalent in your area?
……

Figure 3. Questionnaire used during individual interviews

CHAPTER 3: PIG VALUE CHAIN NETWORK ANALYSIS TO ASSESS THE EFFECTIVENESS OF THE ZONING POLICY: A CASE STUDY OF AFRICAN SWINE FEVER CONTROL IN SOUTH AFRICA.

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3.1 ABSTRACT

Disease outbreaks are a major setback in pig farming. Previous studies have shown that animal movements are one of the main factors that increase the risk of disease introduction. Animal health authorities in South Africa have created disease control zones to prevent the spread of some diseases that are endemic in wild hosts. Disease occurrence and spread is a dynamic process, thus, it is important to periodically reassess the effectiveness of these control zones. In this study, 254 pig farmers were interviewed to gather information on the local socio-economic importance of pig production, the pig husbandry methods employed and the movement of pigs within the Mathenjwa community in an African swine fever (ASF) control area. Social Network Analysis based on farmer interviews showed an extensive trade network within the study area and sporadic exchanges with neighbouring communities, including some located in Mozambique and eSwatini. The maximum distance travelled for selling pigs was 464 km. Husbandry methods employed by the farmers, predominantly single women, increased the risk of disease introduction and transmission. Nonetheless, 67 blood samples tested negative for ASF. Subsistence pig rearing is an important activity, especially to women, and therefore the community needs to be educated on the implications of unsanctioned trade in pigs. Zoning policy seems relevant regarding the intense movements of domestic animals; nevertheless, enforcement of this policy for pig farming is required to ensure that the zoning policy is relevant for the control of diseases. Further studies on the sylvatic cycle are recommended to complete the assessment of the zoning policy in the study area.

Key words: Zoning policy, African swine fever, foot and mouth disease, movement, pigs, social network analysis, transboundary animal diseases

3.2 INTRODUCTION

Subsistence agriculture is regarded as one of the main drivers of economic development in African rural areas (Gomala & Baluchamy, 2018). Approximately 70% of livelihoods in southern Africa are dependent on some form of subsistence agriculture, including crops and livestock (Sibhatu *et al.*, 2015), the latter representing an important part of this agricultural system (Thornton *et al.*, 2010*)*. In most African countries including South Africa, pigs are becoming increasingly important (Dione *et al.*, 2017) with an increase of more than 100% in the past three decades at both industrial and subsistence scales (Penrith, 2013). This can be explained by the species' high fecundity, fast maturity, high food conversion rate, short generation interval, ability to be fed on food scraps (swill), and relatively small space requirements (Ajala *et al.*, 2018). In addition, pig production can be adapted to hugely variable production systems, from exclusive penning to free-ranging (Lekule & Kyvsgaard, 2003).

While the pig industry has been growing over the years, the issue of disease outbreaks prevents the industry from reaching its full potential (Chenais *et al.*, 2017). The management of livestock diseases has been made more challenging by the gain in popularity of the Transfrontier Conservation Area (TFCA) concept. South Africa has TFCAs along its borders with six neighbouring countries. These TFCAs allow the free circulation of wild species such as wild suids, recognised reservoirs for African swine fever (ASF) virus. One such area is the Lubombo TFCA encompassing the Ndumu-Tembe-Futi TFCA between Mozambique and South Africa (SA), Ponto do Ouro-Kosi Bay Marine and Coastal TFCA between Mozambique and SA, Nsubane-Pongola TFCA between SA and eSwatini, Lubombo Conservancy-Global TFCA between Mozambique and eSwatini and Songimvelo-Malolotja TFCA between SA and eSwatini (recently incorporated into the Lubombo TFCA). South Africa may, therefore, be at a higher risk of being affected by transboundary animal diseases (TADs). Although there are strategies to secure the country's borders against the introduction of animals that may harbour diseases (DAFF, 2019) there is still the possibility of introduction of pathogens through various pathways such as fomites, wild animals, as well as the illegal movement or trade of pigs and pork between local communities close to the border (Penrith & Thomson, 2012). Among the six countries sharing borders with South Africa, Mozambique deserves particular attention, since ASF is endemic in that country (Quembo *et al.*, 2016) and in some instances, the disease has spread into South Africa (Jori *et al.*, 2016). African swine fever is the most destructive porcine infection that limits pig production. Mortalities due to ASF can reach 100% for some virus strains (Imbery & Upton, 2017). It is therefore imperative that animal movements between Mozambique and South Africa are monitored as transboundary exchanges of live pigs and pig products are a common risk factor of porcine infectious disease introduction between countries (Lichoti *et al.*, 2017), particularly when these exchanges involve relatives living on the other side of the border (Kouakou *et al.*, 2017).

Since 1935 South Africa has controlled animal diseases, particularly ASF, using the zoning principle defined by the World Organisation for Animal Health (OIE) (OIE, 2018). The delineation of the control, protection, and infected zones relies on scientific knowledge of the presence (or proximity) of the diseases and management policies. These zones have confined

ASF to the northern parts of the country (Magadla *et al.*, 2016). Sporadic outbreaks of ASF have been recorded in the ASF control area, with occasional spread to adjacent areas, but these outbreaks have never affected holdings that complied with the legal requirements (Penrith & Vosloo, 2009). The impacts of livestock movement in disease transmission were clearly exposed in 2012 when the first ASF outbreak outside the ASF control area since 1966 was recorded in South Africa. This was due to animals that were illegally moved from the ASF control zone to an auction site outside the zone (Geertsma *et al.*, 2012).

There are several legislative requirements designed to manage animal diseases that livestock farmers, small or large, need to adhere to. Animal movements are controlled by the State Veterinarian or by inter-zonal approval from the relevant provincial executive officers for any movement between zones. A Red Cross permit is used for movements from protection zones to the free zone even for slaughter. The objective of this permitting system is to ensure that diseased livestock are not exported from areas delineated as protection or control zones.

One powerful tool for analysing animal movements is social network analysis (SNA). Networks provide a conceptual framework to understand relationships between constituent elements such as farms, markets and auctions (Bigras-Poulin *et al.*, 2007). Knowledge of the pig trader network enhances the control of TADs such as ASF (Lichoti *et al.*, 2016). The overarching aim of SNA is to identify nodes that are ‘pivotal’ in terms of disease transmission by virtue of their relationship with other nodes in a network. Dubé *et al.* (2009) postulate that, as part of livestock disease preventive and control measures, it is crucial to understand how livestock trader networks are structured. This knowledge needs to be linked with active surveillance of these diseases i.e. the knowledge of the infectious status of the animals in the area and in neighbouring countries.

The objectives of the study were (1) to characterize the pig husbandry practices in a transboundary area of northern KwaZulu-Natal (NKZN) to discuss potential implications regarding the risk of disease introduction and spread, and (2) to evaluate pig movement within ASF control zones in order to ascertain the integrity of current zoning policy i.e. are pig movements being restricted by policymakers or not?

3.3 METHODS AND MATERIALS

3.3.1 Study area

The study was carried out within the Mathenjwa Traditional authority (total population: 18072; area: 686 km²; households: 3555) (Figure 4). This is a typical South African communal area with subsistence farming as the major economic activity, situated in the northern part of the KwaZulu-Natal province (KZN). The inhabitants of the area grow mainly maize and keep livestock which include cattle, goats, sheep, pigs and chickens. They keep them as a source of income and, food. According to the South African zoning policy, the northern part of KZN is part of the ASF control zone defined in 1935 (Magadla *et al.*, 2016). The Animal Diseases Act 35 (1984), stipulates that pigs in the ASF control zones must be prevented from getting into contact with wild pigs by keeping them in pig proof pens (DAFF, 2018). No re-assessment of ASF presence has been undertaken since the area was declared an ASF control zone. In addition, there is insufficient official data on the number of domestic pigs and pig farms in this area. Therefore, NKZN represents a good example of zoning policy encompassing a mosaic of several wildlife-domestic interfaces where knowledge of the different value chains is needed.

3.3.2 Ethics

The methods used for collecting data from people and pig handling were assessed and approved by the University of Pretoria's Research Ethics Committee (EC 161129-084) and Animal Ethics Committee (EC 046-16). A section 20 permit was obtained from the Department of Agriculture, Forestry and Fisheries for animal sampling and use of samples. Prior to data collection, permission was received from the Mathenjwa local authorities to conduct research in their community. Participation was voluntary and there was no penalty if the farmer decided not to participate or to withdraw from the study. Personal consent was obtained from all the participants. Individual information provided remained private and confidential. Anonymity was guaranteed by not recording the names of study participants, and instead codes were used to identify the source of data.

3.3.3 Data collection

A structured questionnaire was used to collect information on pig farming practices from all small holder pig farmers within the study area (n=254) for eight months from April 2017 to December 2017. The 45 minutes interview comprised 22 questions translated into the Zulu language. The study population consisted of pig owners identified during meetings with groups of cattle farmers during weekly tick control activities at dipping tanks (a concrete tank with water and an acaricide where cattle have to jump into and swim through). This was the best way to obtain ownership information as most farmers do not register small stock such as pigs with the local veterinary office. After identification at the dip tank level, the interviews were conducted at the pig owner's house. To ensure that no pig farm was missed, all the identified pig farmers were asked about their knowledge of any other pig farmers in the vicinity, following the snowball method (Etikan *et al.*, 2016). Interviews were administered by the primary researcher together with trained veterinary technicians.

Data regarding production, farming practices, and trade were collected. For trade data, pig farms were nodes (either origin or destination). In addition, data on the presence of pig farms (and number of pigs per farm) from a previous non-exhaustive study conducted in 2013 were used for a qualitative temporal comparison. Interview data were recorded on Microsoft Excel for analysis in R.

3.3.4 Sampling

The questionnaire survey served as a framework to organise a serological survey in the area to assess the status regarding pig infectious disease such as ASF.

Equation (3.1) was used for sample size determination as it enables detection of the disease within a certain threshold (Dohoo *et al.*, 2010):

$$N = \frac{log\,\alpha}{log(1-P)} \qquad (3.1)$$

Where, α denotes the level of accepted error and P denotes the threshold prevalence. The presence of the diseases was detected at a threshold prevalence of 2%, given the high transmissibility of both diseases, and the level of accepted error was 5%. From equation 3.1, the sample size (N) was calculated as 149. Animals that were six months or older were preferred for antibody testing as young animals were less likely to have been exposed to the diseases and could show cross-reactions due to their developing immune system. Furthermore, the presence of clinical signs, such as anorexia, weight loss or if farmers mentioned previous pig's death on the farm, was used. This was to ensure risk-based sampling, ensuring the chance of finding any positive cases while achieving the threshold prevalence.

3.3.5 Laboratory analysis

Domestic pigs were held while blood samples were obtained from the anterior vena cava and collected into BD Vacutainer™ Serum Tubes with the assistance of qualified veterinary technicians. Sera were aliquoted, stored at 4 ºC and transported to the ASF. Reference Laboratory of Transboundary Animal Diseases (TAD) at the Onderstepoort Veterinary Research, Agricultural Research Council (ARC-OVR), Pretoria, South Africa. Domestic pig blood samples were analysed for the presence of ASF virus antibodies. For ASF, antibodies against ASF virus were detected using the commercial competitive ASFV antibody Blocking p72 Enzyme-linked Immunosorbent Assay (ELISA) (Ingenasa®, Madrid, Spain), based on the purified p72 protein. The Ingezim PPA Compac kit was previously validated by the OIE/FAO/EU Reference Laboratories using 1069 porcine samples. The relative measured sensitivity was 99.36% [95% CI: 98.8–99.9] while the specificity was 98.6 [95% CI: 96.81–100] (Gallardo *et al.*, 2013).

3.3.6 Social network analysis

Pig movement patterns were analysed using social network analysis (SNA) using R software v.3.5.2 (R Development Core Team, 2004). Sociograms or link graphs were drawn using the igraph package in R. In the first phase of the analysis, nodes comprised farms, origins and destinations while directed arcs (edges or links) indicated pig movements. This network was georeferenced, and a map of pig movements was produced using ArcMap 10.6. In the second phase, farms, origins and destinations were grouped by villages and the villages represented the nodes of the network while directed arcs referred again to pig movement. Key network properties were based on individual node and whole network metrics. The definitions of centrality for the study are described in Table 6.

3.4 RESULTS

3.4.1 Trend in subsistence pig farming

3.4.1.1 Demographics and common practices

In 2013, pig production was mainly concentrated in the mountainous, western part of the study area, in the Manyiseni, Ekuhlehleni and Khume communal areas, with 43 pig farmers and 68 pigs. These are illustrated in Figure 2 as white dots. In 2013, the farmer with the largest herd had five pigs and most of the farmers had one or two pigs. In 2017, the census within this study area recorded 254 pig farmers of which 65% started pig farming one to five years before the survey (i.e. 2012-2017), 18% started six to10 years before the survey (2007-2011) while 16% started 11 to 20 years before the survey (1997-2006). The total number of pigs in 2017 was 1158 pigs which are illustrated in Figure 5 as black dots) and the farmer with the highest number of pigs had 80 pigs. Although pig farming is still concentrated in the mountainous parts of the study area, more farmers in the plains are taking up this activity.

3.4.1.2 Characteristics of pig farmers (owners)

The greatest proportion of pig owners were women (72%). Older people (56+ years old) were more involved in pig farming, representing 30% of the pig farmers compared to other age groups (Figure 6).

3.4.1.3 Pig husbandry

Most (61%, n=174) pig owners housed their pigs in some form of shelter. Pig owners that practised free-range farming constituted 31% (n=78%). Tethering was practised by 4% (n=11) of pig owners and (4%, n=11) practiced both free-ranging (after harvesting) and exclusive housing (during cropping season) as a way of minimizing conflict with other community members from pig raids. When pigs were slaughtered, 47% of pig owners indicated that they burn their waste (inedible parts) whilst (35%) said they buried them and 18% threw them away.

3.4.1.4 Importance of pigs to subsistence farmers in the Mathenjwa community

The village of Khume had the highest proportion of individuals engaged in pig farming. Two reasons emerged for keeping pigs in this community. Of the pig rearing inhabitants, 56% indicated that they kept pigs for personal consumption as opposed to selling. Even though most inhabitants indicated that they kept pigs for family consumption, they could sell the pigs if required to. Only 2% of the pig farmers said they have never sold part of their pig stock. Amongst pig farmers, 4%, 23%, 53%, and 18% indicated that they had sold pigs less than two months ago, 2-5 months ago, 6-11 months ago and 12 months ago or above, respectively.

3.4.2 Serum sampling

Serum samples were collected from 67 pigs older than six months within the study area (Figure 7). All the serum samples tested negative for ASF on the ELISA test. The pigs sampled did not present with clinical symptoms of either ASF.

3.4.3 Social network analysis

According to the declarations by the farmers, transactions (the buying and selling of pigs) occurred within the same village, between neighbouring villages and in some instances, the transactions were far-ranging. These involved farmers purchasing from a different district while others resorted to Mozambique or eSwatini (Figure 8). Social network analysis revealed that most transactions occurred within that there were three movements (of 548 movements). from the ASF control zone Of these 15 trades nine were for purchasing pigs while six were as a result of selling pigs. The nodes or villages involved in this trade were located within Bhambanani, Bhekabantu, Kwambuzi, Mahlabeni, Makhanise, Mthanti, Ndabeni, Nondabuya, Pietermaritzburg, and Skhemelele villages as well as some locations in eSwatini and Mozambique.

Overall, the directed graph (Figure 8) had 42 nodes (villages) and 518 edges (pig movements). The average geodesic distance (the shortest path between two farms) was 3.4 edges while the diameter (longest geodesic distance between any pair of farms) was 8 edges. The network density was 0.3, depicting a sparse network considering that the network had less than 100 nodes. The pig trading farms furthest from each other were Ekuhlehleni to Pietermaritzburg, a distance of 495 km.

Based on the centrality measures the five villages with the highest number of pig movements, important for diseases spread are Manyiseni, Ekuhlehleni, Khume, Ndabeni and Mabona (Figure 8). The in-degree values, which represent the extent at which pigs are brought in from outside, indicate that Manyiseni, Ekuhlehleni, Khume, Mabona, and Magwangu villages brought the most pigs from other villages. On the other hand, Manyiseni, Ekuhlehleni, Khume, Ndabeni and Magwangu proved to be villages of influence as they sold the most to other villages based on the outdegree values. Manyiseni, Mthanti, Magwangu, Khume and Makhanise villages had the five highest betweenness values. A high betweenness value indicates that such a node provides the shortest paths, in terms of nodes, and not necessarily distance, to connect two or more other nodes. This implied that the geodesic distances of many pairs of villages encompassed these villages. Nyathini, Nondabuya, Pension Day, Nkawini and Bhambanani villages had the highest closeness centrality values. This meant that the number of villages reachable from these villages increased, or the geodesic distances between the villages decreased.

3.5 DISCUSSION

Subsistence pig rearing has proved to be a worthwhile activity in the study area with subsistence pig rearing increasing over the years. This is consistent with what has been observed elsewhere in Africa and beyond (Chenais *et al.*, 2017, Boland *et al.*, 2013). This has important implications for disease control since subsistence pig farming is often associated with poor husbandry practices (Patr *et al.*, 2016). Subsistence pig production also often involve unmonitored and, at times, extensive pig movements which consequently heightens the risk of disease outbreaks (Tomley and Shirley, 2009).

Several practices and underlying socio-economic circumstances that increase the risk of disease outbreaks and transmission have been identified amongst the pig farmers in the study area. To start, it was discovered that most of the households, 72% (n=183), involved in subsistence pig rearing were headed by women. Women, as a group, are economically disadvantaged and Flatø *et al.* (2017) reported that single women in South Africa are more likely to be poor compared to their male counterparts. This implies that they will choose husbandry methods that are the least expensive (such as free-ranging their pigs) and will invest minimally in pig pens. The observation that subsistence pig farming in the study area is dominated by females agrees with previous studies (Mashatise *et al.*, 2005, Chikwanha *et al.*, 2007, Chiduwa *et al.*, 2008, Halimani *et al.*, 2012) that suggest that this is an important socio-economic activity undertaken by economically deprived groups, especially women. Households headed by single women make up a small proportion of the total households in the community (Torquebiau *et al.*, 2012) but accounted for most of the subsistence pig rearing activities. This is indicative of the important role this form of agriculture plays in empowering women, providing them with a livelihood as they are less likely to be employed elsewhere (Flatø *et al.*, 2017).

The nature of pens and other husbandry practices have an impact on the country's efforts to fight ASF. The South African law stipulates that pig pens in ASF control zones must be double fenced, however, most of the pens in the study area were observed to be made of wooden poles and were structurally unsound. The pens also had mud floors which are seldom cleaned meaning they can potentially perpetuate the presence of soft ticks, a reservoir of ASF virus (Jori *et al.*, 2013, Kagira *et al.*, 2010, Nantima *et al.*, 2015). The state mandates that pigs must be penned to reduce the risk of disease transmission (Phiri *et al.*, 2006), but most of the farmers (61%) indicated that they only confine their pigs to avoid conflicts with neighbours, especially during the cropping season and 4% of the farmers indicated that they pen their stock only during cropping time and exploiting the much cheaper option of free-ranging after harvest. Free-ranging of pigs, coupled with structurally unsound pens that can be breached by pigs, increases the risk of disease outbreaks and transmission within the study area. Free-ranging pigs have been reported as the primary reason for the endemic persistence of ASF in areas such as the island of Sardinia, Italy (Laddomada *et al.*, 2019). Etter *et al.* (2007) opine that the practice of free-ranging pigs is one of the risk factors for the spread of ASF on farms.

Another practice observed in the study area which can increase the rate of disease transmission involves how the pigs are slaughtered. Fifty six percent of the farmers indicated that they reared pigs for personal consumption and slaughter often takes place at homesteads and not registered abattoirs. The community within the study area lacks an operational abattoir and this could result in inedible parts of the pigs being disposed of in unsanitary ways. Eighteen percent of the farmers reported that they disposed of pig offal by way of open rubbish pits where it can be accessed by other free-ranging pigs. Pathogens such as ASFV are particularly problematic because of their prolonged infectiousness in meat products (Beltran-Alcrudo *et al.*, 2019). This is another pathway through which diseases can be spread (Jurado *et al.*, 2018) in the study area given that 31% of the farmers reported that they free-range their pigs as a means of reducing production costs.

It was also noted that subsistence pig rearing in the study area is not a continuous activity since pig farmers from 2013 had either sold or eaten their pigs during the time of the study (2017). This agrees with Nantima *et al.* (2015) who report that subsistence pig farming was often a discontinuous activity. In this study, it was observed that 30% of pig farmers were older than 56 years, and, in a country with a life expectancy of 64 years, this can partly explain the disappearance of pig farms that existed in 2013. Sixty-five percent of pig farmers in the study area emerged in the past five years, suggesting the existence of extensive live pig trading, and subsequent movement activities as pig farmers acquire new stock. Further supporting the argument for an extensive live pig trade network, 44% of the farmers indicated that they sold pigs to other farmers, within and outside their villages. Even though selling enable them to acquire their first batch, this has serious negative effects on the country’s fight against TADs such as ASF since trade in live animals is one of the pathways diseases can be spread (Beltran-Alcrudo *et al.*, 2019).

In an attempt to control the spread of ASF, the South African government legislated a zoning policy for animal disease control and this policy has resulted in some areas being delimited as ASF control zones. The major implication of this zoning policy is that a veterinary permit is required for exporting pigs and cattle from areas within the protection or control zones. Furthermore, the importation of livestock from other areas also has to be monitored. Currently, there is a passive surveillance of pigs for ASF within the ASF control zone.

The World Organisation for Animal Health recommends that policymakers should have knowledge of pig populations and a thorough understanding of the practices of stakeholders involved in pig production and its marketing (value chain) if they are to manage diseases more effectively (Fao, 2011).

The interactions between animals, direct or indirect, are an important factor in the transmission of diseases (Gudelj *et al.*, 2004). Social network analysis revealed a pig movement network with a density (the proportion of direct ties in a network relative to the total number possible) of 0.3, implying that pigs in one village interact, on average, 30% with pigs from other villages. This rather sparse connectivity is indicative of a friendship-network where trade was likely to occur between people who knew each other, a defining characteristic of archaic, under-developed, and unregulated rural economies (Hinrichs, 2000). This observation, low network density, is likely to be the opposite of what one might observe if pigs were traded through the auction system as is the case in more developed markets. In such instances, the density will be barely greater than zero as shown by Fasina *et al.* (2015) who studied livestock movement in the Limpopo Province of South Africa. However, it has to be noted that the described network is a simplified version of the pig trade in the area, as only the first purchase and the last sale of each pig owner was recorded to avoid recall bias.

Another metric that is important when conducting social network analysis is degree centrality. This is a measure of how important a node is within the network. In the study area, the node or village with the highest degree centrality (D_c=326) was Manyiseni, and this can be described as the most important node within the Mathenjwa community pig value chain. Furthermore, it was indirectly linked with Ekhuhlehleni, a node where some farmers procured pigs from eSwatini and directly linked to some pig farmers in Mozambique. Ekuhlehleni also had high in-degree and out-degree implying that it received a lot of pigs, compared to other players in the network, and also sold a lot of pigs to other villages. This finding is important because, according to Moyo and Masika (2009), resources for disease control are often limited in Africa, and knowing the most important nodes in the transmission of contagious diseases can improve the allocation of scarce resources. It allows educational and awareness campaigns to be targeted at the most important nodes or farms.

Makhanise and Magwangu, two of the three villages that received pigs from outside the ASF control zone, were among the nodes with highest betweenness centrality values. High betweenness indicates that the respective node is important in connecting two or more villages that are otherwise not directly linked. This is, again, an important finding because in the event of an outbreak, nodes with high betweenness must be isolated from the rest of the network players first since they will be central in the spread of the diseases. Authorities tasked with reducing disease outbreaks must also focus on these nodes and impart knowledge about proper husbandry methods to the farmers. Routine virus ASF surveillance should also focus on these nodes because they are connected, directly or indirectly, to the highest number of villages.

The final centrality measure that will be discussed is the closeness centrality. High closeness centrality indicates that a node is more central compared to those with lower values and it will require fewer steps to get to other nodes from such a node (Borgatti *et al.*, 2015). The five most central nodes in the study area were Nyathini, Nondabuya, Pension day Ndumo, Nkawini and Bhambanani. These villages are attractive to potential buyers as it would be easier to move pigs to their desired locations during the time of purchase. However, such villages deserve special attention as they can intensify the disease spread in case of an outbreak.

Besides the metrics described above, there were some nodes that are important for disease transmission but may not necessarily have high values for the common measures used to describe a social network. According to farmers' declarations, transboundary and long-distance movement of pigs still occur within the subsistence agriculture systems regardless of its epidemiological risks for disease introduction as well as the existence of laws that discourage such. It was revealed that pigs were acquired from Pietermaritzburg, eSwatini and Mozambique, and moved to Makhanise, Ekuhlehleni and Magwangu, respectively, and it is notable that these nodes were observed to be important in terms of disease transmission. The movement of pigs from Mozambique to Magwangu is particularly worrisome given the fact that ASF is endemic to Mozambique. In addition, pig farmers in the study area were not officially registered as pig keepers and did not report any pig movements or sales of pigs out of the ASF control area to veterinary authorities. The latter contravenes regulation 20 of the Animal Act of South Africa (Act 35 of 1984) related to the restriction of movement of animals.

The last important finding from the SNA was that the farmers were directly linked to each other with no intervention of other stakeholders as intermediaries. Therefore, awareness campaigns on the risks of transboundary animal movements should target the farmers directly (Iglesias *et al.*, 2017; Simulundu *et al.*, 2018).

Regardless of the husbandry methods and animal movements that potentially increase the risks of disease introduction and transmission, all 67 blood samples tested negative for ASF, confirming a prevalence lower than 4.4% for each disease. This view is supported by the farmers reporting no clinical signs or sudden deaths of pigs within the past several years due to ASF. Further research is required to confirm the presence/absence of the tick-warthog sylvatic cycle of ASF and to finalise the assessment of the relevance of NKZN as an ASF control area in SA.

3.6 CONCLUSION

The study provided evidence of an extensive pig network connecting all villages in a rural area bordering Mozambique and eSwatini in NKZN province. The SNA revealed that pigs are not only bought and sold within these closely linked villages but that stock is brought from several hundred kilometres inside South Africa and, according to some farmers, from eSwatini and Mozambique. In the latter country, important TADs such as ASF are endemic or regularly reported. In terms of sales, pig transactions occurred beyond the ASF control area without any official permits. Despite the current apparent absence of the diseases, the proximity to an endemic country and the lack of pig movement records make the zone at risk of introduction and spread of TADs, particularly those affecting pigs. Understanding the social networks that drive observed movements enable the state veterinarian to implement basic biosecurity measures in case of an outbreak. Khume village had the highest proportion of subsistence pig farmers while Manyiseni village was the most connected to others within the network. This implies that ASF awareness efforts should focus on these villages. Such sensitisation in addition to law enforcement (pigs kept in pens, animals and animal movements records) would allow countries such as South Africa to protect their investments by practicing disease control and surveillance using their zoning policy. In addition, further studies should be implemented to evaluate the presence of an ASF sylvatic cycle in transboundary protected areas in order to finalize the assessment of the status of this zoning policy.

3.7 CONFLICT OF INTEREST

There was no conflict of interest.

3.8 ACKNOWLEDGMENTS

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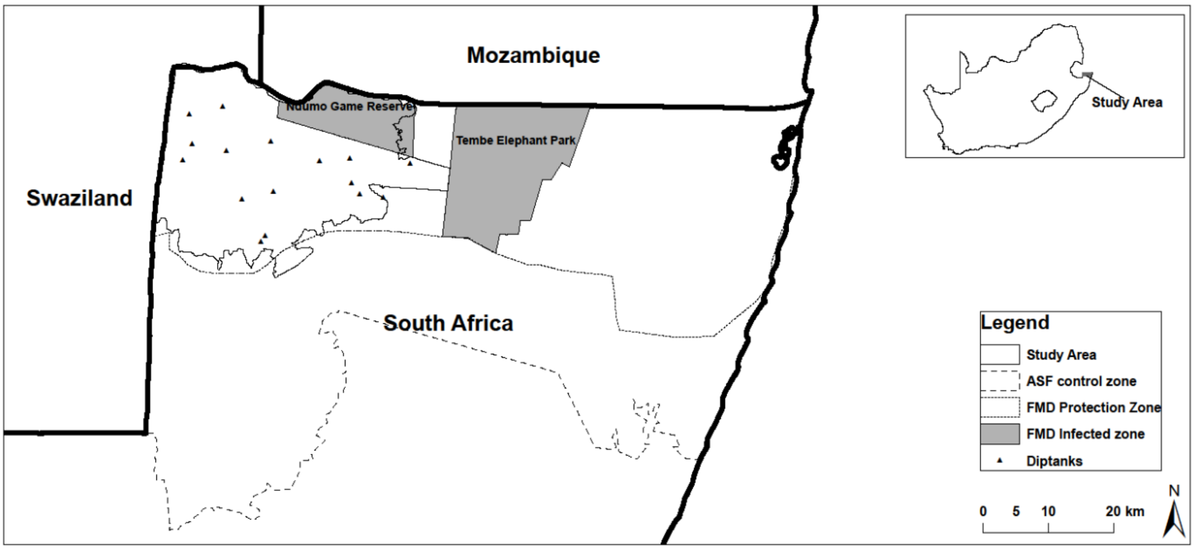

Figure 4. Map of the study area within the Mathenjwa traditional authority.

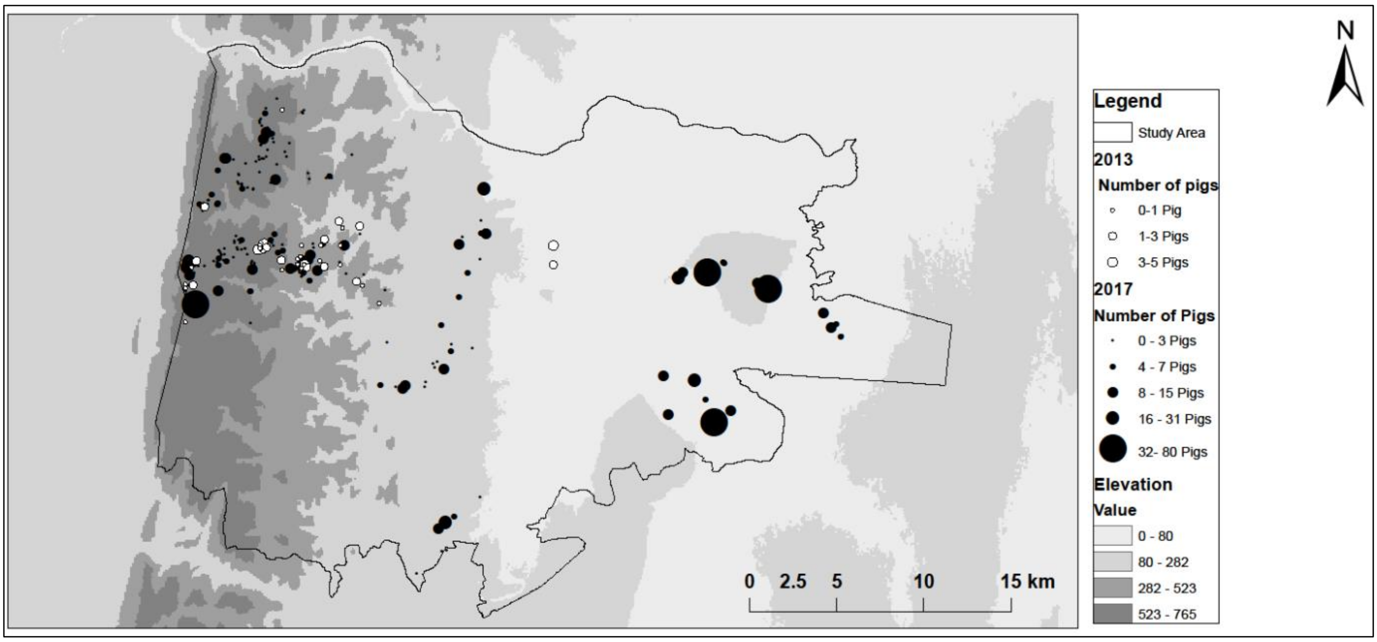

Figure 5. Pig farmers in the study area within Mathenjwa traditional authority during 2013 and 2017.

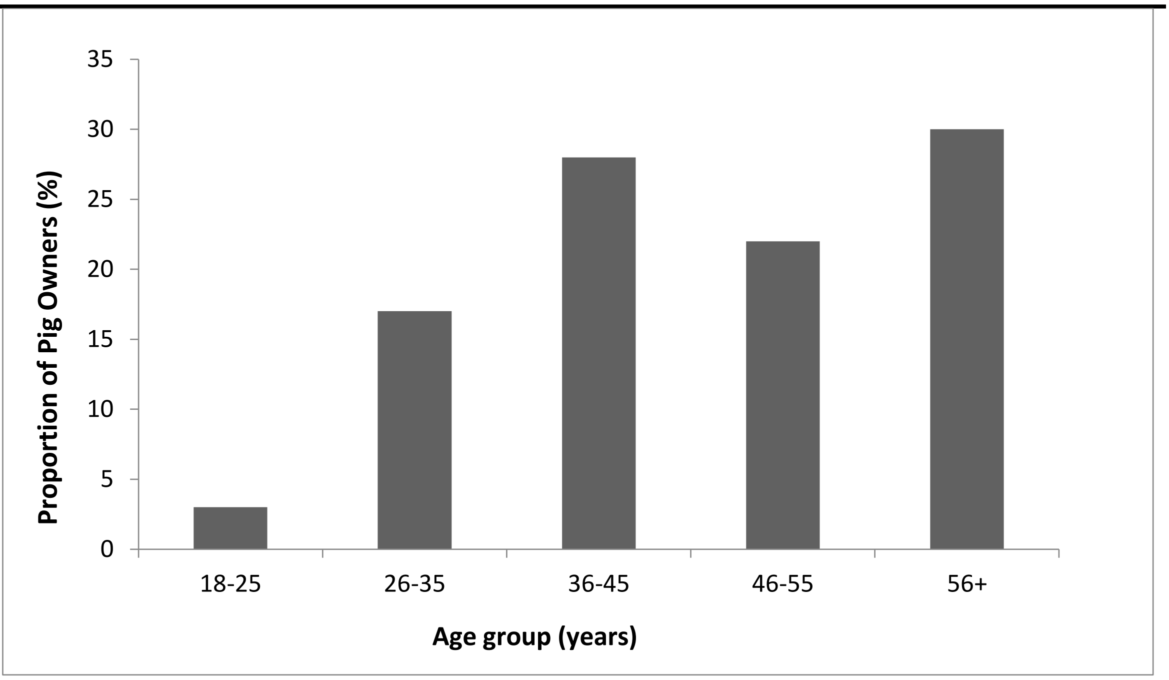

Figure 6. Proportion of pig farmers per age group.

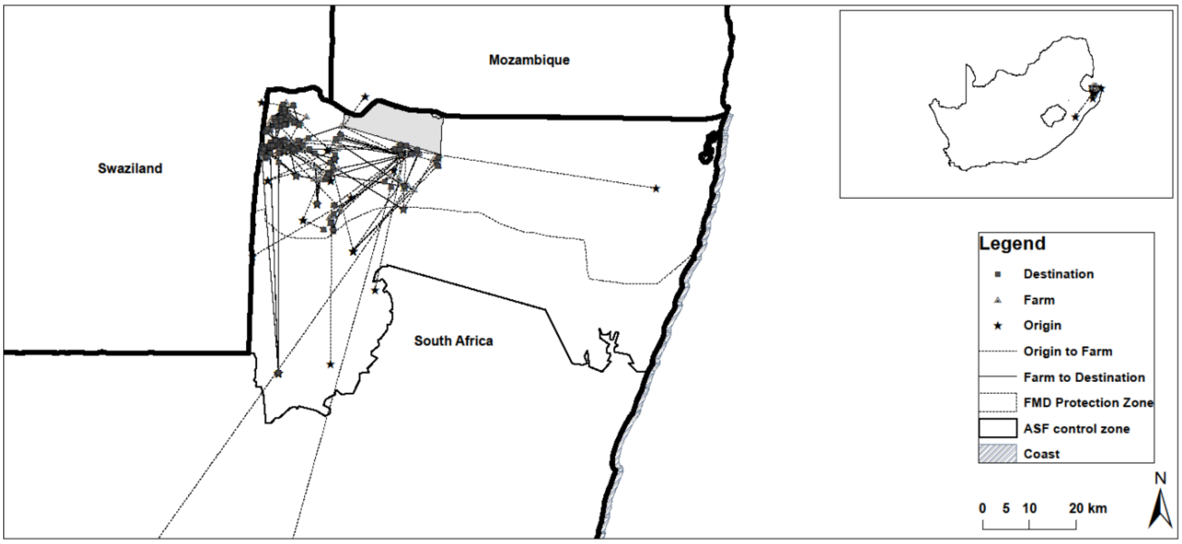

Figure 7. Pig movements in the ASF control zone.

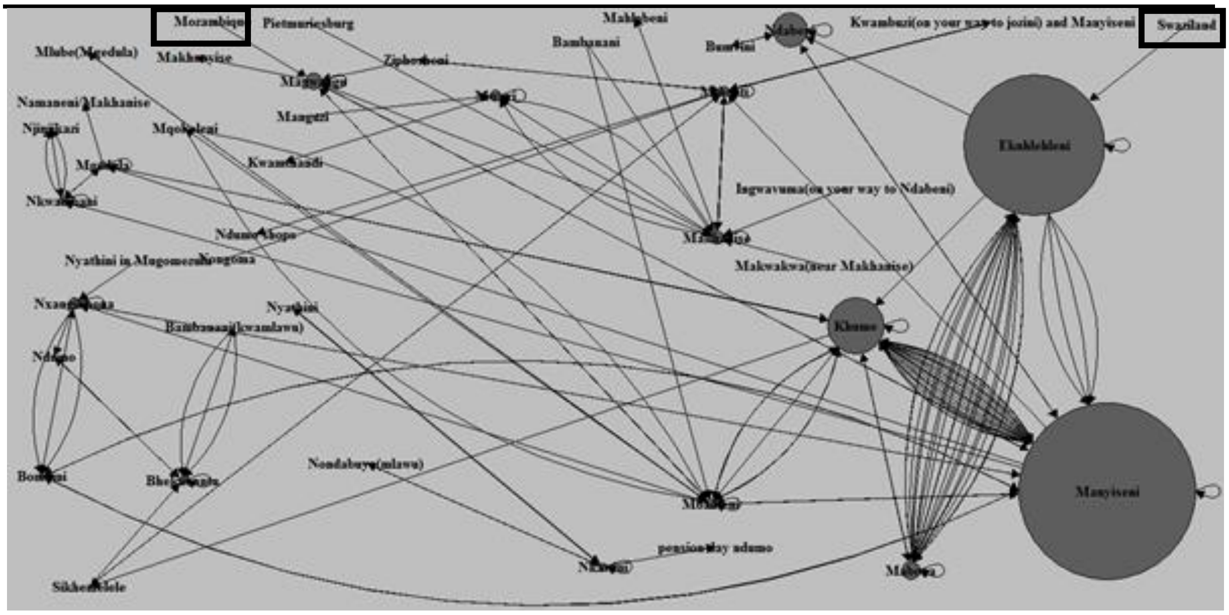

Figure 8. Directed network of pig movements in the Mathenjwa Community, 2017. The arcs are movement of pigs between nodes, which are villages represented by circles (villages of origin, farm or destination). The loops represent the transactions within the same village while the sizes of the nodes represent the values for degree centrality.

Table 6. Definition of centrality measures used in this study.

Term	**Definition**
Closeness	How close a farm was or how quickly one could reach other farms
Betweenness Centrality	How often a farm acted as a bridge to connect to other farms
Degree Centrality	The number of pig movements (connections) a farm had
In-degree Centrality	The number of pig movements observed to a single farm, an indication of contact support of a node
Out-degree	The number of pig movements from a farm, an indication of how influential the node is
Density	The total number of pig movements between farms against all possible pig movements

CHAPTER 4: GENERAL DISCUSSION AND CONCLUSIONS

4.1 INTRODUCTION

The broader implications of the findings will be discussed, and, how the responsible authorities can work towards reducing the risk of disease outbreaks in the study area.

4.2 IMPLICATIONS

Interviews with farmers indicated that pig husbandry in the area is not a long-term activity. Some farmers drop the activity whilst others take it up. This has major implications for the management of diseases in the area. Firstly, it means breeding stock is extensively traded within the community and, in some instances, the stock is brought in from areas where ASF outbreaks are common, such as Mozambique. Furthermore, frequent changes in the farmers keeping livestock observed in the study area means that new farmers may not have the knowledge of diseases that affect their livestock, and, as such, they may delay notifying the veterinary authorities in cases of outbreaks. Finally, changes in the pig farmers make it difficult for the relevant authorities to keep accurate records of pig farmers, useful information in case there is a need to roll out targeted interventions against some diseases.

Individuals engaged in pig husbandry in the study area belong to the low-income bracket and are mostly women. Women in South Africa, as a group, are generally less financially secure compared to men (Kehler, 2001) and it can be assumed that pig farming serves to augment their income and provide a cheap source of protein. One implication of this is that the farmers do not invest much towards the upkeep of the pigs and, as such, it is not surprising that most of the pig pens are made of freely available material (wooden poles) with earthen floors and are structurally unsound. This has several implications for disease management. Structurally unsound pig housing increases the chances of the pigs breaking out, increasing the risk of disease transmission. Improving on farm biosecurity for both small and large scale pig farmers is crucial in reducing the risk of disease in their pig herds and is important in securing livelihoods for the farmers (Costard *et al.*, 2009a). The South African authorities have recognized the importance of controlling pig movements, at the national and local levels, and have stipulated that pig pens must be double fenced to reduce uncontrolled movement of pigs. Unfortunately, due to the economic status of the subsistence pig farmers, this is not possible and, as such, the risk of disease spread in the area is quite high if a disease is introduced. The earthen floors also provide a conducive environment for soft ticks to perpetuate (Wamwatila, 2015), helping to maintain the disease in the area once there is an outbreak.

In an area where domestic pigs and wild suids potentially interact, reducing the risk of contact is of utmost importance. In the study area pig rearing is a secondary activity after crop farming and investment in pigs is minimal. The pigs are allowed to roam free during the times when there are no crops in the fields. In some instances, they are not even penned at night as this is an extra and unnecessary burden on the farmer. This has major implications of disease management as it increases the risk of contact between wild and domestic suids.

The dry season is the leanest in terms of food availability in the reserve and the wild suids may be forced to move out of the reserve to the communal areas. This movement is most likely to be during the night and indirect contact with domestic pigs is possible. The movement of wild suids into the communal areas is likely to be at night because none of the inhabitants reported having seen the wild suids while the fence patrol indicated that both warthogs and bushpigs move from the park into the adjacent communal areas. Even in the absence of direct contact between domestic and wild suids, indirect contact is likely as the wild pigs move closer to farms at night when it is quiet. According to Podgórski *et al.* (2013), wild suids modify their behaviour, and become more nocturnal, to avoid humans or other predators. This means that it is possible that there is more contact, indirect or direct, between domestic and wild suids than is generally assumed.

Although serological tests did not find any evidence of ASF in NGR and the surrounding communities, there is an ongoing threat of disease introduction given the location of the study area in relation to Mozambique where outbreaks of the diseases are common. It is the responsibility of the provincial veterinary services to work with communities to minimize the risk of disease introduction, or damage in case of an outbreak. This is achieved by eliminating, or at least reducing, the contact between domestic pigs from different farms and between domestic pigs and wild pigs.

Ndumo Game Reserve is fenced except on the northern side, but this fence is not effective against wild suids. Creating a fence that can keep wild suids inside is probably not possible because wild suids use holes created by prolific diggers, such as the aardvark, and building a wildlife-proof fence is probably not possible for a large area like NGR. Mysterud and Rolandsen (2019) noted that fencing as a method to mitigate the spread of disease is appealing mainly to politicians, but after considering ecological factors and implications it can be argued that fences barely address the challenges they seek to mitigate. Authorities must therefore explore other options to achieve the goal of minimizing contact between wild and domestic suids in the study area.

One strategy is to empower the communities with knowledge on disease prevention and the importance of adhering to regulations enacted to reduce the risk of disease transmission. Changes in risk behaviour can only be realized if farmers understand that their behaviour can cause health risks, particularly when socio-economic benefits are expected (Gabriël *et al.*, 2017). Educational campaigns, on aspects such as the importance of secure sanitary pig facilities, the dangers of buying and selling pigs from outside the control zone, and how to identify sick pigs and what to do in case of diseases outbreak, can help to change the attitude and practices of the farmers. Chilundo *et al.* (2020), after evaluating the effectiveness of pig farming education in controlling ASF transmission in Mozambique concluded that farmer education is important in managing livestock diseases. In the study area some individuals procured live pigs from Mozambique increasing the risk of importing ASF into South Africa. It cannot be assumed that such individuals know the legal implications of zoning without being specifically being educated on that subject. The individuals who bought the pigs probably did not know that their actions were illegal as well as their full implications. In one study in Saudi Arabia, Alotaibi *et al.* (2020), discovered that farmers were not fully aware of the regulations governing the sector leading to some unknowingly flouting regulations meant to protect their enterprises. Education campaigns can be useful in reducing the prevalence of such incidences. The farmer must be central in the process of managing livestock diseases. Jost *et al.* (2007)

refers to this as participatory epidemiology and states that conventional epidemiological concepts should incorporate farmer input to effectively solve epidemiological challenges. It must also be stressed that farmer education on its own will not bring about the desired changes (Sarti and Rajshekhar, 2003). There is need for a combination of measures if the intended results are to be realized.

Another strategy that can be used is to continuously conduct disease monitoring and surveillance by veterinary officers, allowing for a quicker and more effective response in cases of outbreaks. This approach is only feasible if the veterinary officers know exactly who owns susceptible livestock in the community, in this case pigs. Currently in the study area, because pig rearing is a temporary practice, veterinary officers do not have a complete data set of people who own pigs which makes monitoring and surveillance for ASF difficult as the veterinary department will not know whom to target during monitoring. For instance, at Jozini veterinary station only two to four movements have been officially recorded over a three year period (Y Ngoshe 2020, personal communication, date month). The veterinary department, in order to know who the pig owners are, may need to involve traditional authorities. Pig farmers could be compelled to register with the traditional authorities, creating a centralized register to allow veterinary officials to easily contact these farmers.

The disease monitoring and surveillance should not be limited to domestic pigs. The game reserve does not have a fence on its northern boundary, and, although a fence is not sufficient to keep wild suids in the park, the lack of a fence increases the risk of cattle and/or wild suids straying into the park from Mozambique. It is recommended that routine testing for diseases be part of the reserve management programme. Blood from warthogs and bushpigs culled in the park should be collected for serological tests as frequently as possible. In addition, tick surveys in warthog burrows performed by a collaboration between game guards and veterinarians should be a regular activity in the park. Effective communication between game reserve authorities and veterinary officials is therefore encouraged in order to ensure early disease detection, long before they are transmitted to domestic livestock. Routine testing of a wild population for the presence of diseases that can affect livestock is a common practice in many countries as it is considered critical in the management of diseases (Mur *et al.*, 2012).

There is also the need to control the slaughter of pigs in the area. Livestock offal, if not properly disposed of, can aid in the transmission of diseases. In the study area, pig offal is thrown in open pits where they can be accessed by domestic pigs as well as wild suids. A viable strategy is to have a community abattoir, as in some Ethiopian communities (Sissay *et al.*, 2007), where farmers can slaughter their animals. Having an abattoir has several benefits which includes simplifying data collection for disease surveillance. They can also give the farmers a platform to sell their products and, maybe, obtain higher prices than they would if they slaughter at their homes. This is because a centralized slaughter place can bring more clients to the farmers and the farmers can bargain for a better producer price. Slaughtering livestock at an abattoir also means that other health related challenges can be monitored or avoided, e.g. carcass contamination by organisms such as salmonella (Arguello *et al.*, 2012). It must be pointed out that these facilities need to subscribe to high health and safety standards or else they will be breeding grounds for diseases (Botteldoorn *et al.*, 2003). The abattoir site can also be used as a hub for trading in live pigs. Social network analysis (SNA) revealed an extensive pig and pork trade and the more the interconnections there are in a SNA, the more difficult it will be to control diseases. It can, therefore, be argued that centralizing pig slaughter as well as live pig trade will benefit both the farmers and the veterinary department.

4.3 FUTURE DIRECTIONS AND RESEARCH NEEDS

Further research is recommended, thus exploring a larger number of warthog burrows to confirm the absence of ticks and potential antibodies against ASF and other diseases should be monitored in pigs and wild suids which are potentially exposed to ASF.

4.4 CONCLUSIONS

Serological tests on pigs did not reveal any evidence of the existence of ASF. However, the area is in danger of experiencing outbreaks of these diseases if action is not taken to reduce risk of disease introduction because there is evidence that wild suids, natural carriers of ASF, move from the park into communal areas. In addition, pig husbandry practices of the pig farmers increase the risk of disease transmission making controlling of these diseases difficult. Pigs are a valuable resource as they provide a source of income and protein for some of the poor within our society and it is the mandate of the provincial? veterinary department to ensure that this source of livelihoods is protected The veterinary department needs to engage the farmers more to ensure that they know the risks associated with their husbandry practices as well as what to do in the case of a disease outbreak. Furthermore, there is need for setting up a marketing strategy as well as routine training on how to maximise profits from their projects. This would also entail the opening up of abattoirs or accessible markets and eventually the development of a breeders' cooperative. Finally, disease monitoring and surveillance must be conducted periodically in a participatory approach, both in the communal areas as well as the neighbouring game reserve.

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