EFFECTIVE CONTACT OF CATTLE AND FERAL SWINE FACILITATING POTENTIAL FOOT-AND-MOUTH DISEASE VIRUS TRANSMISSION IN SOUTHERN TEXAS, USA, RANGELAND

A Thesis

by

GUADALUPE R. DE LA GARZA, III

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2007

Major Subject: Wildlife and Fisheries Sciences

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Approved by:

Co-Chairs of Committee,	Susan M. Cooper H. Morgan Scott
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ABSTRACT

Effective Contact of Cattle and Feral Swine Facilitating Potential Foot-and-Mouth
Disease Virus Transmission in Southern Texas, USA, Rangeland. (May 2007)

Guadalupe R. de la Garza, III, B. S., Texas A&M University
Co-Chairs of Advisory Committee: Dr. Susan M. Cooper
Dr. H. Morgan Scott

The focus of this investigation was to address the vulnerability of rangeland animal agriculture in the United States (U.S.) to the introduction of agents of foreign animal diseases (FAD); particularly, foot-and-mouth disease virus (FMDv). I examined rates of inter- and intra-species contacts between domestic cattle and feral swine (*Sus scrofa*) on rangeland in southern Texas.

This study provides empirical data necessary for better epidemiological modeling of potential transfer of diseases between infected and susceptible rangeland animals. My objective was to estimate the rate of effective inter- and intra-species direct and indirect contact (i.e., animal contact that could result in effective disease agent transmission) as a function of time and space, relative to biological and ecological aspects of transmission. An extensive literature review of biological and ecological characteristics, conducive to effective contact that are sufficient to permit transmission of the infectious agent (Abbey 1952), was conducted. My objective was achieved through systematic data collection and analysis of empirical animal contact data recorded through use of animals fitted with global positioning system (GPS) radiotelemetry collars. Geospatial and temporally referenced inter- and intra-species contact data were analyzed using 1) basic descriptive statistics, 2) unadjusted inferential statistics, 3) stratified analysis, and 4) multivariable models.

My investigation produced results in accord with generally accepted notions in addition to significant findings that interestingly counter current preconceptions. Intra-species contact was more common than inter-species, with indirect contact occurring more frequently than direct. Direct contact between species occurred extremely rarely. The most important factors that influenced the rate of contact for both species were water, winter, and cultivated fields.

Information regarding probability of infectious agent survival and transfer will be used in the future to advance current epidemiological models, including geographic-automata (Ward et al. 2007: In Press) and cellular automata models (Doran and Laffan 2005) to better understand and manage integrated domestic cattle and free-ranging wildlife populations. Such modeling provides essential and necessary knowledge for developing prevention, detection, response, and recovery strategies – employed in advance, during, and after a disease outbreak, respectively.

DEDICATION

I dedicate this to my ever-supportive and loving family, who have been there when they were needed most. Each individual continues to offer unique interpersonal gifts that touch me (and others) in various stages of life's journey. I also dedicate this to my graduate advisory committee co-chairs and members – whom I behold with utmost regard – that through their continued support, guidance, and faith in me has made this final product possible. I will never forget all those who have helped in my professional and personal development, all work effort past and present involved in its completion is dedicated to you.

ACKNOWLEDGEMENTS

Sincere gratitude is extended to all those who have assisted and guided me through each aspect of this thesis, namely my graduate advisory committee. Specific recognition to Dr. Susan M. Cooper, committee co-chair, and professional mentor for the past 3 years who has sacrificed her time and energy to make sure that I never lacked in support concerning professional or personal matters. Through you, I have gained valuable knowledge untaught by the academia system. I would also like to thank committee co-chair Dr. H. Morgan Scott for his sincere diligence and never-ending advisory capacity shown through work ethic, patience, and perseverance. This was most evident as he continually overcame obstacles relating to the difficulties in remote collaboration largely in part of the meticulous methodology, data analysis, and its interpretation. Through his years of experience (and magnitude of student-advisor exposure), Dr. Roel R. Lopez has nearly perfected the science of guiding graduate students to success. He provided local guidance through coursework; departmental procedure, academic requirements, and most importantly established a personal bond. This opportunity was originally made possible by Dr. James C. Cathey, who having determined I was a qualified and likely candidate to undertake this study, convinced me to change careers and return to academia. I owe him many thanks as he originally had the faith in me as a student 3 years ago, and I hope that with this thesis completion I proved worthy to gain and keep his faith.

I commend the thorough efforts and assistance of research personnel: Shane Sieckienus, Lang Alford, Andrea Wappel, and fellow graduate student Aubrey L. Deck, for all their hard work in assisting in the field-data collection, and its post-processing.

Their assistance was invaluable and timely as the field portion of the study was conducted 5 hours from campus. Additionally I would like to thank all professors, staff, and fellow students who contributed to my learning and development during the course of the campus and field work.

I also thank all those associated with the Hispanic Leadership Program in Agriculture and Natural Resources for the opportunity to continue my educational pursuits. I especially thank Dr. Manuel Piña, Jr., for his continued support while quietly (and at times not so quietly) overseen my graduate career and encouraged me to take on all challenges along the way.

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INTRODUCTION

Justification

Presently, knowledge regarding effective methods for controlling accidental or intentional introduction of foreign animal diseases (FADs) into the United States (U.S.) is limited by our lack of direct field experience with many of the agents, and a less-than-thorough understanding of all potential host behaviors. This increases vulnerability and uncertainty pertaining to the risk of natural and deliberate disease threats. Introduction of infectious agents of bioterrorism raises global concerns. However, increasing international trade in animals and animal products, tourism, and immigration suggests accidental incursion to be a more probable means of foreign animal disease (FAD) agent incursion (Waldrup and Conger 2002). Human error, negligence, or failure to adhere to biosecurity protocols are possible channels of accidental emergence (England 2002). In the event of disease introduction, a lack of appropriate response infrastructure could lead to large-scale disruption of agricultural and wildlife industries (Franz 1999, Logan-Henfrey 2000, Thomson et al. 2003). Ramifications include extensive local, regional, and national economic losses resulting from domestic and international trade reduction and the concomitant social disruption caused by extensive job losses in agriculture, ranching, and related industries (Hutber and Kitching 2000, Bates et al. 2001, Donaldson et al. 2001, Blancou and Pearson 2003). Recent world events have elevated U.S.

This thesis follows the style of The Journal of Wildlife Management.

agricultural security concerns regarding zoonotic threats (Brown and Slenning 1996, Schoenbaum and Disney 2003), and these concerns must be addressed now.

For this study, I selected foot-and-mouth disease virus (FMDv) as the agent of interest, based on reports of the Office International des Épizooties (OIE). The OIE manages and disseminates animal disease information to 167 member countries. Given the disastrous impact that foot-and-mouth disease (FMD) has on agriculture and wildlife industries worldwide, this disease ranked first on the OIE "List A" of diseases (Office International des Épizooties 2004). In 2004, the OIE merged international threatening diseases List A and List B into a comprehensive list defined collectively as: 1) "transmissible diseases that have the potential for very serious and rapid spread, irrespective of national borders," and 2) "they have particularly serious socio-economic or public health consequences and are of major importance in the international trade of animals and animal products" (Office International des Épizooties 2005). Based on a 1997 FMD outbreak in Taiwan, where approximately 4 million hogs were slaughtered, estimates of economic impacts associated with an FMD epidemic in the U.S. would be in the range of $7 billion in agricultural losses (Brown 1999) and $1.6 billion in lost export trade (Knowles et al. 2005). Estimated costs of disease control (e.g., disinfection, carcass disposal) approach an additional $378.6 million (Knowles et al. 2005).

Foot-and-mouth disease. Also known as aphthous fever and dubbed hoof-and-mouth disease or foot-and-mouth disease is one of the most contagious diseases of cloven-hoofed animals (Alexandersen et al. 2001, Meyer and Knudsen 2001). This includes, but is not limited to members of Bovidae, Suidae, Cervidae, and Camelidae families. In countries where it is endemic, FMD is difficult to eradicate because it is often present in nonclinical (asymptomatic) animals (Samuel and Knowles 2001). The name of the disease derives from clinical signs including formation of vesicles or blisters near the oral mucosa and on coronary bands of the lower extremities. Foot-and-mouth disease virus is of the family Picornaviridae, genus *Apthovirus,* and is further classified into 7 distinct serotypes: A, O, C, Asia 1, and SAT1–3. All serotypes are resistant to a wide range of environmental conditions. Temperatures below freezing can preserve FMDv. Conversely, the virus does not survive well when environmental temperatures exceed 50° C (Meyer and Knudsen 2001, Thomson et al. 2001, Office International des Épizooties 2004).

Transmission from infected to susceptible animals occurs via effective direct contact (DC) or effective indirect contact (IC, Figure 1). Direct contact involves immediate physical or excretory contact from animal-to-animal. Indirect contact involves transmission via aerosol, soil, water, other fomites (i.e., objects or substances facilitating transmission), or animal byproducts; and usually is associated with a lag time (Meyer and Knudsen 2001, Thomson et al. 2001). Effective contact – that instance where susceptible individuals have a high probability of becoming infected cases (Fine 1977) – is qualified by 3 parameters described in Sellers (1971). Probability of viral transmission is enhanced by: “1) the amounts of virus given out by the infected animal; 2) the survival of virus outside the animal; and 3) the amount of virus required to set up disease in the susceptible animal” (Sellers 1971:431).

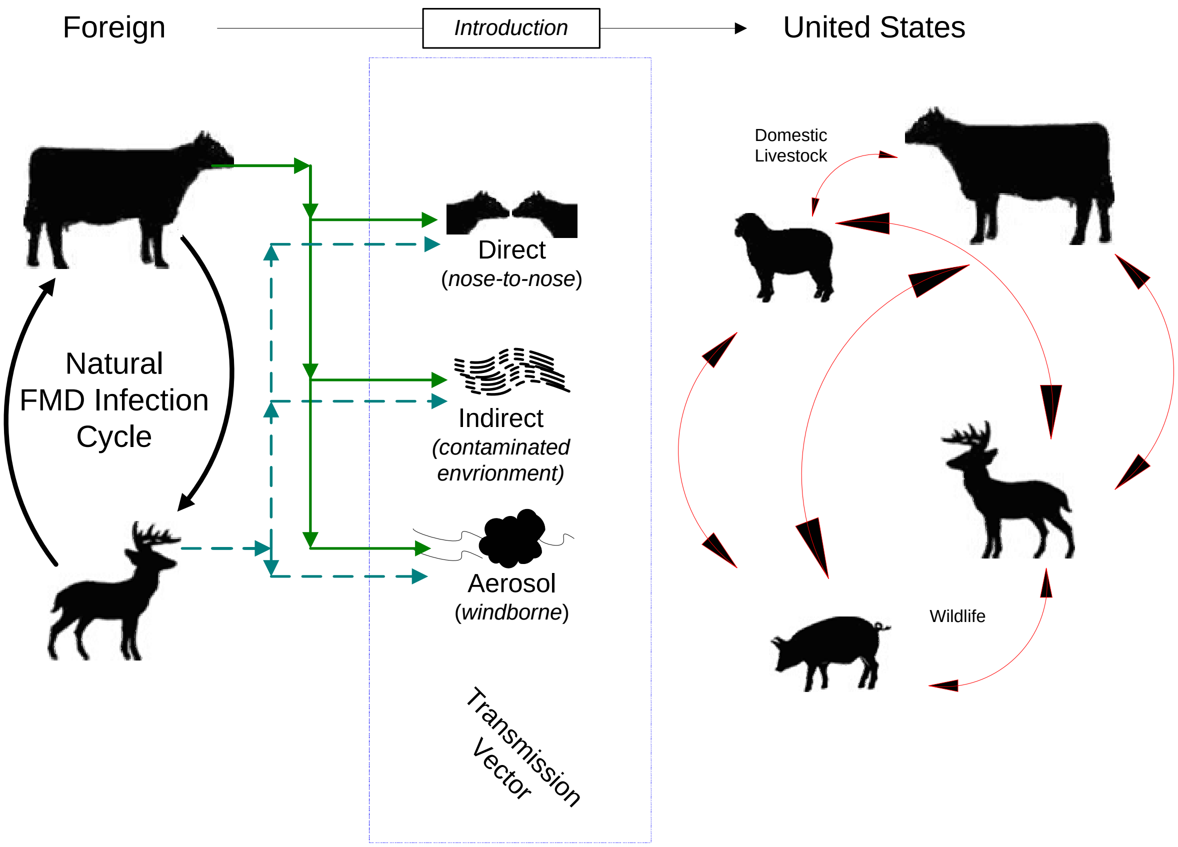


Figure 1. Potential foot-and-mouth disease virus transmission route into the U.S. via effective contact as investigated between domestic cattle and feral swine on rangeland in southern Texas, USA, 2004–2006.

Historically, most FMD outbreaks have occurred in areas where susceptible wildlife species were assumed to be scarce. In cases involving both livestock and wildlife populations, immediate depopulation effectively removes FMDv (Thomson et al. 2001), though it is often difficult to accomplish. The U.S. has been FMD-free since its eradication following the last recorded incursion in 1929. Behavior dynamics (e.g., movement, foraging, habitat requirements) among managed livestock and unrestricted wildlife such as feral swine populations underscore the complexity of managing disease outbreaks. To the best of my knowledge, an epidemiological model conceptualized on a porous system (i.e., unrestricted feral swine movement in or out of locality) and adequately designed and parameterized to address my system of interest has not been published in the peer-reviewed literature. A recently conducted study by Ward et al. (2007: In Press) investigating potential geographic and quantitative spread of FMDv by feral swine and wild white-tailed deer (*Odocoileus virginianus*) to cattle among the South Texas Plains ecological region presented theoretical estimates of infected cattle cases and associated infected area. Both geographic spread and quantitative infection estimates were based on hypothetical assumptions of incursion sites (i.e., location of infectious contact) and neighborhood interactions between herds (i.e., inter- and intra-species contact). Specifically their model was grounded on assumptions including: 1) density estimates were derived from regional- or county-level ecological site carrying capacity datasets, 2) inter- and intra-species contact estimates were homogeneous (i.e., likelihood of inter- and intra-species contact was equal for wildlife and cattle), and 3) wildlife home range estimates were set at an equal maximum. Their methodology discussion and use of estimates as model input stresses the need to incorporate empirical livestock and wildlife land use and contact data as appropriate modeling components.

Feral swine as a host. Studies examining FMDv transmission via inter- and intra-species contact often fail to emphasize wild or feral species as potential carriers, reservoirs, or primary agents of infection (Bates et al. 2001). As a result, there is limited knowledge concerning the potential effects of FMDv following introduction into feral swine populations capable of interaction with domestic livestock (Doran and Laffan 2005). My research addresses this gap in knowledge by examining direct and indirect inter- and intra-species contact among integrated populations of domestic livestock (cattle in this case) and feral swine. I believe the population of feral swine in the southern U.S. (particularly along the Texas-Mexico border) represents a potential reservoir of infection as they are known to be a potent amplifier species for FMDv (Sellers 1971, Thomson et al. 2001). An infectious outbreak harbored by wildlife could be devastating to local and regional economies if an FAD agent such as FMDv were introduced. The virus has the potential to spread rapidly among feral swine for an extended period before being detected; first causing a widespread epidemic, then followed by an intractable period of endemicity in a host species that is virtually impossible to eradicate (Thomson et al. 2003). I hypothesize that the foraging, rooting, and habitat selection behaviors and gregarious nature of feral swine (Bratton 1975, Coblentz and Baber 1987, Coblentz and Bouska 2004), often result in close interaction with livestock. Once introduced into a feral swine population, aspects of viral spread that might pose considerable challenges to eradication efforts include:

1. Obscured presence of an infectious disease outbreak;
2. Lack of knowledge regarding the movement of infected animals;
3. Unknown inter- and intra-species contact rates with associated animal populations;
4. Difficulty in tracking or depopulating feral swine populations due to their utilization of dense or inaccessible habitats (Graves 1984, Gabor et al. 1999).

I examined integrated grazing cattle (i.e., cow-calf pairs) and feral swine (i.e., boars, sows, and shoats) populations, within the southern Texas landscape.

Exploratory study. A 60-day (21 Jul–19 Sep) trial season was conducted in the summer of 2004 in order to collect preliminary data and field-test equipment and procedures. Conducted on the same site as my the research described in this manuscript, this study involved 4 cows and 8 feral hogs fitted with GPS collars to explore actual, as opposed to advertised, battery life of equipment and evaluate study design and protocol. I modified the study design to maximize the spatial distribution of animals and plan effective sample sizes. Four cattle (model L400) and 8 swine (model L200) GPS radiotelemetry collars manufactured by BlueSky Telemetry™ Limited (Edinburgh, Scotland) were used. This equipment featured Wide Area Augmentation System (WAAS) and European Geostationary Navigation Overlay Service (EGNOS) provided mean differential correction accuracy to ±5 m (Hulbert and French 2001). Collar fastenings required modification for field conditions in order to secure them to the sampled animals. Supplementary very-high-frequency (VHF) beacons mounted on all collars provided tracking at approximately ≤1 km and improved collar retrieval efficiency. Effective collar battery life was 10 weeks and 2 weeks for cattle and swine, respectively. Extreme environmental conditions (≥40° C) caused the alkaline batteries to fail and radiotelemetry frequencies to drift. This resulted in tracking difficulty and loss of data. Manufacturer-supplied remote drop-off mechanisms used during the exploratory study did not withstand field conditions.

Empirical data collected during the pilot study suggested a mean of 60% and 99% success in acquiring GPS position fixes for swine and cattle, respectively. For exploratory purposes, (i.e., to establish general parameters used in future investigation), any 2 collared animals interacting within 10 m and 15 min illustrated DC. I defined IC as 2 collared animal interaction within 10 m within 24 hr. Interactions within 50 m and 15 min defined close inter-species interaction. Associated contact rates (rt), calculated as number of contacts/number of hog-days ($n = 14$) respective of season were reported (Deck 2006). (My present research methodology varies substantially from those described in the exploratory study. See Methods). In a 2-week feral hog tracking trial, total DC and IC yielded: direct swine-to-cattle = 0 (rt = 0) and indirect swine-to-cattle = 19 (rt = 1.36). We recorded 7 (rt = 0.5) close swine-to-cattle interactions (Deck 2006). For future studies, I recommend increasing sample size and replicating the research utilizing the varied landscape available on the study site. Knowledge gained from the exploratory study will aid in preparation for future studies when similar equipment and procedures are used.

Research objective

I investigated parameters describing effective contact as a mathematical function of time, space, and the other biological and ecological characteristics of epidemiologic interest. This was accomplished by conducting an extensive critical review of literature relevant to rates of effective DC and IC (i.e., sufficient to transmit FMDv infection) – as it relates to – biological characteristics relative to inter- and intra-species contact of the host– domestic cattle and feral swine, the agent– FMDv, and environmental conditions in southern Texas rangeland. Findings promoted my understanding and thereafter allowed for evaluation of the transmission system depicted by the agent-host-environment triad of epidemiology (Koopman 1998). This resulted in the appropriate evaluation of geospatial data to estimate rate of effective inter- and intra-species contact between domestic cattle and feral swine as a function of time and space.

Working hypothesis. I hypothesized that the rate of effective inter- and intra-species contact between domestic cattle and feral swine varied within the study site ranch over time according to factors such as: 1) contact type (e.g., DC, IC), 2) spatial and temporal disparity, 3) ecosystem class (e.g., grassland, brushland, riparian), 4) anthropogenic effects (e.g., roads, stock ponds, cultivated field), and 5) seasonal climatic conditions.

METHODS

Study area

Regional description. Proximity to international seaports (i.e., throughout the Gulf of Mexico), prolific numbers of feral swine, other wildlife and cattle, and an international border with Mexico warranted the designation of southern Texas as the study area (Figure 2). Regionally, there is increased risk of infectious agent introduction, or agro-terrorists, originating from countries outside the U.S. (England 2002, Waldrup and Conger 2002). A ranch in Zavala County was chose as the study site. This area has historic large-scale cattle ranching operations, abundant wildlife, a hunting industry, and a recent increase in feral swine abundance (Synatzske 1993, Texas Parks and Wildlife 2006). Located in the South Texas Plains ecological region (Griffith et al. 2004), the ranch has common biotic characteristics, and its subtropical climate is characterized by mild winters and hot summers with mean upper and lower temperatures of 18.7 and 6.1° C in January and 31.4 and 22.0° C in July, respectively. The region has gently rolling topography (154–213 m above sea level). Mean annual precipitation is 55 cm (National Weather Service 2005). In agreement with standard research policy, I protected the identity of the participating ranch. Personal identities or ranch identifiers did not appear in any database, manuscript, publication, or report which directly linked to ranch or owner name. In replicating the study among different pastures throughout the ranch, I examined effects of differential locale-specific components on contact between domestic cattle and feral swine.

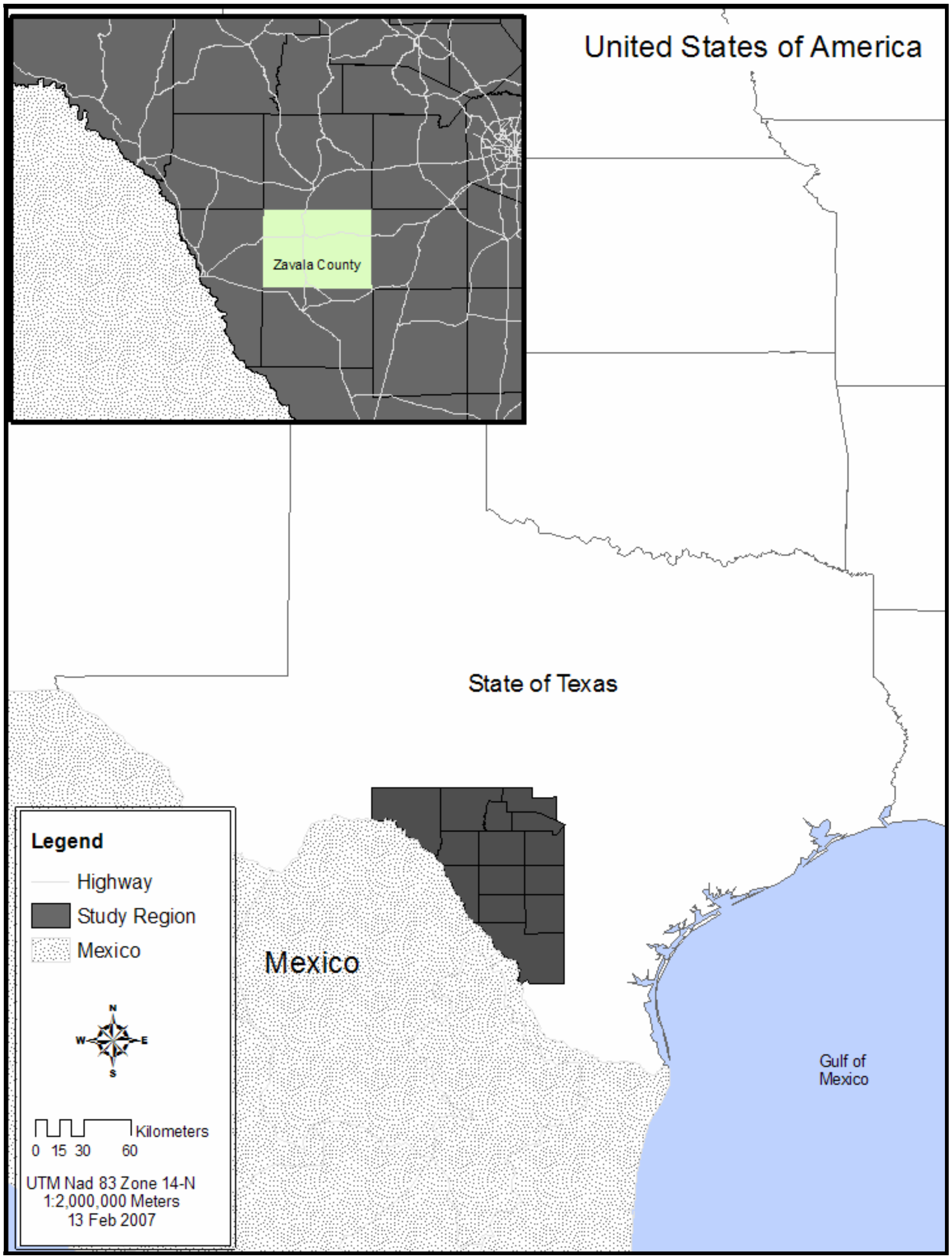


Figure 2. Map of study region, southern Texas, where research was conducted in 2004–2006 to investigate foot-and-mouth disease virus transmission via effective contact between domestic cattle and feral swine on rangeland in southern Texas, USA.

Vegetative composition. The study ranch measures approximately 35,000 ha (mainly low-fenced, but partially high-fenced on the western and southern boundaries) and comprised of mixed semi-arid brushland vegetation including native and introduced grasses, woody species, and dense riparian areas. Improved rangeland is predominately composed of King Ranch bluestem (*Bothriochloa ischaemum*), common buffelgrass (*Cenchruss ciliaris*), common bermudagrass (*Cynodon dactylon*), sideoats grama (*Bouteloua curtipendula*), and brownseed paspulam (*Paspalum plicatulum*). Woody species such as live oak (*Quercus virginiana*) and Texas persimmon (*Diospyros texana*) are common among dense riparian areas, while retama (*Parkinsonia aculeate*) is found adjacent to stock ponds. Dominate woody acacia plants include huisache (*Acacia smallii*), guajillo (*A. berlandieri*), and blackbrush (*A. rigidula*). Other semi-arid brush species such as honey mesquite (*Prosopis glandulosa*), spiny hackberry (*Celtis pallida*), whitebrush (*Aloysia gratissima*), guayacan (*Guaiacum angustifolium*), and various cacti (*Opuntia* spp.) also thrive on this ranch.

Wildlife and livestock composition. Game species managed for hunting include white-tailed deer, northern bobwhite (*Colinus virginianus*), mourning dove (*Zenaida macroura*), Rio Grande turkey (*Meleagris gallapavo*), collared peccary (*Tayassu tajacu*), and some waterfowl. Non-game species include feral swine, bobcat (*Lynx rufus*), coyote (*Canis latrans*), and occasionally mountain lion (*Felis concolor*). Annually, the ranch stocks 12 herds (approx 1,000 cows and 7,000 stocker cattle) which are proportionally subdivided and rotated for grazing. In addition, the ranch operates 13 center-pivot irrigation (CPI) systems in cultivated fields. Water bodies include numerous stock ponds and 2 intermittent creeks.

Study design

Literature review. I conducted a targeted and critical review of literature relevant to FMDv, with a refined focus on domestic cattle and feral swine, and the local environment, in order to delineate the range of biophysical parameters necessary for effective contact to occur. This established suitable parameters associated with FMDv transmission system, specifically relating to the agent-host-environment triad of epidemiology (Koopman 1998).

Epidemiology. I defined the transmission system elements as: 1) agent = FMDv; 2) host = an integrated population of infected and susceptible domestic cattle or feral swine collectively; and 3) environment = current climatic conditions representative of study area and its potential fomites (e.g., air, soil, water, vegetation, and feed). Hourly climatological conditions were collected from area weather stations. Specifically, I investigated transmission system requirements necessary for effective DC and IC for potential FMDv transmission relative to spatial and temporal variability between domestic cattle and feral swine interaction on rangeland in southern Texas. Foot-and-mouth-disease virus transmission requirements include: 1) variable host species viral shedding, 2) proximity, and 3) decay period of extra-host viral infectivity (dependent upon: ambient temperature, humidity, and suitable fomites or other inter-transmissive media ([Sellers 1971, Thomson et al. 2001]). For analysis and modeling purposes I defined DC as occurring <20 m and within 15 min and IC as occurring <20 m and within

360 min. These critical parameters were based on GPS collar accuracy (Hulbert and French 2001) and virus survival (Cottral 1969, Pirtle and Beran 1991, Bartley et al. 2002) findings from the literature review combined with regional climate averages. I used 20 m as the effective contact parameter as it is the minimum combined spatial resolution of 2 GPS-collared animals (based on ± 5 m radius accuracy for each, Hulbert and French 2001).

Regional context. Given the historical nature of FMDv, most empirical and field-based literature is international (i.e., foreign to U.S. territories). The domestic literature is largely laboratory-based. Therefore, I applied the laboratory and foreign-sourced information gathered from the FMDv literature review to biological and behavioral specifics of domestic cattle and feral swine indigenous to the climate and landscapes of the southern Texas study region. Sufficient published biological and ecological data specific to this region is available for both host species sampled in this study (Hellgren 1993; Ilse and Hellgren 1995*a*, *b*; Taylor and Hellgren 1998; Deck 2006). Observation of domestic cattle and feral swine was documented while conducting field research.

Project schedule. To accurately estimate inter- and intra-species DC and IC across a range of landscapes within the clearly defined study region, I intensively tracked concurrent movements of a geographically stratified sample of domestic cattle and feral swine over a 25-month (Jul 2004–Jul 2006) period as follows. Three annual field trials were divided into 4 seasons based on climatic conditions of temperature and precipitation (fall: Sep–Nov, winter: Dec–Feb, spring: Mar–May, and summer: Jun–

Aug). Ranching operations (e.g., cattle grazing schema, and hunting seasons) limited field operations; therefore not all seasons were sampled each year. Each of 8 field (or study) seasons, (A–H) varied in the number of trapping and tracking trials based on feral swine trapping success.

Sampling technique. All trapping, handling, and subsequent animal use followed guidelines established in an approved animal use protocol (Texas A&M University Laboratory Animal Care and Use Committee Animal Use Protocol 2002-380/2005-281, see Appendix, A1). In each season, I randomly sampled 3–4 cows and 2–10 feral hogs. Sample quantities were dependent on available equipment (i.e., their retrieval) and feral swine trapping success. I defined the experimental unit (i.e., smallest replicated independent sample) as each collared animal, in each respective field season. Failure to retrieve feral swine collars by re-trapping or through use of remote drop-off mechanisms necessitated harvesting of feral swine with firearms in order to retrieve data. Each season was set in different pastures; therefore, limited harvesting during the previous season(s) did not affect the population of the next feral swine cohort. Feral swine tracking periods were approximately 4 weeks, and allowed for collar retrieval before beacon batteries expired.

Following the initial exploratory study, I acquired 3 new GPS radiotelemetry hog collars (same model), manufactured by BlueSky Telemetry Limited, thus replacing previously damaged and malfunctioning units. After field-testing, I learned the new models were more reliable in data collection. They also featured extended battery life (4 weeks). Two cattle (model GPS_3300LR) and 2 swine (model GPS_3300S) GPS radiotelemetry collars manufactured by Lotek® Wireless Incorporated (Newmarket, Ontario, Canada) also were purchased. The Lotek collar models featured a rechargeable battery and remote drop-off mechanism capable of withstanding the harsh field conditions of southern Texas. Lotek drop-offs were purchased and refitted for use on the BlueSky collars. In-field Lotek collar battery duration was 10 weeks and 4 weeks for cattle and swine models, respectively. All animal collars stored data onboard and required retrieval for downloading. BlueSky collars featured internal differential correction accurate to ±5m (Hulbert and French 2001). Lotek collars required post-processing differential correction with Program N4 (Lotek Wireless Inc., Newmarket, Ontario, Canada; Moen et al. 1997). Collar programming, run-time setting, uploading, and deployment were conducted via interface (DataTrax™ by BlueSky Telemetry or GPS Host by Lotek Wireless Inc.). Upon deployment, collars recorded a location (i.e., GPS fix) every 15 min. To reduce animal stress and handling time I pre-initialized collars prior to attaching to animals.

Cattle sampling. Before the trapping period for each season, ranch personnel assisted in herding sample cattle into a corral. Squeeze chutes safely restrained cattle subjects while a GPS with VHF-ultra high frequency (UHF) beacon-mounted collar was secured and deployed on each randomly selected cow (representing different herd sub-units). Total chute containment time was approximately 2 min as collars were pre-initialized. I recorded pasture, date, physical description, ear tag identifier, and collar unit code on pre-designed field sheets. After collaring, cattle were immediately returned to the destination pasture for the duration of the season.

Feral swine sampling. Two weeks prior to working cattle when feral swine trapping commences in an area, traps were strategically placed in areas feral swine were likely to frequent. These areas included sites containing feral swine sign (e.g., tracks, scat, rooting, or visual observation) water bodies, and riparian areas often adjacent to dense brush cover. I used 3 corral traps and 3 box traps during the study. Circular corral traps were built on site for each season. They consisted of 2 galvanized stock panels (6.10 m × 1.22 m) secured to 6 T-posts (1.83 m) driven down approximately 0.5 m, and 1 steel gate mounted to a wood post (1.83 m) buried approximately 0.5 m. The spring-hinged gate would shut as animals disturb a trip cord within the corral. Absence of a roof allowed non-target animals (e.g., deer, wild turkey) to escape. A smaller, portable, and more robust design was the box trap. Box traps allowed easier animal containment facilitating less potential for injury during handling. They measured 1.22 m × 1.22 m × 2.44 m, and triggered either a guillotine-type door or a spring-loaded gate. Prior to collaring cattle, the feral swine trap vicinity was be pre-baited with shelled corn (bulk purchased) to establish visitation. During the trapping phase a combination of shelled corn, fruit and vegetables, and sour corn (fermented for approx 1 week) was used.

Traps were checked once daily (7 d/week) early in the morning. While checking traps, I recorded date, trap number or location, trap status (i.e., triggered or not triggered), bait type, animal sign, and whether or not trap was set. I documented and released non-target species. For trapped targeted animals; sex, approximate weight and age, standard morphometric measurements, distinguishing characteristics, collar unit and ear tag identifiers were recorded on pre-designed field sheets. One hog tissue sample/individual notched from the left ear was collected for subsequent pathology investigation (not investigated in this study). Care was taken to ensure that collars were not placed on any animal previously sampled in the study. Manageable feral swine were held with a cable noose on a catchpole, secured with rope, blindfolded, and manually pinned in a lateral position, thereby reducing animal activity, stress, and risk of injury. Once restrained in this manner, feral swine generally remained submissive throughout the collaring process. Field studies reported that drugs such as ketamine and xylazine impede temperature regulation in feral swine (Ilse and Hellgren 1995*a*, Gabor et al. 1997), and were only used to immobilize large and dangerous animals. In this event Telazol® (tiletamine hydrochloride and zolazepam hydrochloride; A.H. Robins Company, Richmond, VA, USA) administered intramuscularly at a dosage of 1 mg/kg by use of a pole syringe, was used. Once the GPS collar was secured, animals were photographed, ear tagged for future identification, and released. If heat stress was apparent, we administered Banamine® (flunixin megalumine, Schering Plough Animal Health, Kenilworth NJ, USA) intramuscularly at 1 mg/kg prior to release.

Radiotelemetry tracking. I tracked animals via radiotelemetry using a multi-band receiver and a 3-element Yagi-Uda antenna for VHF-UHF beacon reception. Tracking of cattle constrained by pasture fencing occurred every 2 days, while tracking feral swine (movements unrestricted by porous fencing) occurred daily. I used a pickup truck or all-terrain vehicle (ATV) for ranch transportation. Animal location and approximate distance with respect to observer were recorded. These data were used to map general movement patterns and used in the event of drop-off failure, when harvest of feral swine was required for collar and data retrieval.

Analysis

Post-processing and data preparation. Geospatial data used in the study included: 1) digital vector features (e.g., ranch pasture boundaries, roads, fences, riparian zones, water bodies, and cultivated fields); 2) digital raster features (e.g., aerial photography); and 3) date- and-time-stamped point-files acquired from GPS collar receivers. Geospatial data were used to reference each animal location relative to: 1) other sampled individuals (at the same or at later times), 2) landscape class, and 3) anthropogenic features (e.g. roads, stock ponds, cultivated fields). Raw attribute data fields collected from each GPS-collared sample included: 1) collar identification; 2) longitude and latitude in decimal degrees; 3) date in day, month, and year; 4) time in hours, minutes, and seconds; and 5) temperature in centigrade. Data acquired from Lotek collar receivers required post-process differential correction. I imported raw data files downloaded from GPS collars into Microsoft Office Excel (Microsoft Corp., Redmond, Washington, USA) for further post-processing and preparation for analysis. I used the programming language Microsoft Office Excel Visual Basic® for Applications (VBA) extensively to systematically create custom programming scripts, which accurately manipulated raw data into the correctly organized, formatted, and cross-platform compatible form. This method was invaluable as all raw data required similar-to-exact post processing; therefore eliminating human-introduced error and mass reiteration. For consistency, all records of Daylight Savings Time (DST) were converted to Central Standard Time (CST, Thorsen 2007). Bonner et al. (2003) provided evidence that changing the projection to Universal Transverse Mercator (UTM) compensated for Earth curvature resulting in increased GPS accuracy. ArcGIS® version 9, featuring ArcMap™ version 9.1 and ArcObjects™ VBA (Environmental Systems Research Institute, Inc.®, Redlands, CA, USA), were used to re-project the coordinate system to geographic coordinate system = UTM and geodetic datum = North American Datum 1983 (NAD 83) Zone 14 North. An ArcObjects VBA script converted longitude and latitude coordinates (i.e., x = longitude, y = latitude) in decimal degrees into UTM (i.e., x = easting, y = northing) in meters. Formatted data file content of each sampled animal included the following data fields:

1. Animal identification code– denoted season, species, and species-record number;
2. Unique identification (UID)– uniquely identified each record/animal and season within entire study dataset;
3. Time– captured real-time stamp in hours, minutes, and seconds, CST;
4. Date– captured real-time stamp in day, month, and year, CST;
5. Date Time– concatenated date and time in 1 field;
6. Temperature– ambient temperature in centigrade;
7. X– easting position coordinate UTM in meters;
8. Y– northing positional coordinate in UTM in meters;
9. Animal Index– numeric expression of date-time stamp in serial format (i.e., number of days since 1 Jan 1900) × 1,000,000 combined with time as fraction of a day (i.e., time of day fraction × [24×60×60]). (For example, 28 Jul 2004 at 12:00:00 is

converted by [38196 × 1,000,000] + [0.5 × 24 × 60 × 60] and expressed as 38196043200.)

To ensure data integrity I conducted quality control checks while post processing. Regularly scheduled data backups safeguarded electronic information and were conducted prior to program execution.

Seasonal index. Due to collar inconsistencies, not all positional records were synchronized at exact ¼-hr fixes. Therefore, I created season indices that allocated positional records to a prescribed time-step rule of 15 min using the animal index field. These indices assigned all records using universal minimum (time-min. field) and maximum (time-max. field) time ranges allotted for each 15-min segment. Sub-hour minimum and maximum ranges were: 1) 00:00–14:59 (MIN:SECS), 2) 15:00–29:59, 3) 30:00–44:59, and 4) 45:00–59:59. Each day (1 day = 96 records) spanned from 00:00:00–23:59:59 (HR:MIN:SECS). The index consisted of time-minimum and time maximum fields. Each season index initiated at 00:00:00 on the first day of the earliest animal deployment, and terminated at 23:59:59 of the latest day of the last animal record. I removed surplus index records (i.e., occurring before and after earliest and latest animal deployment times). This methodology allowed only 1 positional record for each animal within each 15-min zone (consistent with my rule). In cases where >1 positional record was collected within a 15-min interval, the first recorded time point (entire record) was overwritten by any subsequent time point record(s) that met the 15-min period criteria. Each record was classified into day or night hours using average sunrise and sunset data (National Oceanic and Atmospheric Administration [NOAA] 2007).

Climatological data. Hourly observations of surface climatological data were obtained from 3 weather stations local to the study site: 1) La Salle County Airport, Cotulla, TX, 2) Del Rio International Airport, Del Rio, TX, and 3) Garner Field Airport, Uvalde, TX. Distance from study site to weather station was approximately 32 km to Uvalde and 145 km to Cotulla and Del Rio. Primary source of climatological data was Garner Field Airport due to its proximity. Missing observations from Garner Field were filled with La Salle County and Del Rio International airport data. These data are submitted to the U.S. NOAA for quality control and analysis; then published and archived by the U.S. National Climatic Data Center (NCDC). The following hourly climatic observations were replicated to produce 4 identical records (1 per ¼-hour) then appended to each respective seasonal index:

1. Wind direction– measured in a clockwise direction between true North and the direction from which the wind is blowing, in angular degrees;
2. Wind speed rate– rate of horizontal travel of air past at a fixed point, in meters/sec;
3. Air temperature– ambient air temperature, in centigrade;
4. Dew point– temperature to which air must be cooled at constant pressure and water vapor content in order for saturation to occur, in centigrade;
5. Liquid precipitation amount– measured liquid precipitation fall, in millimeters;
6. Relative humidity– ratio of the partial pressure of air water vapor to the saturated vapor pressure of water, in centigrade;

7. Weather station– identifier of each data source.

(NOAA 2005).

Animal record join. A program I designed in Microsoft Office Excel VBA subjected an entire seasonal dataset to the rule established by using the season index; resulting in a flat file of all records/animal/season listed in 15-min intervals. The program operated by searching each animal index field (date-time stamp) and when the value was >= time-minimum and <= time-maximum fields of the index, then that animal record was appended laterally to the index file. This enabled lateral comparison among all animal samples/season partitioned into unique 15-min intervals.

To calculate the occurrence of DC (that is, animal contact <20 m distance within 15 min), an animal-to-animal matching script written in Microsoft Office Excel VBA queried each animal-subject, animal 'A', (one/execution) of a season, then a second animal, animal 'B', with a communal 15-min indexed positional record was joined to the former. The process continued until all animals containing time-ordered records were appropriately matched, without duplicating a matched-pair. Likewise, pairing for IC estimates (that is, animal contact <20 m distance within 360 min) another animal-to-animal matching program was used to query the distance from time point 1, of animal 'A' (the record), to each of the subsequent time points for the contacted animal ('B') out to a maximum of 360 min for animal 'B'. The records were joined when any subsequent 15-min time period (up to 360 min) during which the minimum distance criterion of <20 m was met. Note that, by definition, a direct contact was also counted as an indirect contact. Future analyses (not the subject of this thesis) will incorporate abiotic (e.g., temperature, precipitation, humidity, soil type) and biotic (e.g., vegetative structure, landscape features) phenomena into a mathematical function to weigh exponential decay of virus survival incorporated into assessing the probability of effective DC and IC.

Spatial-temporal analysis. The smallest analysis unit was each matched pair of animals within 20 m and within 15 min (DC) or 360 min (IC). Records of the match-paired table at a date-time index value, constituted a positional fix for each animal where recorded. Euclidean distances between each set of paired animal records were calculated in Microsoft Office Excel VBA then imported into STATA version 9.2 (STATA Corp., College Station, TX) for further analysis and modeling. Distance calculation was similar to methodology presented in Bonner et al. 2003 as distance between each animal pair was determined by Euclidean length of the hypotenuse made at the right angle based on both GPS locations. Euclidean distance:

$$d = \sqrt{(X_1 - X_2)^2 + (Y_1 - Y_2)^2}$$

where X_1 represented X-UTM (easting) for animal 1, Y_1 represented Y-UTM (northing) for animal 1, X_2 represented X-UTM (easting) for animal 2, and Y_2 represented Y-UTM (northing) for animal 2 was calculated for each record accordingly. Resulting value was distance in meters.

Land-use modeling. Landscape features of the ranch were digitized using 2004 color infrared (CIR) digital orthorectifed quarter quadrants (DOQQ) at 1 m resolution (National Agriculture Imagery Program [NAIP]). Four classes of digitized landscape features included: 1) roads (all roads described in analysis and discussion are ranch roads) and fence lines, 2) riparian zones, 3) water bodies (creeks and stock ponds), and 4) cultivated field (irrigated and non-irrigated). Each feature was then buffered according to the following: 1) road and fence line coverage = 20 m either side of the line, 2) riparian coverage = 50 m either side of the center-line, 3) water = within 50 m of itself (including the polygon), and 4) cultivated field = the polygon itself (including boundary). A fifth class, open range, included everything that was not one of the 4 categories above. Ilse and Hellgren (1995*a, b*) conducted feral swine home-range survey studies in the local region using minimum convex polygon approaches (MCP). I used Hawth's Tools to calculate MCP in hectares for each animal (Beyer 2004). Using ArcGIS 9, I calculated seasonal pasture size, aggregate MCP of all animals collared/season, and percent area of each landscape feature relative to the aggregate MCP. In addition, I calculated differential land use (% GPS fixes in a given landscape) by species relative to the 4 buffered landscape types and open ranged which have potential for influencing inter- and intra-species contact.

Effective contact rate modeling. Based on knowledge of the transmission system gained from the literature, coupled with empirical data acquired from intensive tracking of concurrent animal movements, the relational impact of biophysical variables upon rate of inter- and intra-species DC and IC derived from spatial distribution was evaluated using a variety of analyses. Specifically these were 1) cow-cow, 2) hog-cow (and vice versa), and 3) hog-hog interactions for both IC and DC (the latter were reciprocal, the former were not). Rates were calculated using an estimated density of 0.038 feral hogs/ha (Gabor et al. 1999) on nearby rangeland and extended to estimate interactions at the population level on a per hectare per 15-min time period. Cattle stocking densities were provided for each season by the ranch administration. Relative rates (RRt) of inter- and intra-species DC and IC were estimated in STATA 9.2 as the antilog of the sum of the coefficients of the variables of interest, adjusted for all significant ($P < 0.05$).

I used estimated feral swine densities, known cattle stocking densities, and derived home range estimates using animal MCP. For stratified analysis, I investigated the effect that features of interest had (adjusted for hog vs. cow) on the rate at which each species was contacted / hectare per 15 min for each of 4 contact types across all study seasons. Relative rates were indexed to 1. That is, <1 = relatively less contact effect by feature and >1 = relatively more contact effect by feature, relative to all other features listed. These features included road, riparian zone, surface water, cultivated field, open range (landscape not falling within any above category), daytime (vs. nighttime), season (4 traditional) and hunting season (vs. not hunting season).

The stratification explicitly compared each feature against all others combined, while investigating the possibility for combining rate estimates of hog or cow contact (direct or indirect) for each of the recorded species (cow or hog). That is to say, if for example, a landscape feature increased probability of direct contact with a hog for both hogs and cows, a common estimate (Mantel-Haenszel relative rate) could be presented. If, on the other hand, there was a different effect of landscape on contact rate based on the contacting species, no common estimator would be presented.

Rates of DC and IC for all 4 contact types were further analyzed using 4 random-effects Poisson regression multivariable models of varying complexity. Poisson models are used for count (i.e., contact) data with either an exposure or offset variable. Typically, the exposure or offset is measured as a function of the number of individuals at risk and the exposure period is either implicitly or explicitly stated. For my study, I accounted for time, individuals, and representative landscape per individual MCP within the 'exposure' variable in the Poisson model. These models were developed in STATA 9.2. The multivariable model allowed for expanding the investigative and predictive dimensions first described while using stratified assessment of relative contact rates, adjusted for the contacting species (i.e., hog vs. cow).

The models were developed as follows. First, the importance of each independent variable was assessed in a simple relation with the dependent variable, while adjusted for species (hog vs. cow). Only those variables exhibiting a significant relation (using the likelihood ratio χ^2 test of significance at $P < 0.05$) were included in further analysis. There was one exception to this rule. Where stratified analyses (see above) indicated the potential for significant interaction effects of species with the independent (e.g., landscape) variable in question, those variables were forced into subsequent models, regardless of p-value. Next, all independent variables meeting selection criteria were introduced into a multivariable starting model. Then, a backwards elimination strategy was employed to remove either variables (1 degree of freedom [df]), or groups of indicator variables (*n* df) that were non-significant using the likelihood ratio χ^2 test of significance at $P < 0.05$, until a final main effects model remained. Then, interaction terms were constructed for the species variable as the product with each remaining independent variable and assessed as to their significance using the significance tests as noted above. The final model included main effects and significant interaction terms ($P < 0.05$). The Poisson model reflected counts (contacts) with an 'exposure' term constructed as the weighted number of hectares represented by the number of collared target animals proportional to the carrying capacity and MCP, every 15 min. The random-effect element accounted for serial dependence of location for each collared animal. That is, animals were more likely to be measured in the same location during each subsequent 15-min fix, than they were at non-time-adjacent fixes.

The estimated rate of contact (counts/ha every 15 min) was calculated as the antilog of the sum of the model coefficients for combinations of main effects and interaction terms of interest. Coefficient of contact (unique for each variable and volatile between models) was indexed to 0, where an increase from 0 illustrated an increase risk of contact. Relative rates of contact (RRt) for each contributing main effect (or groups of main effects and interaction term), adjusted for the presence of the other independent variables, may be calculated as the antilog (e^x) of the coefficient of any one variable, or the antilog of the sum of the coefficients of several variables (without including the intercept term), respectively.

Landscape features were equivalent to those used in the stratified analysis. Models varied by contact type (e.g. direct or indirect), contacted animal-term (e.g. cow or hog), independent variables, and their parameterization. Binary variables used in the models included species type, landscape feature, season, daytime, and hunting season (where the referents were the contrasting collection of modeled variables). The variable 'season' (defined as a 3-month period associated with climate) was not equivalent to study season (A–H) which was dependent on sampling dates. Temperature in Kelvin was the only continuous variable utilized. A single degree increase in Kelvin meant an increased relative rate of contact if the coefficient > 0 and a decreased rate if coefficient < 0. The models I used for this analysis were: 1) direct contact with a feral hog, 2) indirect contact with a feral hog, 3) direct contact with a cow, and 4) indirect contact with a cow.

RESULTS

Generalized descriptive statistics

Study description. Mean seasonal weather descriptive statistics were based on days/season. Mean ambient temperature was 22.5 °C (range = 0–41, SE = 2.1, Table 1). Mean relative humidity was 57.6% across all study seasons. The study began in a relatively wet year with a study maximum of 4.1 mm of rain during the first field season, and ended in a drought with a low season amount of 0.76 mm for the last season. Mean precipitation by season was 1.4 mm/day (SE = 0.4). Study pastures were designated as those accessible to collared cattle and differentiated by field season. Mean pasture size was 1,900 ha (SD = 1,964) and ranged from 948 ha (season H) to 3,882 ha (season G, Table 1). Feral swine were not restricted (as cattle), therefore landscape feature percentages usually extended outside the study pasture (Figure 3). Overlap of landscape features from season-to-season was not accounted for in the analysis. Mean road and riparian zone area were near equal at 11% (SD = 11) and 10% (SD = 9), respectively. Water (e.g., intermittent creeks and stock ponds) with mean seasonal area of 2% (SD = 2) and cultivated field at 5% (SD = 5) accounted for a smaller proportion of the landscape (Figures 4–11).

GPS collar operation and sampling. I used GPS radiotelemetry collars to track concurrent movements of 25 cows and 40 feral hogs (9 boars, 6 sows, 25 shoats) over 8 field seasons between July 2004–July 2006 (Tables 2–4). Feral hog classification was

Table 1. Weather and landscape elements describing conditions during 2004–2006 study to estimate inter- and intra-species direct and indirect contact for potential transmission of FMDv between cattle and feral swine on rangeland in southern Texas, USA.

Element	Summer 2004 A	Fall 2004 B	Winter 2004 C	Spring 2005 D	Summer 2005 E	Fall 2005 F	Winter 2005/6 G	Summer 2006 H
Weather[a]								
Temp (C)	27	20	16	25	27	13	22	30
Temp max (C)	38	33	31	37	41	33	39	39
Temp min (C)	16	3	0	8	10	2	1	20
Relative humidity %	69	76	16	67	61	53	61	58
Dew point (C)	20	15	9	17	18	2	12	19
Precipitation (mm/d)	4.1	1.31	1.72	0.71	0.73	0.97	0.98	0.76
Landscape								
Pasture size (ha)	1,383	2,418	2,556	994	1,958	1,059	3,882	948
Aggregate MCP (ha)	1,405	1,812	3,225	2,154	2,400	2,136	5,275	5,546
% area road[b]	12.24	12.42	11.81	10.86	10.83	11.99	10.39	10.35
% area riparian zone[b]	15.94	7.51	10.29	11.28	5.29	9.08	6.67	12.44
% area water[b]	3.49	2.15	2.23	4.13	1.92	1.08	1.91	1.97
% area cultivated field[b]	6.26	3.97	0.09	2.41	7.96	7.07	5.97	4.40

[a] Mean season weather variables pertinent to the survival of FMDv in the environment are based on the days in each season (= 64, SD = 8)

[b] % based on aggregate MCP area of cows + hogs

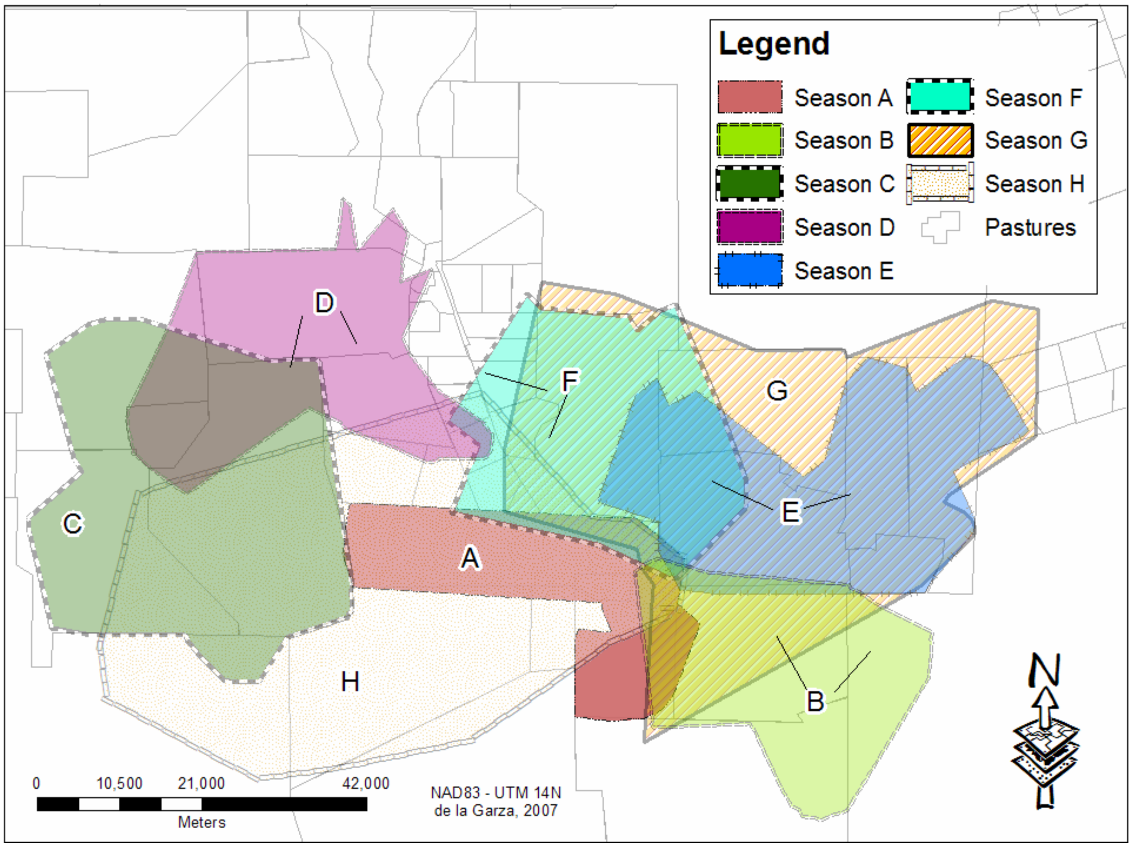
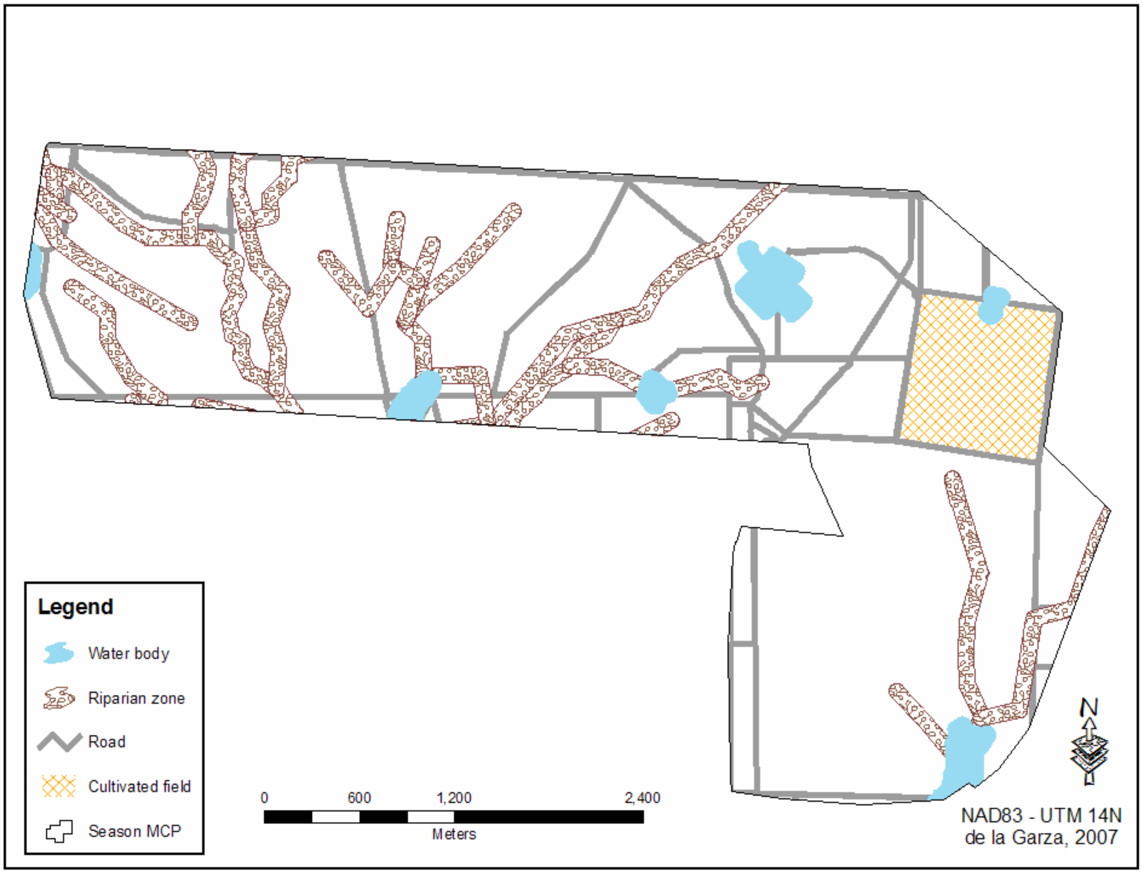
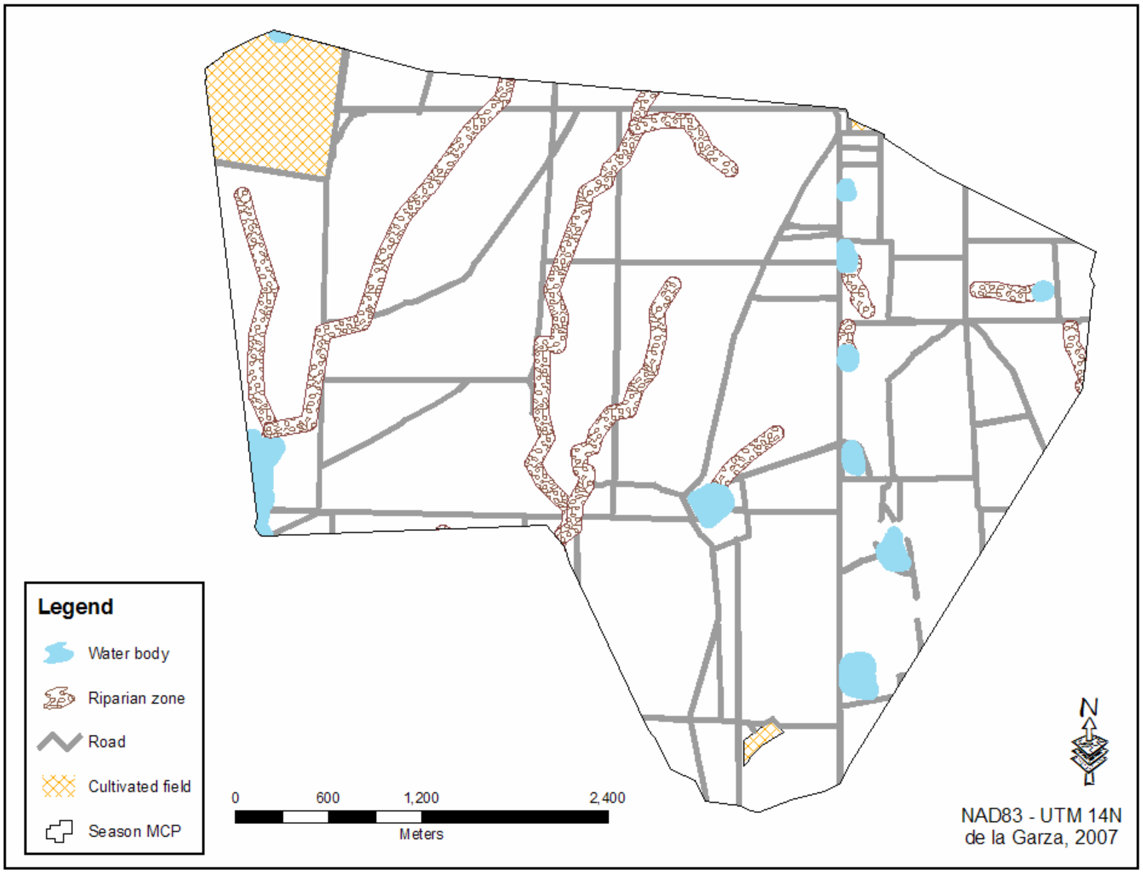


Figure 3. Seasonal overlap of aggregate minimum convex polygon (MCP for cows + hogs) in relation to study pastures for entire 2004–2006 study of effective contact rates on rangeland in southern Texas, USA.



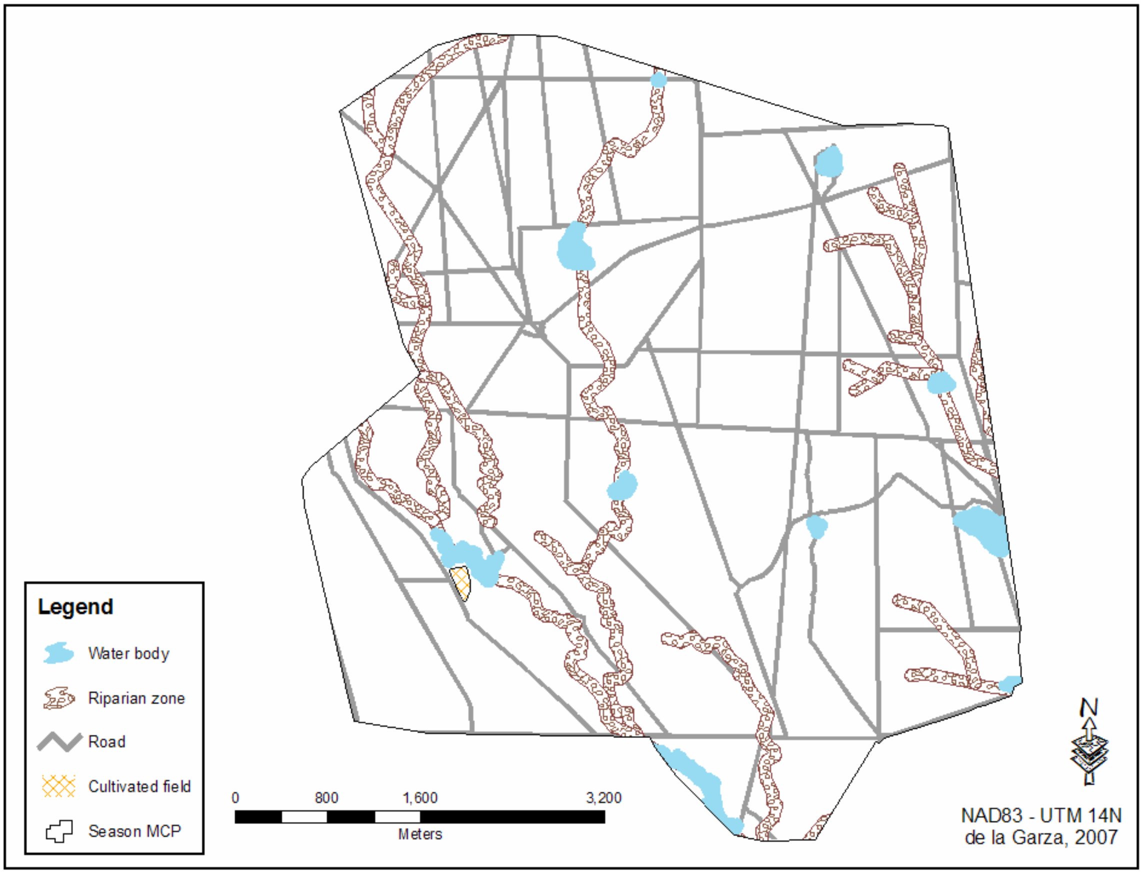
Note: Buffering scheme: 1) road and fence line coverage = 20 m either side of the line, 2) riparian coverage = 50 m either side of the center-line, 3) water = within 50 m (including the polygon) of itself, and 4) cultivated field = the polygon (including boundary). Area results (ha): aggregate MCP = 1,405, road = 172, riparian zone = 224, water body = 49, and cultivated field = 89.

Figure 4. Season A representative area illustrating maximum land use of collared cattle and feral swine aggregate minimum convex polygon (MCP) and descending overlay of buffered landscape features of interest: water body, riparian zone, road, and cultivated field; to investigate their effect on inter- and intra-species direct and indirect contact for potential transmission of FMDv on rangeland in southern Texas, USA, 2004–2006.



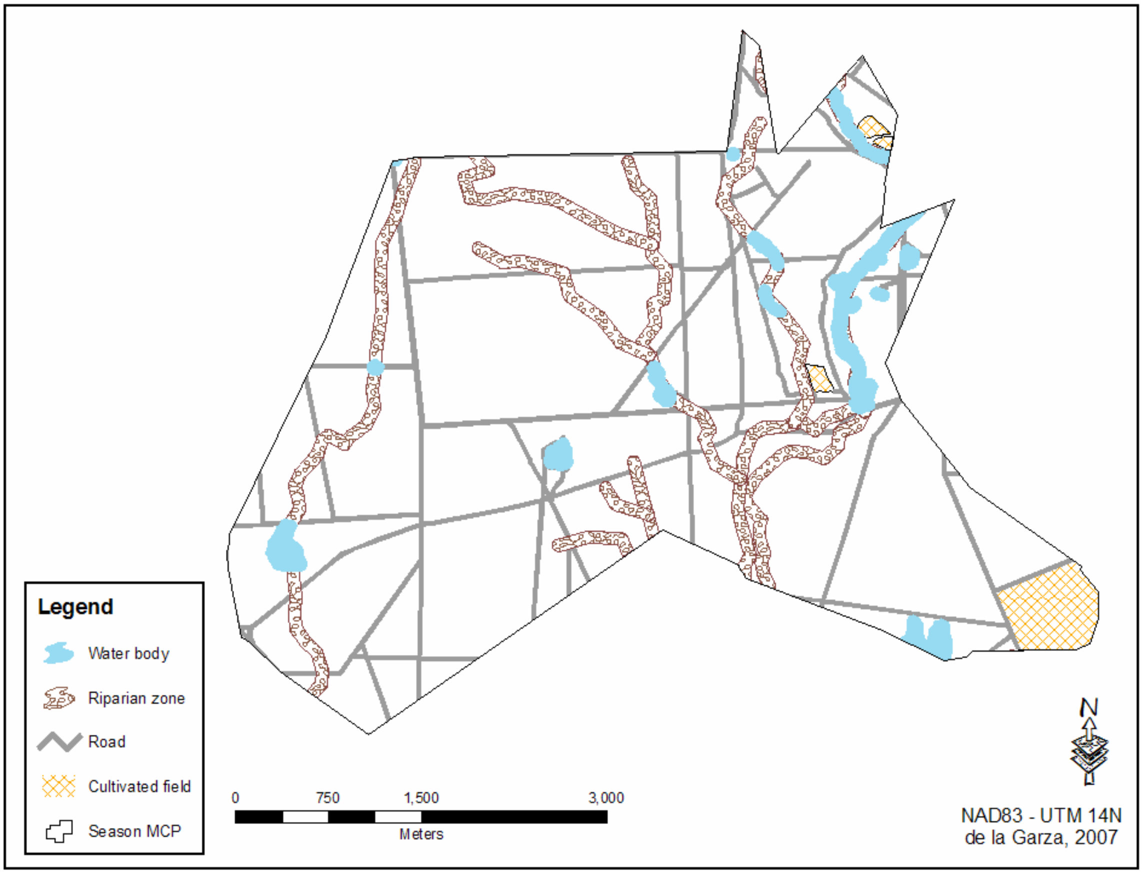
Note: Buffering scheme: 1) road and fence line coverage = 20 m either side of the line, 2) riparian coverage = 50 m either side of the center-line, 3) water = within 50 m (including the polygon) of itself, and 4) cultivated field = the polygon (including boundary). Area results (ha): aggregate MCP = 1,812, road = 225, riparian zone = 136, water body = 39, and cultivated field = 72.

Figure 5. Season B representative area illustrating maximum land use of collared cattle and feral swine aggregate minimum convex polygon (MCP) and descending overlay of buffered landscape features of interest: water body, riparian zone, road, and cultivated field; to investigate their effect on inter- and intra-species direct and indirect contact for potential transmission of FMDv on rangeland in southern Texas, USA, 2004–2006.



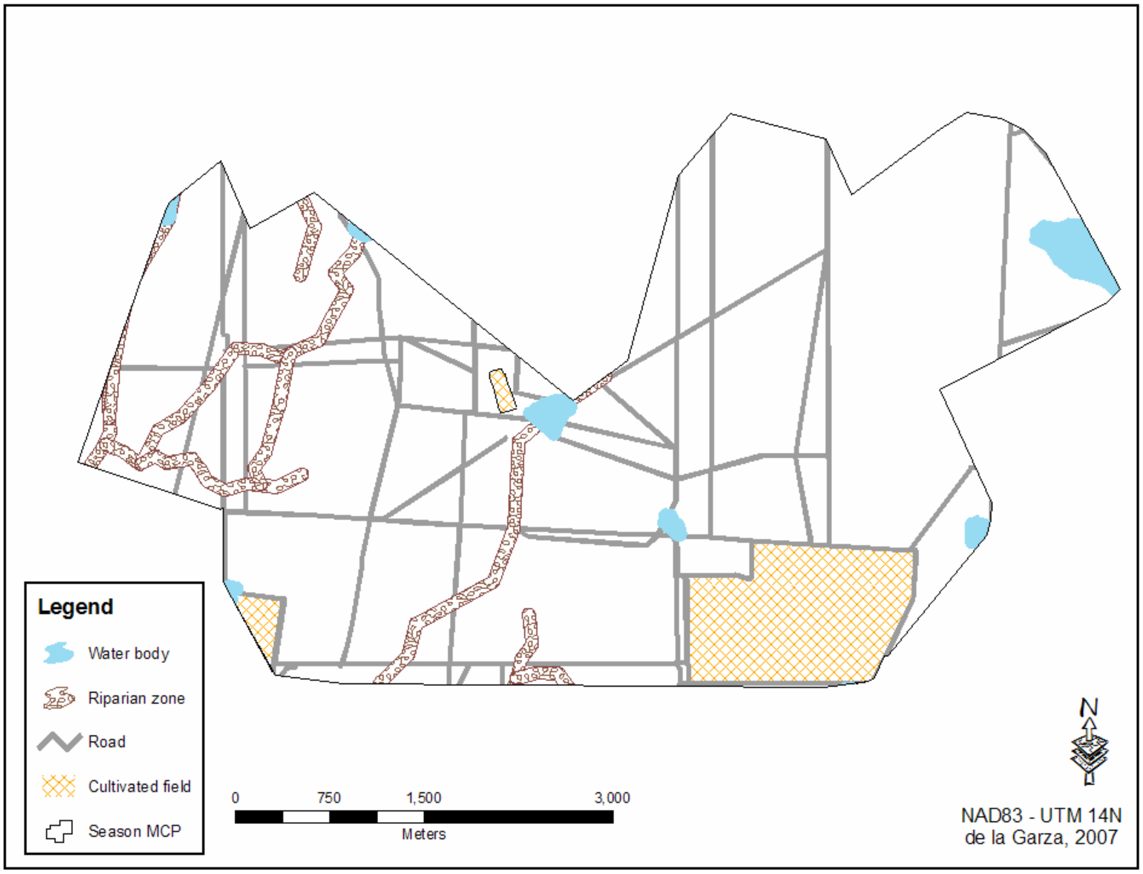
Note: Buffering scheme: 1) road and fence line coverage = 20 m either side of the line, 2) riparian coverage = 50 m either side of the center-line, 3) water = within 50 m (including the polygon) of itself, and 4) cultivated field = the polygon (including boundary). Area results (ha): aggregate MCP = 3,225, road = 381, riparian zone = 332, water body = 72, and cultivated field = 3.

Figure 6. Season C representative area illustrating maximum land use of collared cattle and feral swine aggregate minimum convex polygon (MCP) and descending overlay of buffered landscape features of interest: water body, riparian zone, road, and cultivated field; to investigate their effect on inter- and intra-species direct and indirect contact for potential transmission of FMDv on rangeland in southern Texas, USA, 2004–2006.



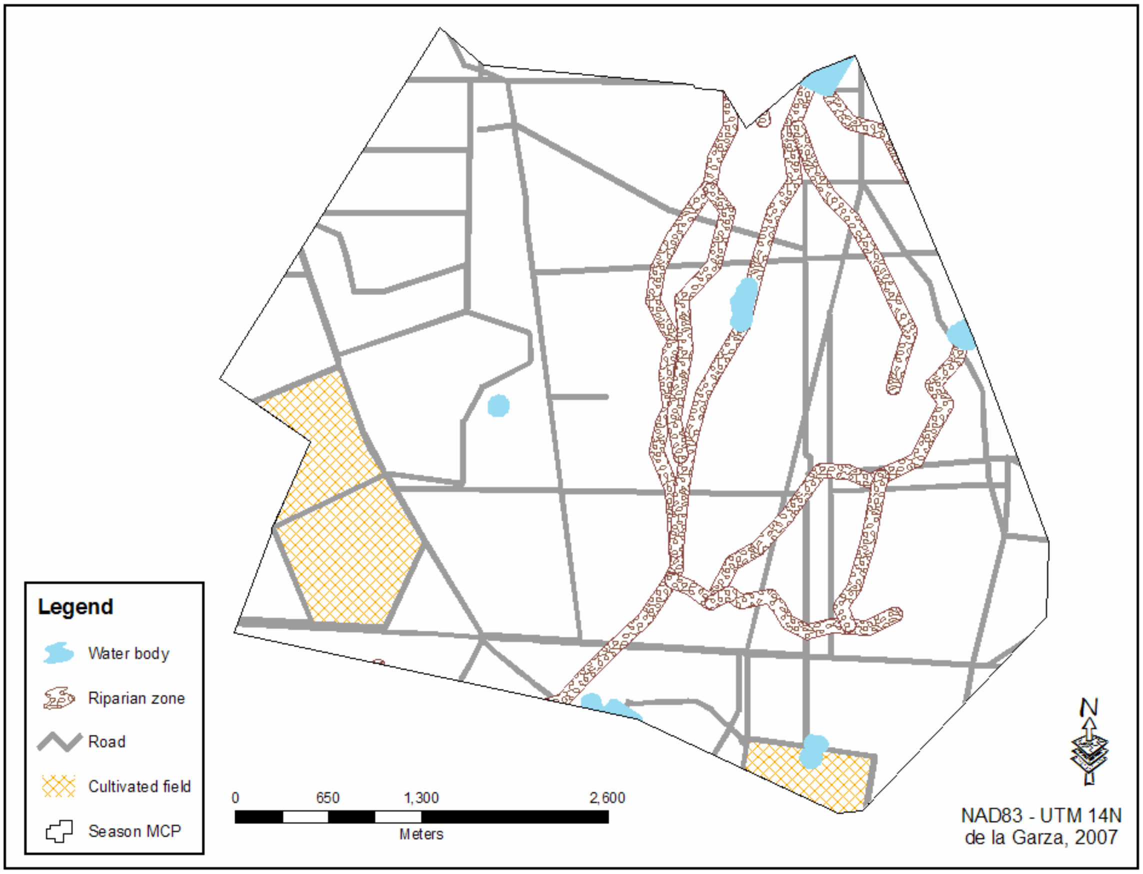
Note: Buffering scheme: 1) road and fence line coverage = 20 m either side of the line, 2) riparian coverage = 50 m either side of the center-line, 3) water = within 50 m (including the polygon) of itself, and 4) cultivated field = the polygon (including boundary). Area results (ha): aggregate MCP = 2,154, road = 234, riparian zone = 243, water body = 89, and cultivated field = 52.

Figure 7. Season D representative area illustrating maximum land use of collared cattle and feral swine aggregate minimum convex polygon (MCP) and descending overlay of buffered landscape features of interest: water body, riparian zone, road, and cultivated field; to investigate their effect on inter- and intra-species direct and indirect contact for potential transmission of FMDv on rangeland in southern Texas, USA, 2004–2006.



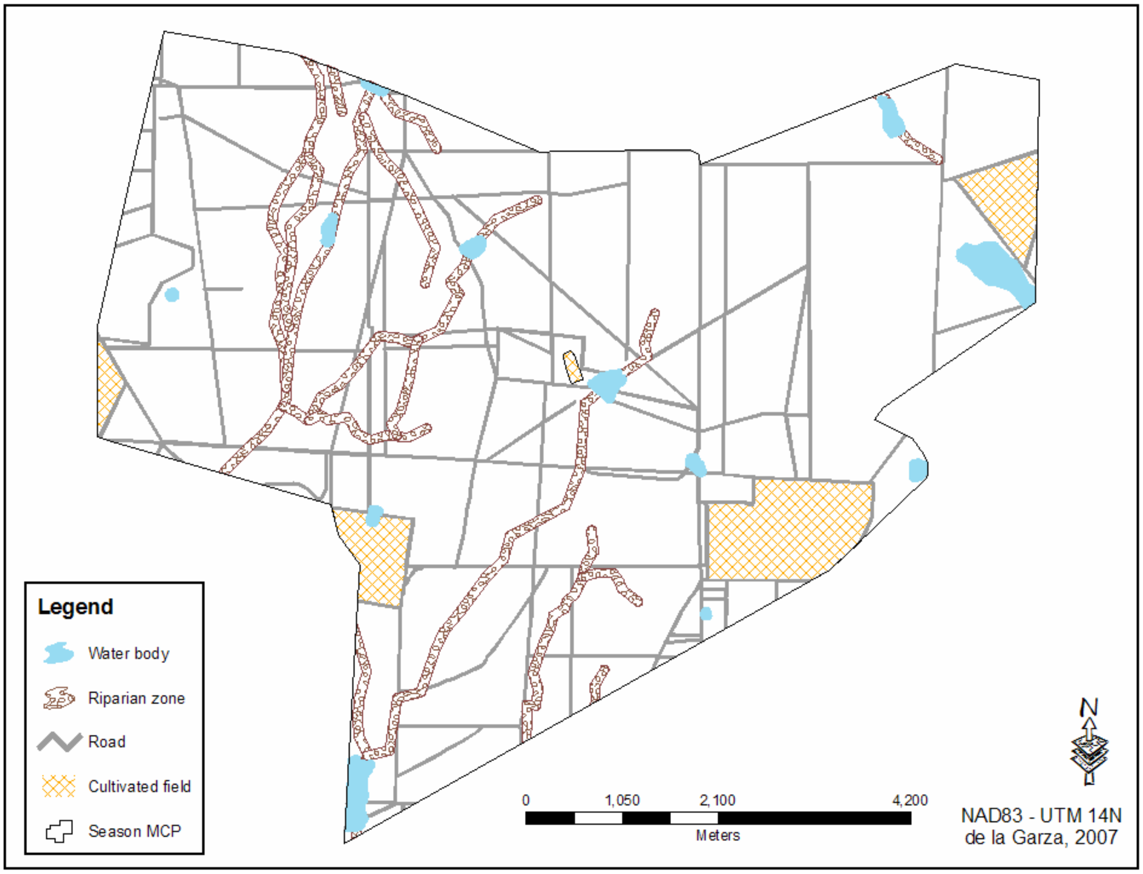
Note: Buffering scheme: 1) road and fence line coverage = 20 m either side of the line, 2) riparian coverage = 50 m either side of the center-line, 3) water = within 50 m (including the polygon) of itself, and 4) cultivated field = the polygon (including boundary). Area results (ha): aggregate MCP = 2,400, road = 260, riparian zone = 127, water body = 46, and cultivated field = 191.

Figure 8. Season E representative area illustrating maximum land use of collared cattle and feral swine aggregate minimum convex polygon (MCP) and descending overlay of buffered landscape features of interest: water body, riparian zone, road, and cultivated field; to investigate their effect on inter- and intra-species direct and indirect contact for potential transmission of FMDv on rangeland in southern Texas, USA, 2004–2006.



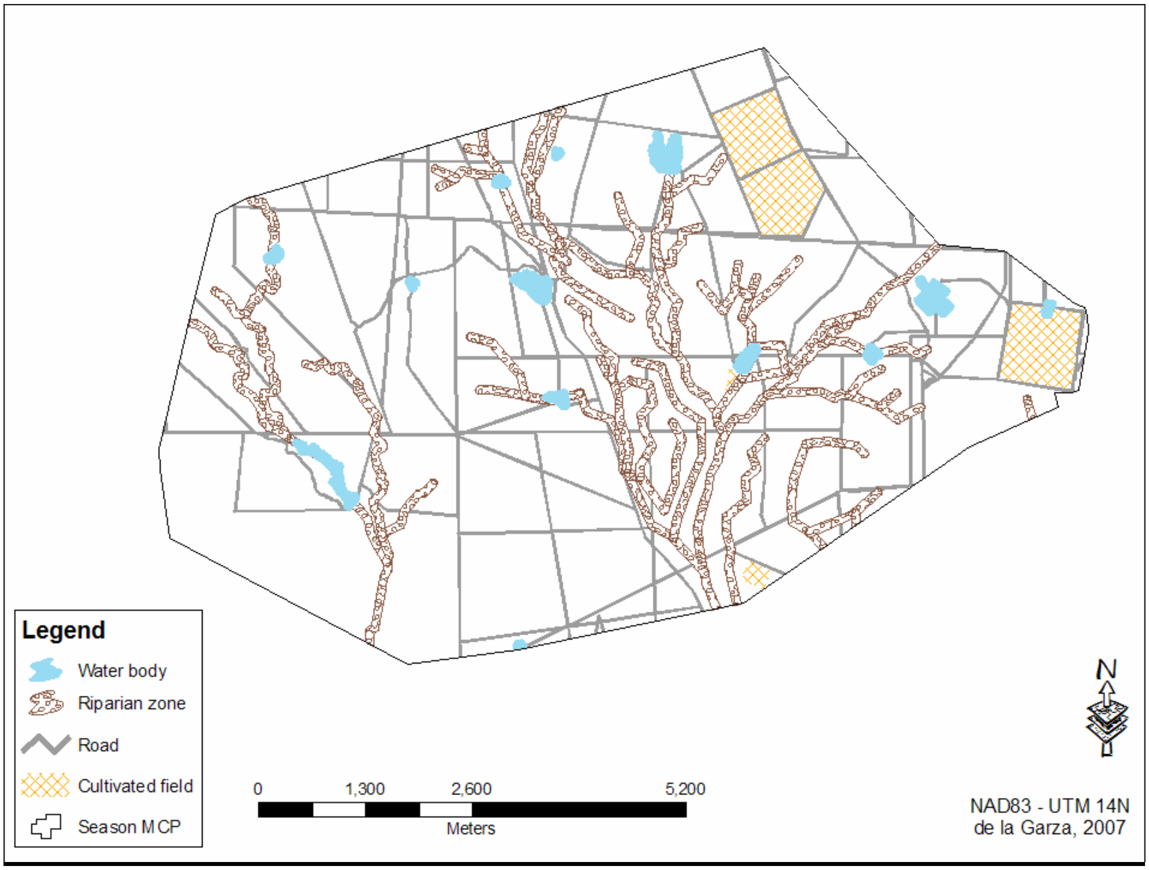
Note: Buffering scheme: 1) road and fence line coverage = 20 m either side of the line, 2) riparian coverage = 50 m either side of the center-line, 3) water = within 50 m (including the polygon) of itself, and 4) cultivated field = the polygon (including boundary). Area results (ha): aggregate MCP = 2,136, road = 256, riparian zone = 194, water body = 23, and cultivated field = 151.

Figure 9. Season F representative area illustrating maximum land use of collared cattle and feral swine aggregate minimum convex polygon (MCP) and descending overlay of buffered landscape features of interest: water body, riparian zone, road, and cultivated field; to investigate their effect on inter- and intra-species direct and indirect contact for potential transmission of FMDv on rangeland in southern Texas, USA, 2004–2006.



Note: Buffering scheme: 1) road and fence line coverage = 20 m either side of the line, 2) riparian coverage = 50 m either side of the center-line, 3) water = within 50 m (including the polygon) of itself, and 4) cultivated field = the polygon (including boundary). Area results (ha): aggregate MCP = 5,275, road = 548, riparian zone = 352, water body = 101, and cultivated field = 315.

Figure 10. Season G representative area illustrating maximum land use of collared cattle and feral swine aggregate minimum convex polygon (MCP) and descending overlay of buffered landscape features of interest: water body, riparian zone, road, and cultivated field; to investigate their effect on inter- and intra-species direct and indirect contact for potential transmission of FMDv on rangeland in southern Texas, USA, 2004–2006.



Note: Buffering scheme: 1) road and fence line coverage = 20 m either side of the line, 2) riparian coverage = 50 m either side of the center-line, 3) water = within 50 m (including the polygon) of itself, and 4) cultivated field = the polygon (including boundary). Area results (ha): aggregate MCP = 5,546, road = 574, riparian zone = 690, water body = 109, and cultivated field = 244.

Figure 11. Season H representative area illustrating maximum land use of collared cattle and feral swine aggregate minimum convex polygon (MCP) and descending overlay of buffered landscape features of interest: water body, riparian zone, road, and cultivated field; to investigate their effect on inter- and intra-species direct and indirect contact for potential transmission of FMDv on rangeland in southern Texas, USA, 2004–2006.

Table 2. Description of field season dates, number of animals fitted with GPS collars, and GPS location records acquired, to estimate inter- and intra-species direct and indirect contact for potential transmission of FMDv between cattle and feral swine on rangeland in southern Texas, USA, 2004–2006.

	Date			*n*		No. of GPS locations acquired			% night fixes	
Season	Begin	End	Day	Hog	Cow	Hog	Cow	Total	Hog	Cow
A	20 Jul 2004	19 Sep 2004	61	2	4	645	19,364	20,009	58.76	50.37
B	4 Oct 2004	26 Nov 2004	53	7	3	5,199	12,032	17,231	60.43	50.14
C	4 Feb 2005	19 Apr 2005	74	6	3	4,476	20,344	24,820	56.03	49.96
D	20 Apr 2005	2 Jul 2005	73	10	3	2,554	9,359	11,913	65.39	50.02
E	16 Aug 2005	7 Oct 2005	52	5	4	905	5,869	6,774	60.44	50.14
F	19 Nov 2005	26 Jan 2006	68	4	2	10,554	10,619	21,173	49.95	47.67
G	24 Feb 2006	1 May 2006	66	4	4	9,353	12,995	22,348	53.43	49.83
H	26 May 2006	30 Jul 2006	65	2	2	5,015	12,533	17,548	51.27	49.73

Table 3. Seasonal description (season A–D) of collared cattle and feral swine, duration of collar deployment, and mean area use by each class of animal (minimum convex polygon [MCP] with SD and 50% quartile) acquired to estimate inter- and intra-species direct and indirect contact for potential transmission of FMDv on rangeland in southern Texas, USA, 2004–2006.

				Days collared		Area use (MCP ha)		
Season	Class	*n*	(herd *n*)		Range		SD	Q_2
A summer 2004								
	Cows (herd)	4	(203)	51	21–61	546.86	374.17	477.27
	Boars	1		7		13.52		
	Sows	0						
	Shoats	1		7		361.00		
B fall 2004								
	Cows (herd)	3	(121)	44		886.85	328.74	1,060.89
	Boars	0						
	Sows	3		12		701.85	317.40	612.96
	Shoats	4		16		941.00	249.30	962.26
C fall 2004								
	Cows (herd)	3	(152)	54	16–75	1,906.73	421.99	1,663.81
	Boars	1		74		2,011.67		
	Sows	1		14		422.05		
	Shoats	4		12	8–16	380.50	310.14	232.24
D spring 2005								
	Cows (herd)	3	(84)	12	5–16	877.49	709.65	933.16
	Boars	2		43	12–74	449.70	308.47	449.70
	Sows	2		14	13–14	333.33	57.02	333.33
	Shoats	6		8	2–14	232.67	135.05	283.27

Table 4. Seasonal description (season E–H) of collared cattle and feral swine, duration of collar deployment, and mean area use by each class of animal (minimum convex polygon [MCP] with SD and 50% quartile) acquired to estimate inter- and intra-species direct and indirect contact for potential transmission of FMDv on rangeland in southern Texas, USA, 2004–2006.

				Days collared		Area use (MCP ha)		
Season	Class	*n*	(herd *n*)		Range		SD	Q_2
E summer 2005								
	Cows (herd)	4	(84)	16	3–53	695.13	345.57	677.38
	Boars	1		4		790.06		
	Sows	0						
	Shoats	4		6	4–10	286.50	404.87	142.38
F fall 2005								
	Cows (herd)	2	(141)	69	69–69	1,195.24	100.12	1,195.24
	Boars	1		30		962.90		
	Sows	0						
	Shoats	3		29	19–37	767.67	534.55	635.35
G winter 2005/6								
	Cows (herd)	4	(84)	36	27–60	985.72	1,012.48	841.22
	Boars	2		42	17–66	2,361.85	45.30	2,361.85
	Sows	0						
	Shoats	2		31	31–31	1,638.50	391.23	1,638.73
H summer 2006								
	Cows (herd)	2	(121)	66	66–66	1,029.70	7.00	1,029.70
	Boars	1		30		5,397.71		
	Sows	0						
	Shoats	1		29		1,447.00		

determined by size and maturity (shoats were not sexed). Seasonal mean cow and feral hog sample size was 3.1 (median = 4.5) and 5 (median = 3), respectively. Due to variability in feral swine trapping success, sample size varied from season to season. Field season length was depended on collar battery longevity, where higher-voltage cow collars functioned longer than hog collars. Interestingly there were slightly more nighttime GPS fixes for feral hogs (56.9%) than cows (49.7%).

Animal-to-animal pairs used to estimate DC and IC were constructed in the following 4 contact type combinations: 1) inter-species = cow-to-hog (CH) and hog-to-cow (HC) and 2) intra-species = cow-to-cow (CC) and hog-to-hog (HH). Seasons yielding increased frequency of potential for DC (based on no. of paired GPS fixes <20 m apart within 15 min) by contact type were: CC (season B–C), CH or HC (season G–H), and HH (season B, F, Table 5). On the other hand, increased frequency of potential for IC (<20 m apart within 360 min) were found for: CC (season A–C, E, H), CH (season B, F–H), HC (G–H), and HH (season B, F).

Actual occurrence of interactions were as follows. Across all seasons total occurrences of DC for CH or HC was 12 (= 2, SD = 2), CC was 5,915 (= 739, SD = 1,140), and HH was 1,530 (= 191, SD = 258). Interestingly, total inter-species IC events for CH and HC were nearly equal at 140 and 144 (= 18 and 18, SD = 23 and 30), respectively. Total CCIC was 17,481 (= 2,185, SD = 2,916), and HHIC was 5,642 (= 705, SD = 951).

Spatial distribution. Minimum convex polygons created for each animal of the study illustrated area use in hectares. Unrestricted to pastures, feral swine boars were the most mobile with an MCP range of 14–5,398 ha (= 1,713, SE = 652); followed by shoats 232–1638 ha (= 757, SE = 195); then sows 333–701 ha (= 486, SE = 69, Tables 3–4). Cattle area use (MCP) ranged from 547–1,906 ha and was restricted to pastures of various sizes within each season. Aggregate MCP (total for both species) area was always usually larger than total study pasture area each season. Mean aggregate MCP was 2,994 ha (SD = 3,193) and highest in season H (5,546 ha), lowest in season A (1,405). Only season B had a lower aggregate MCP than the boundaries of the study pasture (606 ha difference).

In general, cattle and feral swine proportional use of the landscape varied through the study (Table 6, Figure 12). However, season A demonstrated the single occurrence of parallel use (approx 14% each) of a particular feature, roads. Both species utilized open range (defined as all other landscape unassociated with one of the 4 previously described landscape features) in greater proportion (cattle = 52%, feral swine = 45% of fixes) relative to road, riparian zone, water, or cultivated field. On average, among the investigated landscape features of interest, cattle frequented roads (23%) and cultivated fields (19%) more than water and riparian zones (7% each). Conversely, collared feral swine illustrated a more even land use compared to cattle. Feral swine spent more time in riparian zones (24%), but the other features were used at similar levels (water = 15%, roads = 14%, cultivated field = 11%).

Table 5. Summary of paired GPS fixes acquired to estimate inter- and intra-species direct and indirect contact for potential transmission of FMDv between cattle and feral swine on rangeland in southern Texas, USA, 2004–2006.

	Potential direct contacts No. of paired fixes within 15 min						Potential indirect contacts No. of paired fixes within 360 min							
	Intra-species (direct contact[a])				Inter-species (direct contact[a])		Intra-species (indirect contact[b])				Inter-species (indirect contact[b])			
Season	Hog-hog		Cow-cow		Hog-cow or cow-hog		Hog-hog		Cow-cow		Hog-cow		Cow-hog	
A	0	(0)	23,043	(473)	2,271	(0)	0	(0)	46,396	(1,666)	2,279	(0)	4,111	(1)
B	2,755	(620)	11,295	(907)	13,516	(1)	7,908	(2,019)	23,289	(2,526)	14,124	(2)	22,108	(11)
C	2,890	(96)	19,520	(3,463)	13,190	(0)	7,916	(254)	39,654	(9,078)	13,428	(2)	19,531	(5)
D	936	(90)	3,439	(89)	2,533	(0)	3,507	(362)	6,955	(512)	2,554	(2)	6,092	(2)
E	237	(0)	1,666	(540)	905	(1)	846	(0)	3,382	(1,391)	905	(4)	1,807	(2)
F	11,548	(587)	4,027	(63)	17,446	(0)	23,518	(2,403)	10,163	(247)	20,981	(7)	17,782	(15)
G	5,917	(115)	7,499	(17)	19,972	(6)	13,864	(503)	15,612	(89)	20,524	(47)	22,988	(66)
H	1,656	(22)	6,259	(360)	9,995	(4)	3,614	(101)	12,533	(1,972)	10,030	(80)	11,077	(38)

[a] Number of respective fixes resulting in direct contact (defined as an animal pair < 20m and within 15 min of each other)

[b] Number of respective fixes resulting in indirect contact (defined as an animal pair < 20m and within 360 min of each other)

Table 6. Seasonal usage of landscape features by GPS-collared cattle and feral swine (% GPS locations) and landscape features (buffered to account for geospatial error in mapping animal locations over 15 min and variation in mapped landscape features) in southern Texas, USA, 2004–2006.

		% GPS fix within landscape/season							
Animal	Landscape feature	A	B	C	D	E	F	G	H
Cow	Within 20 m either side of midline of road	14.73	14.61	36.16	21.47	42.51	10.3	25.97	16.93
	Within 50 m either side of midline of riparian zone	14.25	3.47	6.88	11.21	3.77	2.93	10.66	3.75
	Within 50 m from edge of water body	12.82	1.42	1.88	8.07	5.72	3.76	13.76	5.57
	Within cultivated field	10.04	1.25	0.01	0.05	31.03	38.53	0.45	69.64
	Not within either above 4 features	60.23	80.29	57.78	67.37	26.89	48.25	59.58	12.95
Hog	Within 20 m either side of midline of road	14.42	31.47	21.69	9.01	10.94	6.95	8.71	7.68
	Within 50 m either side of midline of riparian zone	71.78	14.1	8.85	17.89	29.28	10.58	4.27	36.67
	Within 50 m from edge of water body	10.7	25.87	5.97	18.09	23.98	2.19	23.01	17.71
	Within cultivated field	0	6.17	0	33.09	2.54	20.76	15.95	11.31
	Not within either above 4 features	19.38	40.7	70	28.39	50.83	62.37	54.01	34.3

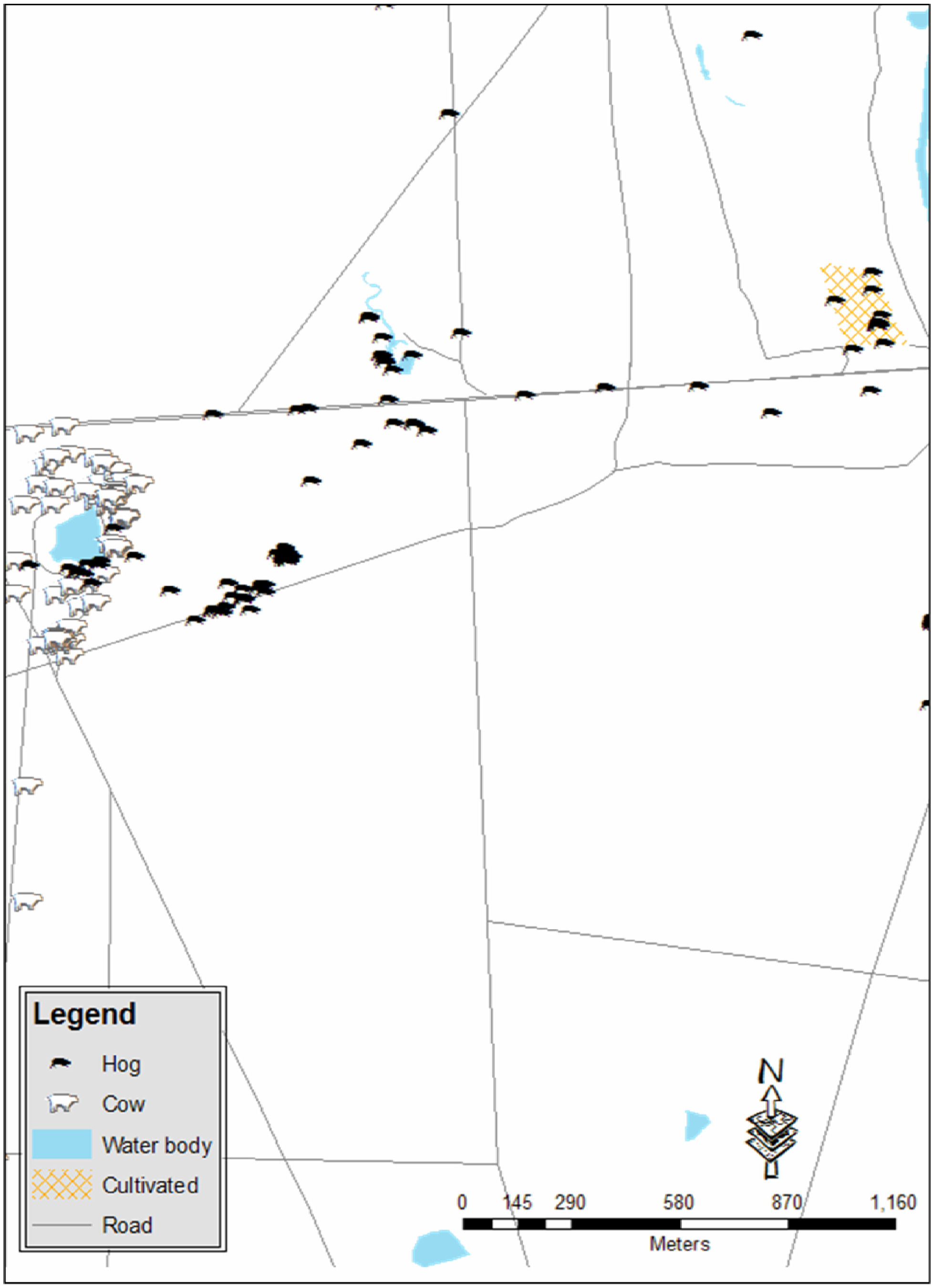


Figure 12. Overlay illustrating movement and utilization of selected landscape features of interest that may influence interaction between a GPS-collared cow and feral hog animal pair. Time-scale is over several days (within 1 season), therefore this is for illustrative purposes only and does not indicate a direct or indirect contact event as investigated at specific space-time parameters.

Geospatial analysis

Stratified relative contact rate analysis. For discussion, suffixes of DC and IC are appended to each contact type (e.g., CHDC or CHIC for cow-to-hog direct and indirect contact, respectively). Feature-effect was assessed while adjusted for the potential for interaction with species. Across all contact types, location within 50 m of the center-line of a riparian zone showed no significance ($P = 0.292$–0.974) of effect on rate of contact (Table 7). Location within 50 m of the edge of a surface water polygon increased CHDC 12-fold compared to a smaller 1.5 increase for HHDC. Location within a cultivated field increased likelihood of CHDC (RRt = 3.2) but decreased HHDC (RRt = 0.8). Relative rate of contact was 1.6 times greater for CHDC during daylight hours and 0.7 times less for HHDC. Daytime-effect on DC and IC increased CH and decreased HH at equal proportions. Hunting season, road, and open range did not influence ($P > 0.05$) direct contact rates of either species with feral swine. Relative rates of indirect contact with a feral hog were affected by all features ($P < 0.05$) except riparian zone (Table 8).

Table 7. Stratified analysis of relative rates (RRt) of direct contact with a feral hog (by cow vs. hog) based on each feature in southern Texas, USA, 2004–2006.

Feature[a]	Variable	RRt[b]	95% CI
Road	Cow	0.3342	0.0077, 2.2990
	Hog	2.1953	2.0216, 2.3819
Riparian zone	Cow	0.0000	0, 6.1769
	Hog	0.6899	0.5991, 0.7910
Water	Cow	11.8369	2.9623, 43.325
	Hog	1.5012	1.3552, 1.6598
Cultivated field	Cow	3.2801	0.8209, 12.005
	Hog	0.8592	0.7767, 0.9487
Open range	Cow	0.0744	0.0017, 0.5118
	Hog	0.7984	0.7437, 0.8570
Daytime	Cow	1.6558	0.4523, 6.6160
	Hog	0.7301	0.6779, 0.7859
Hunting season	Cow	0.2644	0.0061, 1.8192
	Hog	0.7798	0.7252, 0.8381

[a] For landscape features, referent = all other; for daytime, referent = night; for hunting season, referent = closed season

[b] RRt is indexed to 1 for the given feature, increases if RRt > 1 and decreases if RRt <1

Table 8. Stratified analysis of relative rates (RRt) of indirect contact with a feral hog (by cow vs. hog) based on each feature in southern Texas, USA, 2004–2006.

Feature[a]	Variable	RRt[b]	95% CI
Road	Cow	0.5560	0.3185, 0.9170
	Hog	1.7784	1.6584, 1.9056
Riparian zone	Cow	0.7861	0.2833, 1.7574
	Hog	0.5703	0.5046, 0.6424
Water	Cow	3.8816	2.4298, 5.9924
	Hog	1.1917	1.0900, 1.3008
Cultivated field	Cow	6.4451	4.5317, 9.2181
	Hog	1.3718	1.2801, 1.4690
Open range	Cow	0.1481	0.0883, 0.2371
	Hog	0.7607	0.7187, 0.8050
Daytime	Cow	1.7107	1.2019, 2.4497
	Hog	0.6828	0.6431, 0.7247
Hunting season	Cow	0.2539	0.1235, 0.4700
	Hog	1.1541	1.0904, 1.2215

[a] For landscape features, referent = all other; for daytime, referent = night; for hunting season, referent = closed season

[b] RRt is indexed to 1 for the given feature, increases if RRt > 1 and decreases if RRt <1

Presence of animals in a cultivated field increased both inter-and intra-species IC, where RRt for CHIC = 6.4 and HHIC = 1.3. For water-effect, relative rate of HHIC increased from that of cultivated field and CHIC decreased by a factor of 1.6. Road and hunting season illustrated similar effect for both CHIC and HHIC, where rate of HHIC was slightly increased and CHIC decreased. Open range showed a decrease in risk of inter- and intra-species contact with a feral hog. For DC with a cow, only water and cultivated field influenced CCDC and HCDC (Table 9). For both contact types, feral swine risk increased whereas cattle risk decreased. Water increased HCDC by 8.9-fold and cultivated field increased the same contact by a factor of 2.1. Road, riparian zone, cultivated field, and hunting season did not influence IC with cattle (Table 10). As with DC, water increased HCIC (RRt = 5.7), but decreased CCIC (RRt = 0.2). There was increased risk of feral hog contacting cattle during the daytime (RRt = 5.8). Open range reduced all relative rates of IC.

Table 9. Stratified analysis of relative rates (RRt) of direct contact with a cow (by cow vs. hog) based on each feature in southern Texas, USA, 2004–2006.

Feature[a]	Variable	RRt[b]	95% CI
Road	Cow	1.8910	1.7873, 2.0001
	Hog	1.6479	0.1704, 8.2576
Riparian zone	Cow	1.1460	1.0245, 1.2784
	Hog	2.2468	0.2324, 11.258
Water	Cow	0.1399	0.1022, 0.1868
	Hog	8.9337	2.0560, 38.818
Cultivated field	Cow	0.4576	0.4164, 0.5018
	Hog	2.1084	0.3518, 9.2357
Open range	Cow	0.9378	0.8891, 0.9892
	Hog	0.0000	0, 0.3471
Daytime	Cow	0.9277	0.8792, 0.9788
	Hog	3.0328	0.6923, 18.175
Hunting season	Cow	0.1834	0.1634, 0.2051
	Hog	0.0000	0, 0.5215

[a] For landscape features, referent = all other; for daytime, referent = night; for hunting season, referent = closed season

[b] RRt is indexed to 1 for the given feature, increases if RRt > 1 and decreases if RRt <1

Table 10. Stratified analysis of relative rates (RRt) of indirect contact with a cow (by cow vs. hog) based on each feature in southern Texas, USA, 2004–2006.

Feature[a]	Variable	RRt[b]	95% CI
Road	Cow	1.6016	1.5246, 1.6821
	Hog	2.2600	1.3591, 3.6386
Riparian zone	Cow	0.9587	0.8650, 1.0599
	Hog	0.6128	0.2189, 1.3878
Water	Cow	0.2003	0.1611, 0.2463
	Hog	5.7991	3.7269, 8.9250
Cultivated field	Cow	0.9361	0.8810, 0.9940
	Hog	0.7896	0.4031, 1.4272
Open range	Cow	0.8270	0.7904, 0.8651
	Hog	0.4016	0.2536, 0.6249
Daytime	Cow	0.9549	0.9124, 0.9992
	Hog	5.8873	3.4492, 10.621
Hunting season	Cow	0.2100	0.1916, 0.2297
	Hog	0.2220	0.1186, 0.3886

[a] For landscape features, referent = all other; for daytime, referent = night; for hunting season, referent = closed season

[b] RRt is indexed to 1 for the given feature, increases if RRt > 1 and decreases if RRt <1

Multivariable models of contact rate. Direct contact with a feral hog was the least complex model with 7 variables, an interaction term + intercept term. The general linear form of the multivariable model for direct contact with a feral hog was as follows:

$$\ln y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \beta_8 X_1 X_2$$

$$\ln y = -13.38 + 7.11X_1 + 2.34X_2 - 0.18X_3 - 0.12X_4 + 0.12X_5 + 1.64X_6 + 1.59X_7$$
$$- 2.40X_1 X_2$$

Where:

y = rate of contact with a hog/ha 15 min;

β_0 = coefficient of intercept (constant);

β_1 = coefficient for species

$X_1 = 1$ for hog, and

$X_1 = 0$ for cow;

β_2 = coefficient for location within 50 m of water body

$X_2 = 1$ for near water, and

$X_2 = 0$ for not near water;

β_3 = coefficient for location within a cultivated field

$X_3 = 1$ for cultivated field, and

$X_3 = 0$ for not cultivated field;

β_4 = coefficient for daytime hours

$X_4 = 1$ for daytime hours, and

$X_4 = 0$ for nighttime hours;

β_5 = coefficient for April–June

$X_5 = 1$ for April–June, and

$X_5 = 0$ for not April–June;

β_6 = coefficient for July–September

$X_6 = 1$ for July–September, and

$X_6 = 0$ for not July–September;

β_7 = coefficient for October–December

$X_7 = 1$ for October–December, and

$X_7 = 0$ for not October–December;

β_8 = coefficient for interaction product term of species by water body

$X_1 = 1$ for hog, and

$X_1 = 0$ for cow;

$X_2 = 1$ for near water, and

$X_2 = 0$ for not near water;

therefore $X_1 \times X_2 = 1$, if species = 1 & water = 1;

else $X_1 \times X_2 = 0$.

Only summer was not significantly different from spring referent ($P = 0.448$), and the only non-significant level of the variable forced into the final model (Table 11). Factors representing an increased risk of contact were species = hog (RRt = 1227) versus cow and being near water (RRt = 10.3). The interpretation is that feral swine are 1,227 times more likely to contact other hogs than are cows for every 15 min per hectare of land, adjusted for the potential confounding effects of landscape, season, and time of day. Fall and winter also increased potential risk of DC with swine at RRt of approximately 5 for each. Cultivated field and daytime represented decreasing risk of RRT = 0.8.

Table 11. Final multivariable model for rate (/ha every 15 min) of direct contact with a feral hog[a] using a random-effects Poisson regression multivariable model for species (hog = 1, cow = 0), landscape features, time of day, and season in southern Texas, USA, 2004–2006.

Hog	Coef.[b]	RRt[c]	SE	Z	P>| Z |	95% CI
Species[a]	7.11	1227.8513	0.6981	10.19	< 0.001	5.74, 8.48
Water	2.34	10.3766	0.6562	3.57	< 0.001	1.05, 3.62
Cultivated field	-0.18	0.8328	0.0638	-2.87	0.004	-0.31-0.05
Daytime	-0.12	0.8889	0.0423	-2.78	0.005	-0.21, -0.03
Summer	0.12	1.1292	0.1603	0.76	0.448	-0.19, 0.43
Fall	1.64	5.1762	0.6426	2.56	0.011	0.38, 2.90
Winter	1.59	4.8861	0.1613	9.83	< 0.001	1.27, 1.90
Species × water	-2.40	0.0911	0.6585	-3.64	< 0.001	-3.68, -1.11
Intercept	-13.38	0.0000	0.6417	-20.85	< 0.001	-14.63, -12.12

[a] Model referent terms: for landscape features (road, riparian, and open range = referent); for season (spring = referent); and for time of day (night = referent)

[b] Coef. of contact is indexed to 0 for the given feature. Increased risk of contact if Coef. > 0 and decreased risk of contact if Coef. < 0

[c] Antilog of the sum of coefficients of interest = rate ratio. A random effect was included to account for the serial dependence of location for each animal. Rates are adjusted to account for both the variation in home range and for the relative proportion of the carrying capacity of hogs and cows represented by GPS-collared animals

The multivariable model for indirect contact with a hog included the same variables as for DC, but also with temperature (K), daytime (versus night) and a species × temperature K interaction term. The general linear form of the multivariable model for indirect contact with a feral hog was as follows:

$$\ln y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \beta_8 X_8 + \beta_9 X_1 X_2 \\ + \beta_{10} X_1 X_2$$

$$\ln y = -34.65 + 28.62 X_1 + 1.14 X_2 + 0.11 X_3 - 0.20 X_4 + 0.08 X_5 + 0.06 X_6 + 2.16 X_7 \\ + 1.33 X_8 - 1.19 X_1 X_2 - 0.08 X_1 X_5$$

Where:

y = rate of contact with a hog/ha 15 min;

β_0 = coefficient of intercept (constant);

β_1 = coefficient for species

$X_1 = 1$ for hog, and

$X_1 = 0$ for cow;

β_2 = coefficient for location within 50 m of water body

$X_2 = 1$ for near water, and

$X_2 = 0$ for not near water;

β_3 = coefficient for location within a cultivated field

$X_3 = 1$ for cultivated field, and

$X_3 = 0$ for not cultivated field;

β_4 = coefficient for daytime hours

$X_4 = 1$ for daytime hours, and

$X_4 = 0$ for nighttime hours;

β_5 = coefficient for temperature in K

X_5 = temperature in K

B_6 = coefficient for April–June

$X_6 = 1$ for April–June, and

$X_6 = 0$ for not April–June;

B_7 = coefficient for July–September

$X_7 = 1$ for July–September, and

$X_7 = 0$ for not July–September;

β_8 = coefficient for October–December

$X_8 = 1$ for October–December, and

$X_8 = 0$ for not October–December;

β_9 = coefficient for interaction product term of species by water body

$X_1 = 1$ for hog, and

$X_1 = 0$ for cow;

$X_2 = 1$ for near water, and

$X_2 = 0$ for not near water;

therefore $X_1 \times X_2 = 1$, if species = 1 & water = 1;

else $X_1 \times X_2 = 0$

β_{10} = coefficient for interaction product term of species by temperature in K

$X_1 = 1$ for hog, and

$X_1 = 0$ for cow;

X_5 = temperature in K

therefore $X_1 \times X_5 = 1$, if species = 1 & temperature in K.

Summer was the only level of the seasonal variable not significantly different from its spring referent ($P = 0.591$, Table 12). Species (where species = hog) had the greatest effect of HHIC (RRt = 2.6 e^{12}). Fall (RRt = 8.7), winter (RRt = 3.7), and water (RRt = 3.1) increased CHIC and HHIC at greater relative rates than cultivated field (RRt = 1.1) and temperature K (RRt = 1.0). Interaction terms species × water and species × temperature K had the effect of decreasing the relative risk of CHIC near water (RRt = 0.3) and with increased temperatures (RRt = 0.9), respectively for hogs versus cows. Overall, relative risk of CHIC and HHIC decreased during daytime hours (RRt = 0.8).

Table 12. Final multivariable model for rate (/ha every 15 min) of indirect contact with a feral hog[a] using a random-effects Poisson regression multivariable model for species (hog = 1, cow = 0), landscape features, time of day, temperature (K), and season in southern Texas, USA, 2004–2006.

Hog	Coef.[b]	RRt[c]	SE	Z	P>| Z |	95% CI
Species[a]	28.62	2.6945E+12	4.8744	5.87	< 0.001	19.06, 38.17
Water	1.14	3.1249	0.2499	4.56	< 0.001	0.64, 1.62
Cultivated field	0.11	1.1120	0.0443	2.39	0.017	0.01, 0.19
Daytime	-0.20	0.8152	0.0363	-5.63	< 0.001	-0.27, -0.13
Temp K	0.08	1.0827	0.0162	4.90	< 0.001	0.04, 0.11
Summer	0.06	1.0650	0.1171	0.54	0.591	-0.16, 0.29
Fall	2.16	8.7146	0.4367	4.96	< 0.001	1.30, 3.02
Winter	1.33	3.7731	0.1057	12.57	< 0.001	1.12, 1.53
Species × water	-1.19	0.3036	0.254468	-4.68	< 0.001	-1.69, -0.69
Species × temp K	-0.08	0.9239	0.0163	-4.84	< 0.001	-0.11, -0.04
Intercept	-34.65	8.9430E-16	4.820713	-7.19	< 0.001	-44.09, -25.20

[a] Model referent terms: for landscape features (road, riparian, and open range = referent); for season (spring = referent); and for time of day (night = referent)

[b] Coef. of contact is indexed to 0 for the given feature. Increased risk of contact if Coef. > 0 and decreased risk of contact if Coef. < 0

[c] Antilog of the sum of coefficients of interest = rate ratio. A random effect was included to account for the serial dependence of location for each animal. Rates are adjusted to account for both the variation in home range and for the relative proportion of the carrying capacity of hogs and cows represented by GPS-collared animals

Direct contact with a cow was progressively more complex than the previous two models (11 variables or interaction terms + intercept constant). Its structure was the same for DC upon hog, however road and species × road were added and daytime subtracted (as it was not significant for cattle contact). The general linear form of the multivariable model for direct contact with a cow was as follows:

$$\ln y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \beta_8 X_8 + \beta_9 X_1 X_2 + \beta_{10} X_1 X_4 + \beta_{11} X_1 X_5$$

$$\ln y = -0.27 - 147.66 X_1 + 0.34 X_2 + 0.21 X_3 + 0.58 X_4 - 0.02 X_5 - 0.79 X_6 - 0.50 X_7 + 1.28 X_8 + 1.57 X_1 X_2 + 2.59 X_1 X_4 + 0.46 X_1 X_5$$

Where:

y = rate of contact with a cow/ha 15 min;

β_0 = coefficient of intercept (constant);

β_1 = coefficient for species

$X_1 = 1$ for hog, and

$X_1 = 0$ for cow;

β_2 = coefficient for location within 20 m of road

$X_2 = 1$ for near road, and

$X_2 = 0$ for not near road;

β_3 = coefficient for location within 50 m of water body

$X_3 = 1$ for near water, and

$X_3 = 0$ for not near water;

β_4 = coefficient for location within a cultivated field

$X_4 = 1$ for cultivated field, and

$X_4 = 0$ for not cultivated field;

β_5 = coefficient for temperature in K

X_5 = temperature in K

β_6 = coefficient for April–June

$X_6 = 1$ for April–June, and

$X_6 = 0$ for not April–June;

β_7 = coefficient for July–September

$X_7 = 1$ for July–September, and

$X_7 = 0$ for not July–September;

β_8 = coefficient for October–December

$X_8 = 1$ for October–December, and

$X_8 = 0$ for not October–December;

β_9 = coefficient for interaction product term of species by road

$X_1 = 1$ for hog, and

$X_1 = 0$ for cow;

$X_2 = 1$ for near road, and

$X_2 = 0$ for not near road;

therefore $X_1 \times X_2 = 1$, if species = 1 & road = 1;

else $X_1 \times X_2 = 0$

β_{10} = coefficient for interaction product term of species by cultivated field

$X_1 = 1$ for hog, and

$X_1 = 0$ for cow;

$X_4 = 1$ for near cultivated field, and

$X_4 = 0$ for not near cultivated field;

therefore $X_1 \times X_4 = 1$, if species = 1 & cultivated field = 1;

else $X_1 \times X_4 = 0$

β_{11} = coefficient for interaction product term of species by temperature in K

$X_1 = 1$ for hog, and

$X_1 = 0$ for cow;

X_5 = temperature in K

therefore $X_1 \times X_5 = 1$, if species = 1 & temperature in K.

The coefficient for species = hog of -147.66 (RRt = 7.4×10^{-65}) stood out (lowest modeled result) and is interpreted that the rate of feral swine contacting a cow via direct contact, after adjusting for potential confounding factors, is greatly decreased when compared to a cow contacting a cow (Table 13). Other factors differentially influencing increased rate of contact for swine with a cow were species × cultivated field (RRt = 13.3), species × road (RRt = 4.8), and winter (RRt = 3.6), meaning additional increases associated with hogs only. According to this model, contact with a cow is reduced if species = hog, season = summer or fall, and if temperature decreases (cow only).

Table 13. Final multivariable model for rate (/ha every 15 min) of direct contact with a cow[a] using a random-effects Poisson regression multivariable model for species (hog = 1, cow = 0), landscape features, temperature (K), and season in southern Texas, USA, 2004–2006.

Cow	Coef.[b]	RRt[c]	SE	Z	P>| Z |	95% CI
Species[a]	-147.66	7.4621E-65	22.0162	-6.71	< 0.001	-190.82, -104.51
Road	0.34	1.4073	0.0203	16.83	< 0.001	0.31, 0.38
Water	0.21	1.2280	0.0561	3.66	< 0.001	0.09, 0.31
Cultivated field	0.58	1.7841	0.0570	10.15	< 0.001	0.46, 0.69
Temp K	-0.02	0.9840	0.0017	-9.73	< 0.001	-0.02, -0.01
Summer	-0.79	0.4523	0.0395	-20.09	< 0.001	-0.87, -0.71
Fall	-0.50	0.6079	0.0862	-5.77	< 0.001	-0.66, -0.32
Winter	1.28	3.6092	0.2016	6.37	< 0.001	0.88, 1.67
Species × road	1.57	4.8227	0.6934	2.27	0.023	0.21, 2.93
Species × cultivated field	2.59	13.3155	0.8314	3.11	0.002	0.95, 4.21
Species × temp K	0.46	1.5910	0.0719	6.46	< 0.001	0.32, 0.61
Intercept	-0.27	0.7621	0.5706	-0.48	0.634	-1.39, 0.84

[a] Model referent terms: for landscape features (riparian and open range = referent); and for season

[b] Coef. of contact is indexed to 0 for the given feature. Increased risk of contact if Coef. > 0 and decreased risk of contact if Coef. < 0

[c] Antilog of the sum of coefficients of interest = rate ratio. A random effect was included to account for the serial dependence of location for each animal. Rates are adjusted to account for both the variation in home range and for the relative proportion of the carrying capacity of hogs and cows represented by GPS-collared animals

The final and most complex multivariable model was for indirect contact with cow (15 variables or interaction terms + intercept term). The general linear form of the multivariable model for indirect contact with a cow was as follows:

$$\ln y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \beta_8 X_8 + \beta_9 X_9$$
$$+ \beta_{10} X_{10} + \beta_{11} X_1 X_2 + \beta_{12} X_1 X_3 + \beta_{13} X_1 X_5 + \beta_{14} X_1 X_6 + \beta_{15} X_1 X_{10}$$

$$\ln y = -2.06 - 48.75 X_1 + 0.29 X_2 - 0.08 X_3 + 0.40 X_4 + 0.66 X_5 - 0.01 X_6 - 0.56 X_7$$
$$- 0.33 X_8 + 0.88 X_9 - 0.01 X_{10} + 1.08 X_1 X_2 - 0.89 X_1 X_3 + 0.60 X_1 X_5 + 0.99 X_1 X_6 + 0.15 X_1 X_{10}$$

Where:

y = rate of contact with a cow/ha 15 min;

β_0 = coefficient of intercept (constant);

β_1 = coefficient for species

$X_1 = 1$ for hog, and

$X_1 = 0$ for cow;

β_2 = coefficient for location within 20 m of road

$X_2 = 1$ for near road, and

$X_2 = 0$ for not near road;

β_3 = coefficient for location within 50 m of riparian zone

$X_3 = 1$ for near riparian zone, and

$X_3 = 0$ for not near riparian zone;

β_4 = coefficient for location within 50 m of water body

$X_4 = 1$ for near water, and

$X_4 = 0$ for not near water;

β_5 = coefficient for location within a cultivated field

$X_5 = 1$ for cultivated field, and

$X_5 = 0$ for not cultivated field;

β_6 = coefficient for location within daytime hours

$X_6 = 1$ for daytime hours, and

$X_6 = 0$ for nighttime hours;

β_7 = coefficient for April–June

$X_7 = 1$ for April–June, and

$X_7 = 0$ for not April–June;

β_8 = coefficient for July–September

$X_8 = 1$ for July–September, and

$X_8 = 0$ for not July–September;

β_9 = coefficient for October–December

$X_9 = 1$ for October–December, and

$X_9 = 0$ for not October–December;

β_{10} = coefficient for temperature in K

X_{10} = temperature in K

β_{11} = coefficient for interaction product term of species by road

$X_1 = 1$ for hog, and

$X_1 = 0$ for cow;

$X_2 = 1$ for near road, and

$X_2 = 0$ for not near road;

therefore $X_1 \times X_2 = 1$, if species = 1 & road = 1;

else $X_1 \times X_2 = 0$

β_{12} = coefficient for interaction product term of species by riparian zone

$X_1 = 1$ for hog, and

$X_1 = 0$ for cow;

$X_3 = 1$ for near riparian zone, and

$X_3 = 0$ for not near riparian zone;

therefore $X_1 \times X_3 = 1$, if species = 1 & riparian zone = 1;

else $X_1 \times X_3 = 0$

β_{13} = coefficient for interaction product term of species by cultivated field

$X_1 = 1$ for hog, and

$X_1 = 0$ for cow;

$X_5 = 1$ for near cultivated field, and

$X_5 = 0$ for not near cultivated field;

therefore $X_1 \times X_5 = 1$, if species = 1 & cultivated field = 1;

else $X_1 \times X_5 = 0$

β_{14} = coefficient for interaction product term of species by daytime

$X_1 = 1$ for hog, and

$X_1 = 0$ for cow;

$X_6 = 1$ for daytime, and

$X_6 = 0$ for nighttime;

therefore $X_1 \times X_6 = 1$, if species = 1 & daytime = 1;

else $X_1 \times X_6 = 0$

β_{15} = coefficient for interaction product term of species by temperature in K

$X_1 = 1$ for hog, and

$X_1 = 0$ for cow;

X_{10} = temperature in K

therefore $X_1 \times X_{10} = 1$, if species = 1 & temperature in K;

Daytime was the only non-significant (*P* = 0.518) variable when compared to referent = night (Table 14); however, the interaction term with species was highly significant indicating a differential increased rate for swine, but not cattle. The coefficient for species = hog of -48.75 (RRt = 6.7×10^{-22}) indicated that chance of feral swine contacting a cow via indirect contact, after adjusting for potential confounding factors, is greatly decreased relative to other cattle. Factors that decreased relative rates of CCIC and HCIC were riparian zone (RRt = 0.9), summer (RRt = 0.5) and fall (RRt = 0.7) relative to spring (referent), and temperature K (RRt = 0.9). Conversely, road (RRt = 1.3), water (RRt = 1.4), cultivated field (RRt = 1.9), and winter (RRt = 2.4) slightly increased relative rates of CCIC and HCIC compared to baseline referent values of the variables. Of the interaction terms where species = hog, only species × riparian zone (RRt = 0.4) reduced HCIC for hogs relative to cows. All other interaction terms increased relative rates of HCIC where species × road (RRt = 2.9) and species × daytime (RRt = 2.7) had greatest effect on differentially increasing rates for hogs when compared to cows.

Table 14. Final multivariable model for rate (/ha every 15 min) of indirect contact with a cow[a] using a random-effects Poisson regression multivariable model for species (hog = 1, cow = 0), landscape features, time of day, season, and temperature (K) in southern Texas, USA, 2004–2006.

Cow	Coef.[b]	RRt[c]	SE	Z	P>|Z|	95% CI
Species[a]	-48.75	6.7390E-22	4.7868	-10.18	< 0.001	-58.13, -39.36
Road	0.29	1.3331	0.0176	16.35	< 0.001	0.25, 0.32
Riparian zone	-0.08	0.9199	0.0357	-2.34	0.019	-0.15, -0.01
Water	0.40	1.4864	0.0403	9.83	< 0.001	0.31, 0.47
Cultivated field	0.66	1.9270	0.0423	15.52	< 0.001	0.57, 0.73
Daytime	-0.01	0.9895	0.0164	-0.65	0.518	-0.04, 0.02
Summer	-0.56	0.5701	0.0318	-17.67	< 0.001	-0.62, -0.49
Fall	-0.33	0.7210	0.0570	-5.74	< 0.001	-0.43, -0.21
Winter	0.88	2.4058	0.1373	6.39	< 0.001	0.61, 1.14
Temp K	-0.01	0.9910	0.0015	-6.18	< 0.001	-0.011, -0.006
Species × road	1.08	2.9533	0.2388	4.53	< 0.001	0.61, 1.55
Species × riparian zone	-0.89	0.4118	0.3696	-2.40	0.016	-1.61, -0.16
Species × cultivated field	0.60	1.8137	0.2544	2.34	0.019	0.09, 1.09
Species × daytime	0.99	2.7038	0.2221	4.48	< 0.001	0.55, 1.42
Species × temp K	0.15	1.1562	0.0161	9.01	< 0.001	0.11, 0.17
Intercept	-2.06	0.1275	0.5215	-3.95	< 0.001	-3.08, -1.03

[a] Model referent terms: for species (hog = 1, cow = 0); for landscape features (open range = referent); for season (spring = referent); for time of day (night = referent); and temperature (K)

[b] Coef. of contact is indexed to 0 for the given feature. Increased risk of contact if Coef. > 0 and decreased risk of contact if Coef. < 0

[c] Antilog of the sum of coefficients of interest = rate ratio. A random effect was included to account for the serial dependence of location for each animal. Rates are adjusted to account for both the variation in home range and for the relative proportion of the carrying capacity of hogs and cows represented by GPS-collared animals

DISCUSSION

Feral swine sampling

Feral swine sample population primarily consisted of unsexed shoats, then boars, and, then sows. This distribution may affect my results on a season-to-season basis because of social behavior differences as females remain in local groups with juveniles, whereas boars are solitary (Sweeny and Sweeney 1982, Ilse and Hellgren 1995*a*, Ilse and Hellgren 1995*b*, Gabor et al. 1999). Personal experience during the study suggests increased trapping success of younger shoats; possibly due to their naïve nature and close integration with the group. This was also apparent in the number of simultaneous shoat trappings where >1 individual was trapped concurrently. Consequently, many trapped shoats were too small for collars and were released. Feral swine boars were the most mobile, followed by shoats then by sows according to MCP analysis for area use. This distribution correlated with their documented social movement patterns (Sweeny and Sweeney 1982; Ilse and Hellgren 1995*a*, *b*; Gabor et al. 1999). Though feral swine demographics were recorded and attempted to be fit to the multivariable model, this analysis did not evaluate important intra-species differences based on demographic class. Future analyses using these demographic data and incorporating these into epidemiological models may be useful.

Contact relative to spatial distribution

Species effect on contact rate. Intra-species CC and HH were more common than inter-species CH and HC contact. Indirect contact (<20 m, within 360 min) occurred frequently within species with cattle-cattle surpassing feral swine-swine by 1.5-

fold. This is perhaps not surprising, as the extended lag-time between interaction points increased the number of potential contacts. This also fit my preconceived notion that herding animal species would interact more often with each other than they would across species. Within-species occurrence of DC (<20 m, within 15 min) declined relative to IC for both. Note that any DC was also by nature an IC. A decrease in occurrence of IC to DC was expected as a criterion of same place, same time offers a smaller window of interaction potential than does same place, later time to 6 hrs. Direct contact between species occurred extremely rarely. This fits with the biological principle that different species represent a unique ecological niche; and though integrated locally, do not tend to readily interact with one another. As hypothesized, IC between species declined dramatically from that within-species as livestock and feral animal behavior differ. Interestingly, total inter-species IC events for CH and HC were nearly equal (difference of 4 events over the study period). After close examination, I determined that this was not an artifact of matched animal pairing, instead a result of an apparent trend of inter-species behavior over time (see Table 5). This was supported by the extent of variation of number of observed contacts by study season for both CH and HC.

Regarding overall contact occurrence, only the near-exact and proportional inter-species IC between cattle and feral swine were opposite to expected outcomes. In summary, differences in social behavior for livestock versus wildlife may provide biological support for the overall disproportions and variability of contact occurrence between and within species. The extended time-window (in the case of indirect contact) allowed for increased contact, evident across all such interaction.

To further address the similarity between inter-species IC, I suggest metareplication (replicating the entire study) to evaluate the phenomenon in the present findings (Johnson 2002). Based on this evidence, it is possible to speculate that over many seasons, the number of CH and HC indirect contacts tend to even out (as illustrated to within a difference of 4 events). That would suggest that any effect associated with apparent seasonal, day-night, or landscape differences (e.g., order of presence, diurnal vs. nocturnal use of specific landscape) washes out over time.

Note on land use. For purposes of discussion, proportion of land use described were for the 4 features of interest (road, riparian zone, water body, and cultivated field) across all study seasons, and did not include open range (that area not represented by one of the 4 features). However, open range (or other rangeland) was modeled for relative rate of contact. The increased utilization of open range relative to all other features for both species was likely because of disproportion of size relative to the features of interests, which were a subset.

Road effect on contact rate. Cow contact (i.e., a cow being contacted by either species) was more common on roads relative to other rangeland; this suggests cattle used roads as travel corridors. Frequency of hog contact (i.e., a hog being contacted by either species) on roads was not different from open range. Cattle frequented roads more than any other landscape feature. Road use by collared cattle at higher percentages than smaller and disassociated landscape features may be attributed to a combination of feature area size and habitat selection, as road network areas tended to be greater. Cattle use of roads was consistent with findings described in Depew (2005) where this selection was documented (increased in summer and spring) on rangeland in southern Texas. My study site had an extensive road network (which included interior and perimeter fences), and may have provided both species with accessible energy-efficient travel corridors. Aggregate road area during the season could have offered travel corridors, as well as readily available forage for cattle in the ditches. As expected, wildlife tended to use roads for travel. However, decreased CH interaction on road was not expected. This may be due to differences in their behavior in the presence of other animals of either the same or different species. Recall that direct contact required close proximity at the same time. On the other hand, indirect contact permitted one animal to lag behind another by up to 6 hours. This would permit use of the same landscape, but without the behavioral issues associated with direct contact.

Riparian zone effect on contact rate. Riparian zones did not influence direct cow contact frequency, but within these areas IC was less frequent when compared to open range. A possible explanation is while cattle frequented riparian areas at lower proportions than other features, cows utilized its shade but did not regularly travel or forage within them. In addition, when cattle increased use of road or cultivated field a decrease in visitation to dense riparian zones would result. A surprising finding was that hog contact frequency in riparian areas was not increased. This is not consistent with land use as GPS data show collared feral swine spent the greatest amount of time in riparian zones compared to all other landscape features. The use of riparian areas was likely under-reported since the dense brush and habitat features interfered with hog fixes and might explain the differential day and night fixes for hogs but not cattle. This countered preexisting notions of feral swine interaction most often occurring in riparian zones. I speculate that feral swine use riparian zone cover primarily for resting, but not for feeding and moving, thereby decreasing interaction rates in these areas.

Water effect on contact rate. Relative to open rangeland, cow and hog were both more likely to be contacted near water by the other species. This was the only feature having significant influence for all contacts ($P < 0.05$). Water increased the relative rate for all contact types (inter-and intra-species) except for CC where contact was not affected by water. Interesting, yet perplexing, was the existence of an inverse relationship of water effect on CH and HC for indirect contact. That is, when RRt of CH was greatest, RRt of HC was lowest. Also, HC was greatest when CC was lowest. This disproportionate relationship may be due to differences in land use as described previously. Feral swine on average spent more time near water compared to cattle. Cattle used water at lower proportions compared to other features, suggesting they use water primarily for hydration and cooling. Water use by feral swine was ranked second. Behavior such as wallowing, and rooting suggests feral swine actively select for water at a greater proportion.

Cultivated field effect on contact rate. Cow contacts were more frequent in cultivated fields than open rangeland. Compared to open range there were less DC but more IC for hogs in cultivated fields. The GPS data suggested both species spent significant amounts of time in cultivated fields, when access was available (cows) and cropping was present (hogs). Cultivated field use ranked second for cattle and fourth for feral swine compared to other features. In cases where cattle were not restricted to cultivated fields, utilization of cultivated fields by collared cattle at higher percentages may have been attributed to preferred habitat selection. Rather large central-pivot irrigation fields and other cultivated land on the ranch could offer a nearby rich concentration of forage for cattle and feral swine resulting in increased utilization.

Daytime, season, and temperature effect on contact rate. Frequency of cow contact was not affected by daytime compared to nighttime hours. This may be attributed to the fact that while cattle are diurnal, they may chose to graze at night during hot weather. As expected, frequency of hog contact decreased during daytime. This may likely be due to increased nocturnal movement of feral swine, and increased sedentary duration in daytime hours, especially near water where contact with cattle may occur during the day (Deck 2006).

Seasonal differences influencing contact rate compared summer, fall, and winter to the referent spring. For a cow, contacts were less frequent in summer and fall, but more frequent in winter. This may be due to an increase in spatial distribution as diffusion during summer and fall occurred as cattle scattered in search of food. During winter, when natural forage is scarce, cattle utilize cultivated fields where increased contact may result. For a hog, contacts were more frequent in fall and winter. This may be due to cooler weather, sparse forage, and visitation to cultivated fields.

For each degree increase in temperature Kelvin, RRt for direct and indirect CC contact was slightly reduced, however hog interaction term (species × temp K) for direct and indirect HC increased RRt slightly. Conversely for IC of a hog, CH increased while HH (interaction term applied) decreased for each increase in temperature Kelvin.

Interestingly, a pattern existed between inter- and intra-species contact. Inter-species contact tended to occur at higher temperatures, while intra-species contact occurred at lower temperatures. The temperature effects were adjusted for season; therefore, the effect in general is across seasons. Though temperature effect varied slightly from the season-based pattern described above, combining both in the model illustrated the effect of temperature change across all seasons.

Confounding factors

It should be noted that the study precision and estimates concerning the disproportionate land use, stratified relative rates of contact, and model-derived rates may be affected to an unknown degree by small sample size and GPS collar accuracy. Ideally direct contact criterion would be set to 0 m and exact time points, however GPS precision limits this (Schauber et al. 2007), and time fixes were not identical. In addition, I believe the Euclidean distance calculation did not introduce significant error due to earth curvature, as distance between GPS points was relatively small (max length of study area < 21 km), and UTM referencing were used (Bonner et al. 2003). To account for the possible introduction of temporal autocorrelation, an artifact of near-in-time successive data (Swihart and Slade 1985), the multivariable model introduced a random-effect element that accounted for serial dependence of location for each collared animal. This strengthened our inference upon the data (i.e., that successive locations were independent points within each animal). Furthermore, independence across animals was assumed. On average, cow collars performed twice as long, and due to various (uninvestigated in this study) reasons acquired more positional fixes. I hypothesize that reduced GPS fixes for feral swine may be due to confounding field conditions such as habitat selection in relation to their spatiotemporal distribution (e.g., dense riparian or brushland areas at mid-day that may cause receiver failure) or other species-specific factors (Hulbert and French 2001, Deck 2006). This suggestion may have self-supporting empirical basis, as feral swine percent-night fixes were 57% — compared to cattle at a baseline 50%; therefore the largely nocturnal species presented evidence related to its spatiotemporal distribution. Area use derived using MCP method (Coblentz and Baber 1987, Ilse and Hellgren 1995*b*) included all area traveled while collared, and provided maximum potential for interaction as opposed to a reduced normal home range derived by other methods (Girard et al. 2002). Though MCP may underestimate the true home range (Girard et al. 2002), given the scope of research (radiotelemtery sample duration, constrained livestock, and relatively small sample area/season), I feel this approach was sufficient. Dates between season (defined as a 3 month period associated with climate) used in the multivariable model was not equivalent with study season (A–H) dates which were dependent on sampling periods. Therefore, direct comparisons between study season (A–H) and season-variable seasonal trends were not conducted. Future analysis may account for this. To reflect discussion in Schauber (et al. 2007), due to positional error my estimation of contact rates are explicitly crude and cannot precisely predict effective agent transmission. Difficulties arose concerning use of different GPS radiotelemetry collar models (from different manufactories) such as performance issues, onboard technical protocol (standardized time), post processing, and drop-off mechanism. Feral swine sampling ultimately affected many factors such as sample size, duration of sample, demographics, and herd representation. Other problems and concerns were discussed in a similar research study conducted in series with the present work (Deck 2006).

Future research

This project will provide information on future modeling of effective contact rates conducive to disease agent transfer between free-ranging wildlife and rangeland livestock. The empirical spatial distribution and derived contact data may be used to update current epidemiological models conceptualized on livestock-wildlife interaction such as the geographic-automata model described in Ward (2007:In Press). Additional analyses using the same data have already been conceptualized (some already started) amidst the analysis of this thesis project. These include applying specific climatological data, soil moisture index, and viral-decay functions to predict FMDv survival in southern Texas. These will impact the ‘effective’ contact component time, space, and survival and spread of the disease agent in those 2 dimensions, respectively. Furthermore, when incorporated into mathematical models of infectious diseases, these data will increase their predictive utility. Better prediction and response measures will help limit potential incursions of FADs and help safeguard agricultural, ranching, and wildlife industries both domestic and abroad. I anticipate that knowledge gained in this study will significantly enhance our understanding of the complex issues involved with safeguarding of resources.

Cooperation

My research scope provided a unique opportunity for collaboration among multi-disciplinary and multi-institutional research partners. I appreciate the continued support of ranch personnel, as their involvement was essential to the successful completion of the proposed research. These industry partners maintain on-going collaboration efforts with researchers; illustrating their interest in preserving and strengthening the natural resource for which they are stewards. Support for my research initiative was provided by members of Texas A&M University Agriculture Research and Extension Center at Uvalde, the Hispanic Leadership Program in Agriculture and Natural Resources, and the United States Department of Agriculture.

Summary

Spatial distribution and consequently disproportional land use of collared cattle was ultimately influenced by stocking density and herd placement; therefore limiting access to landscape features. The proportional use between landscape features of interest by collared feral swine may have been a result of their free-ranging ability, thus expanding past that area accessible by restricted cattle. Studies have documented increased utilization of riparian zone (as source of cover and water) by feral swine especially during summer, fall, and spring (Ilse and Hellgren 1995*b*, Gabor et al. 1999, Deck 2006), which was consistent with my findings.

A summary of general contact findings are as follows. Factors that influenced feral swine contact most: water, cultivated field, night, fall, and winter. Factors that influenced cattle contact most: water, road, cultivated field, and winter. Common factors between species included: water, winter, and cultivated field. With regard to disease-threat management, findings suggest that potential response strategies include: removing cattle from rangeland, watering cattle only in elevated troughs (unavailable to feral swine), removing cattle from cultivated fields then cutting (plowing or burning if infection is present). For management of feral swine it is advised to bait for hogs at water and cultivated fields prior to their clearing.

CONCLUSION

My investigation of inter- and intra-species contact rates between GPS-collared cattle and feral swine on rangeland in southern Texas, produced results in accord with generally accepted notions in addition to significant findings that interestingly counter current preconceptions. Given the complexity of the system attributed to free-ranging wildlife (Morgan et al. 2006) and further increased by feral swine behavior, the lack of literature on the system (namely species and methodologies employed) suggests the possibly of being one of the first of its kind. This is evident as there is a known lack of reliable knowledge (especially refined empirical data) on the subject matter (Pech and Hone 1988, Doran and Laffan 2005, Deck 2006, Richomme et al. 2006, Ward et al. 2007: In Press). Morgan (et al. 2006) emphasizes the need for data of the type presented in this thesis. He then continues by describing the difficulty involved with accurately estimating effective contact of wildlife by adding: “this leaves us with a dilemma: the complexities which we really ought to include in our models are the very ones that are hardest to quantify", (Morgan et al. 2006:249). As a result, relative reference literature used for discussion and implications were sparse. There is a growing demand for modeling and investigating the possibility of emergent diseases crossing the domestic livestock-wildlife barrier (Doran and Laffan 2005, Morgan et al. 2006, Richomme et al. 2006, Ward 2007: In Press). Few epidemiological models are constructed for this cross-species type system. My research highlights the need to consider different parameters and refine those current models. The empirical spatiotemporal data and derived contact rates described here will give wildlife biology and epidemiology powerful tools to propagate research and adequately address this knowledge gap via analytical modeling.

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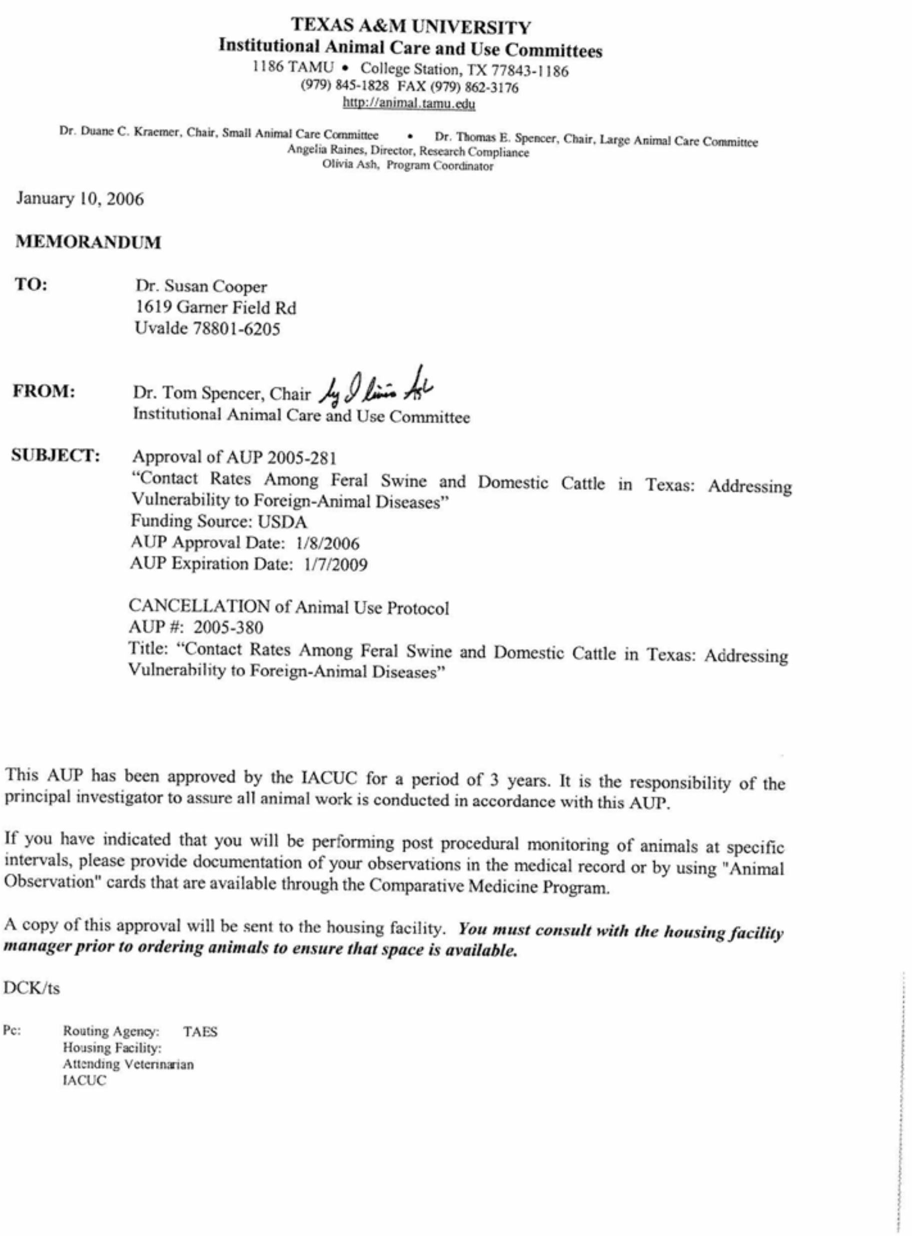
APPENDIX



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January 10, 2006

MEMORANDUM

TO: Dr. Susan Cooper
1619 Garner Field Rd
Uvalde 78801-6205

FROM: Dr. Tom Spencer, Chair
Institutional Animal Care and Use Committee

SUBJECT: Approval of AUP 2005-281
"Contact Rates Among Feral Swine and Domestic Cattle in Texas: Addressing Vulnerability to Foreign-Animal Diseases"
Funding Source: USDA
AUP Approval Date: 1/8/2006
AUP Expiration Date: 1/7/2009

CANCELLATION of Animal Use Protocol
AUP #: 2005-380
Title: "Contact Rates Among Feral Swine and Domestic Cattle in Texas: Addressing Vulnerability to Foreign-Animal Diseases"

This AUP has been approved by the IACUC for a period of 3 years. It is the responsibility of the principal investigator to assure all animal work is conducted in accordance with this AUP.

If you have indicated that you will be performing post procedural monitoring of animals at specific intervals, please provide documentation of your observations in the medical record or by using "Animal Observation" cards that are available through the Comparative Medicine Program.

A copy of this approval will be sent to the housing facility. ***You must consult with the housing facility manager prior to ordering animals to ensure that space is available.***

DCK/ts

Pc: Routing Agency: TAES
Housing Facility:
Attending Veterinarian
IACUC

A-1. Institutional animal care and use protocol documentation for 2004–2006 investigation of foot-and-mouth disease virus transmission via effective contact between domestic cattle and feral swine on rangeland in southern Texas, USA.

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