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OBSERVATIONS ON THE CONTACTS AND HOME RANGES OF FERAL GOATS IN RELATION TO THE SPREAD OF DISEASES OF LIVESTOCK

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ABSTRACT: Many diseases of livestock, such as foot and mouth disease (FMD), rinderpest, pest des petite ruminants, and maedi-visna, are exotic to Australia and contingency plans are in place to counteract their introduction. Epidemic modeling fulfills a vital role in these plans. Feral goats occur at high density with livestock in the high-rainfall zone of eastern Australia. Contact within and between groups of domestic and feral ungulates contribute to the behavior of disease in sympatric populations, and are essential parameters for epizootic models. A project in central New South Wales, Australia is investigating the contacts and home range sizes of feral goats in order to construct models for FMD transmission. Preliminary analysis has shown that contacts between feral goats and sheep were fewer than between feral goats, and that the home ranges of goats in the study were small (<2.5 km²). This paper discusses: the home ranges of feral goats in different environments; the interactions between feral goats and sheep; the potential of feral goats to maintain and spread exotic diseases common to goats and sheep; and modeling of disease transmission between feral goats and sheep.

KEY WORDS: feral goats, sheep, contacts, home range, disease transmission, exotic diseases

INTRODUCTION

The interactions between sheep (*Ovis aries*) and feral goats (*Captra hircus*) are probably the most common of all interactions between domestic and feral livestock in southern Australia. The diets of sheep and goats overlap (Harrington 1982), and the two species are often seen together where they are sympatric (Landsberg and Stol 1996). Many serious diseases of ruminant livestock are currently exotic to Australia (Geering et al. 1997). In areas where they co-occur, feral goats and sheep would potentially have an epidemiological role in an exotic disease to which both are susceptible. Exotic diseases, once established in farmed livestock, might spread into sympatric populations of feral goats, making disease eradication more difficult. The transmission of diseases depends on the rate of contact between animals, the duration of the infectious period, and the infectiousness of the disease (Thrusfield 1995). To produce predictive models that are useful for planning for exotic disease outbreaks, these three variables must be known or estimated.

Feral Goats in Australia: Their Distribution and Ecology

Goats were domesticated from the wild goat (*Captra aegagrus*) of southwest Asia (Harris 1962) approximately 9000 BP (Clutton-Brock 1992) and are now divided into a large number of breeds selected for meal, milk, and fiber production. The first goats that came to Australia were brought with the First Fleet in 1788 (Australian Geographic Society 1996) to provide meat and milk for the journey from England and the penal colony at Port Jackson. There have been numerous importations since then, including cashmere and angora goats between 1832 (Mitchell 1988) and 1900 (Evans 1980), Texan and South African angoras in the early and mid 1980s, and Boer goats from the late 1980s to the present (M. Lollback, pers. commun.). The feral population (not managed, movements not restricted by fences) (Figure 1) is derived from accidental and purposeful releases of domestic goats, a process that continues today (Parkes et al. 1996). The most extensive populations occur in semi-arid rangelands (Parks et al. 1996), but the highest densities live in high rainfall areas (>600 mm mean annual rainfall) where capture and control are difficult (Fleming, Tracey, and Jones, unpublished data; compared with O'Brien 1984, King 1992, Freudenberg and Barber 1999).

Figure 1. The distribution of feral goats (shading) in Australia (after Parkes et al. 1996).

Feral goats are generalist herbivores and the choice of available forage principally governs diet (Harrington 1982). Goats will take a proportion of senescent forage, and browse and digest low quality, more fibrous diet more efficiently than sheep (Devendra 1978). These characteristics allow goats to exploit drought-affected habitats longer than sheep even though the nutritional requirements of goats are higher than sheep (Huston 1978).

The distribution and abundance of feral goats in semi-arid areas is believed to be associated with the availability of water (Parkes et al. 1996). In wetter areas, feral goats can obtain most of their water requirements from their forage (Parkes et al. 1996), and viable populations exist on islands that have no permanent fresh water (e.g., Macaughley Island; Williams and Rudge 1969). Feral goats can occur in areas with rainfall above 225 mm per annum and the presence of dingoes seems to affect their distribution (Parkes et al. 1996). Home ranges are smaller in high rainfall zones.

Feral Goats and Disease

Feral goats are susceptible to many of the same diseases as domestic ungulates. In Australia, goats are implicated in the spread and maintenance of endemic sheep diseases including ovine footrot (Claxton and O'Grady 1986), macroparasite infection (Le Jambre 1984), and caseous lymphadenitis (Batey 1986). Zoonoses, including leptospirosis (Hungerford 1975) and Q-fever (Harrington 1982), can also be carried by feral goats.

Australia enjoys a trade advantage because of its freedom from many serious diseases of livestock. Goats are susceptible to exotic diseases such as foot and mouth disease (FMD), rinderpest, pest des petite ruminants, bluetongue, Rift Valley fever, scrapie, goat pox, and contagious caprine pleuropneumonia (Geering et al. 1995). The presence of these diseases in the Australian domestic or feral herds would cause serious production losses and closure of many markets for Australian livestock products, and severely affect the balance of trade and the national economy (Wilson and Choquenot 1996). Therefore, Australia has in place contingency plans, called AUSVETPLANS, to eradicate these diseases should they occur in domestic animals or wildlife.

Because the above diseases are exotic, plans rely heavily on the predictions of epidemiological models. Commonly, models of the progress of disease from infected individuals through susceptible populations of con-specifics can be called SIR (Susceptible, Infectious Recovered) (e.g., Boccora and Cheong 1992) or SL (or E) IR (Susceptible, Latent (Exposed), Infectious, Resistant/Recovered) models (e.g., Ferguson et al. 1997). These fall into two basic categories: deterministic (e.g., Pech and Hone 1988) and stochastic (e.g., Hone et al. 1992). Deterministic models simply describe the progress of diseases through homogeneously mixed populations. Stochastic models respond to variability that exists in heterogeneously mixed populations and are, therefore, more complex than deterministic models. Both types of models can be spatial (e.g., Pech and McIlroy 1990) or non-spatial (e.g., Pech and Hone 1988), the former

having components reflecting the distribution of a population in a landscape.

All models require that the rate of disease transmission, the transmission coefficient (sometimes termed β, which has the units km^2 day^{-1} $individual^{-1}$; Caley 1993) be known or estimated. The transmission coefficient describes the rate of transmission of diseases from infected to susceptible individuals (Anderson and May 1979) and is the most influential parameter in all disease models. The coefficient incorporates disease and host animal components including: the infectiousness of the disease; the mode of transmission; and behavioral characteristics that relate to contact between individuals. The empirically derived contact rate between individuals, $\underline{C}$ (units=contacts $individual^{-1}$ day^{-1}; Caley 1993) is an analogue of β measured in veterinary epidemics and becomes useful in models through equations like,

$\beta=2$ x $\underline{C}/\underline{N}(\underline{N}-1)$,
where $\underline{N}$ is the population size (Caley 1993).

The first step in calculating the contact rate and the transmission coefficient is to measure the number of contacts per hour of observation, which I have termed, $\underline{c}$.

Home range use is obviously an important determinant of the amount of contact within and between species. The home range areas of feral goats differ between environment, and male goats usually have larger home ranges than females (e.g., King 1992; Holt and Pickles 1996). At the high rainfall site of O'Brien (1984), the mean home range of feral goats was approximately 1 km^2. Freudenberg and Barber (1999) found mean male home ranges of 29.4 km^2 and female home ranges of 10.9 km^2 at Louth in semi-arid northwest New South Wales.

This paper discusses feral goats in Australia, the transmission of diseases, and provides preliminary data about the home ranges of feral goats and the contacts between sheep and feral goats. It draws some conclusions about the potential of feral goats to maintain and spread diseases common to goats and sheep in an area where both species occur at high population density.

METHODS

The study site, near Coolah (149°50'E, 31°48'S) (elevation: 640 to 1015 m) on the tablelands of central New South Wales, has a population of feral goats occurring at high density (15.5 to 24.7 goats km^{-2} mean density and local densities to 75 goats km^{-2}) and also has managed, fenced sheep and cattle at high density (250 to 800 sheep equivalents km^{-2}).

Feral goats have been mustered on 12 occasions, and 877 goats have been individually double-eartagged for identification, sexed, aged, and had their reproductive status determined. The individually numbered eartags are discernible at approximately 140 m with the aid of 10x magnification binoculars. The marked goats are used for home range estimation, movement determination, and as focal animals for contact observations. Radio-collars have been fitted to 55 goats to study their movements and home ranges, and these animals are also used as focal animals. Radio-tracking is undertaken using hand-held and fixed-tower antennae.

This paper has been peer reviewed.

Contacts, $\underline{c}$, are determined using direct observation and are defined as approaches, between individuals, of one body length or less per hour of observation. This definition encompasses the degree of contact required for those diseases, such as FMD, where transmission is most likely between sheep and goats in close proximity or physical contact sharing respired air (McVicar and Sutmoller 1968). Goats and sheep are of similar body length (approximately 1 m) and a body length is easy to estimate regardless of the distance of the goats and sheep from the observer. During the period from May 1997 to December 1999, a total of 9,248 contacts were recorded during 1,200 observation periods. After first testing for equivalence of variance using $\underline{F}$-ratios, Student's $\underline{t}$-statistics (Snedecor and Cochran 1967) were used to compare the contacts of male, female, and juvenile goats with other goats, and of sheep and male, female, and juvenile goats.

Home ranges were estimated using the Minimum Convex Polygon (MCP) method including 95% of fixes (Harris et al. 1990) in Ranges V (Kenwood and Hodder 1996). The validity of home range estimates were checked using incremental analysis where home range size is plotted against cumulative number of position locations (Harris et al. 1990). For this paper, the home ranges of those goats with valid incremental analyses for positions located between August and December 1997 were calculated and, after first testing for equivalence of variance using $\underline{F}$-rations, Student's $\underline{t}$-statistics (Snedecor and Cochran 1967) were used to contrast the areas used by female and male goats.

RESULTS

The contacts between goats were more frequent than between goats and sheep (Table 1). On 91.5% of observations, goats did not contact sheep. Female and juvenile goats contacted other goats at the same frequency, and males contacted other goats more frequently than juvenile goats. There was no difference in the rate of contact with sheep made by the three types of goat.

The short-term home ranges of feral goats were small (range: 0.5 to 4.6 km^2) and male feral goats had larger home ranges (mean=2.23 km^2, S.E.=0.26, n=15) than female feral goats (mean=1.4 km^2, S.E.=0.18, n=18; $\underline{t}$=2.699, $\underline{P}$=0.006, d.f.=31). Topography and vegetation distribution appeared to be important in defining home ranges. Home ranges were not limited by fences, per se, although fencing was often aligned with topographical features.

DISCUSSION

Because feral goats are gregarious, contacts within groups were high. Although the density of sheep was high, contacts with feral goats were much lower than between feral goats. Therefore, assuming equal susceptibility between species, there is a greater chance of spread and maintenance of a disease such as FMD within species than between the species. However, often there are threshold densities above which diseases will spread within populations and between populations (Anderson and May 1979). Further study is needed to ascertain what these densities are for the various exotic diseases to

which sheep and goats are susceptible. Conversely, where the transmission of disease appears to be dependent on the proportion of individuals that are infected, e.g., *Brucella* infection in Yellowstone bison (Dobson and Meagher 1996), there is no threshold density of animals, because the proportion of the population that is infected is equivalent for all population sizes.

The home ranges calculated here are only for the late winter/spring/early summer period and, therefore, likely underestimate the true home ranges of feral goats at the site. However, the mean home range areas for female goats were closer to those reported by O'Brien (1984) (1 km^2) than King (1992) (17.1 km^2), Holt and Pickles (1996) 15.4 km^2, or Freudenberg and Barber (1999) (10.9 km^2). This was expected because the environment near Coolah is much more productive than in the arid and semi-arid areas of King (1992), Holt and Pickles (1996), and Freudenberger and Barber (1999), but less productive than Moreton Island where O'Brien (1984) undertook home range studies. The larger home range of males implies that they would be more likely to spread disease between groups of goats if male home ranges overlapped more than one group of females.

Modeling is required to forecast the progression of diseases between feral goats and sheep. As previously mentioned, models of increasing complexity are possible, from simple deterministic (e.g., Anderson and May 1979; Pech and Hone 1988), through spatial deterministic (e.g., Pech and McIlroy 1990), through stochastic (e.g., Hone et al. 1992), through lattice spatial models (e.g., Rhodes and Anderson 1997) through multispecies deterministic (e.g., Dobson and Meager 1996), multispecies stochastic and multispecies lattice models to combined GIS and epidemiology two-species models. Contact rates and transmission coefficients can be calculated using the contacts, $\underline{c}$, determined in this paper and density estimates yet to be derived. Longer-term home range estimates from this study will allow GIS modeling of habitat use and preferences, and disease spread.

On completion of my study, models will be applied for FMD in sympatric sheep and feral goats, and for caprine arthritis-encephalitis (CAE) in feral goats. The basic deterministic (SLIR) model (e.g., Pech and Hone 1988) uses a set of derivative equations which describe the rate of movement of animals between the four states of disease, i.e., Susceptible, Latent, Infected, and Recovered and assumes logistic growth. For each disease, a set of equations and parameters (including host birth and death rates, density-dependent reduction in host births) is required for each species. These equations will be solved using β terms for within and between species transmission, threshold densities, and the rate of population changes in the presence of disease for FMD in sheep and goats and CAE in goats. In the two-species deterministic model of Dobson and Meagher (1996), there are two β terms, β_{ij} for within-species transmission and β_{ij} for between-species transmission. In my case, the empirically-derived, equivalent β terms will be used.

The logistic growth term is removed and replaced by a varying death rate, $\underline{b}$' (Pech and McIlroy 1990), and a variable β term, β' (eg., Dexter 1995) in a stochastic model of FMD. To obtain variable β' terms, random draws from the empirically derived βs for different

Table 1. The mean contacts (contacts/hour of observation; S.E. in brackets) of feral goats and sheep at Coolah, New South Wales and comparisons between the mean contacts that males, females, and juvenile goats made with other goats and with sheep.

Type of Goat	Contact With	
	Other Goats	Sheep
Male	35.00 (6.49)	1.53 (0.45)
Female	24.95 (2.19)	2.55 (1.01)
Juvenile	21.87 (2.61)	1.77 (0.57)
All Goats	28.18 (2.54)	2.13 (0.59)

Contacts with Other Goats			t	P	df
Male cf female goats			1.467	0.070	513
Female cf juvenile goats			0.905	0.183	288
Male cf juvenile goats			1.877	0.031	511
Contacts with Sheep					
Males cf female goats			0.921	0.179	908
Female cf juvenile goats			0.675	0.250	717
Male cf juvenile goats			0.327	0.372	258
All goats			9.819	<0.001	1324

densities of goats will be used in much the same manner as Dexter (1995) did for FMD in feral pigs (*Sus scrofa*).

Diffusivity constants, $\underline{D}$ (Pech and McIlroy 1990), area required in spatial stochastic models and their use assumes that movement of the disease through a population resembles diffusion of gases. $\underline{D}$ is related to movements, thus;

$$\underline{D} = \frac{1}{4}\underline{n}(\Omega^2),$$

where $\underline{n}$ is the number of straight line distances moved between locations of an animal and Ω^2 is the mean square length of straight line movements. Straight-line movements of feral goats will be derived from radio-telemetry and ground-based locations, and a spatial stochastic model for FMD in sheep and feral goats run.

A combined GIS and deterministic two-species FMD model, similar to the distribution model for red and gray squirrels used by Rushton et al. (1997) will be constructed using home range and movement information for sheep and feral goats.

Threshold densities $(\underline{N}_T)$ can be calculated from deterministic models using the equation,

$$\underline{N}_T = (\alpha + \underline{b} + \upsilon)/\beta \text{ (Anderson and May 1979)}$$

or SIR models or,

$$\underline{N}_T = (\sigma + \underline{b})(\alpha + \upsilon + \underline{b})/\beta\sigma \text{ (Hone 1994)}$$

when latent animals are included. The latter equation will be used to derive threshold densities in my first set of models, substituting empirically derived parameters for sheep and feral goats. In the second (stochastic) set of models, $\underline{b}$' and β' will be substituted.

The likely influence of the increasingly popular domestic goat industry on the spread and maintenance of diseases shared by sheep and goats in Australia also requires investigation. I expect that diseases will spread more quickly between domestic goats and sheep because the densities at which they are run are usually higher than that at which feral goats are tolerated. Models of FMD could be fitted with parameters from domestic goat/sheep interactions. Study of endemic diseases in domestic goats and sheep under intensive husbandry common to the stud goat industry would assist in planning for exotic diseases.

This paper has been peer reviewed.

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