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Goats and sheep often graze together and guardian dogs are commonly used for protection from predators. The objective of this experiment was to characterise how goats, sheep and guardian dogs interact spatially when grazing the same pasture by use of global positioning system (GPS) collars as an unobtrusive means of behaviour monitoring. In 2002 and 2003, three meat goats and two sheep in a group of 12 of each species were randomly chosen and, along with a guard dog, fitted with GPS collars. Minimum distance travelled between consecutive 30-min fixes and distance between any two animals at the same fix time were calculated using spherical geometry. In 2002, the dog travelled the least between fixes during the day but more at night than either goats or sheep. However, in 2003, there was not a significant species difference in distance travelled in 24 h or during the day or night. All species travelled significantly more during day than night but none were stationary at night. Distance amongst goats and between sheep tended to be greater during day than night; distance between goats and sheep was greater than the distance amongst goats or between sheep. Hence, goats and sheep interacted as two separate entities rather than as one large herd/flock. Distance between the dog and goats was closer than between the dog and sheep, indicating a clear preference of the dog for goats that could relate to a difference in previous exposure to the two species. In summary, based on these findings protection by a guardian dog would be greater for a small group of goats than sheep and much greater than for a mixed species group. Or, with a large group of grazing animals, the number of dogs required for a certain level of protection would rank goats < sheep < mixture of goats and sheep.

Keywords: goats; sheep; GPS; guardian animal; spatial behaviour

Introduction

In the USA and elsewhere, guardian dogs are commonly used to protect small ruminants from predation and theft (Andelt and Hopper 2000; Smith et al. 2000; Hansen et al. 2002). In some instances, the dog may be required to guard more than one species of small ruminants that is a mixed group of goats and sheep. Moreover, how these three species interact behaviourally when sharing a common pasture is unknown. Most ethologic studies involving small ruminants have been on sheep, with little attention given to goats and/or mixed species groups (Rutter 2002; Schlecht et al. 2006). Sheep and goats in mono-species groups generally form small cohesive units, move as one entity into new or unfamiliar terrain, demonstrate a strong preference to remain in the group and become very distressed when separated (Launchbaugh and Howery 2005). Cattle and sheep in mono-species groups also have been shown to maintain distinct social spacing within and across groups. Hill-climbing and bottom-dwelling cows maintained separate areas in a large pasture and did not consistently graze together, even using different water sources (Bailey et al. 2004). Scottish hill sheep will monopolise an area of a hill and avoid close contact with other groups of sheep sharing the same pasture (Rutter 2002). In one study examining the social behaviour of a mixed group of goats and sheep (Yasue et al. 2000), an interaction period of one year was needed to thoroughly integrate goats and sheep for behavioural responses as a single entity.

In addition to how different animal groups interact with one another, grazing animals can exhibit usage preferences for particular grazing areas. For example, a small herd of 18 Saanen goats preferred certain areas of the pasture for resting or eating and utilised those areas much more frequently than others (Matsuzawa and Shiraishi 1989). Locational differences amongst individuals in preferences for resting or eating were also noted, especially amongst the four dominant bucks in the herd. Goats also develop a strong social structure, and when new goats are introduced into a herd the structure is disrupted for up to 4 weeks (Launchbaugh and Howery 2005).

The traditional method of human surveillance to monitor domestic animal behaviour is labour

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intensive, can affect subject behaviour, and usually does not offer 24-h monitoring over an extended period (Roberts et al. 1995). Recently, global positioning system (GPS) collars have provided an unobtrusive solution with a high degree of location accuracy (Turner et al. 2000; Agouridis et al. 2004). The new generation of GPS collars is small and lightweight enough not to interfere with or restrict grazing and other activities (Hulbert et al. 1998) or cause physical harm to the animals (Krausman et al. 2004). In cattle, GPS collars have been used to evaluate management techniques while grazing in riparian zones (Turner et al. 2000), assess effects of salt and water manipulation on animal distribution in large pastures (Ganskopp 2001), monitor grazing and resting activities (Schlecht et al. 2004; Ungar et al. 2005), study individual preferences for areas of land differing in topography (Bailey et al. 2004) and characterise factors influencing energy used in grazing (Brosh et al. 2006). In goats, GPS collars have been used to estimate distance travelled as a possible factor associated with energy expended during grazing (Goetsch et al. 2009; Beker et al. 2010) and to evaluate forage utilisation in a traditional shepherded herd on extensive rangeland (Arnon et al. 2011).

GPS collars have also been employed to monitor grazing behaviour of cattle, sheep and goats in a mixed animal group (Schlecht et al. 2006). In this study, GPS units were used for spatial-temporal modelling of livestock-resource interactions of co-grazing animals when herded and free-grazing. Interest was not in interactions of the different species but how they reacted to the same grazing environment. However, only four GPS units were deployed in the study and it is not clear if all units were used on the same or different species simultaneously. Units were deployed for 1-day measurement periods. Nonetheless, GPS collars have not been used to simultaneously monitor activities in a mixed herd of goats and sheep and their accompanying guard dog. Such information would be of value in grazing management decisions such as the degree of protection to the different ruminant species afforded by a guard dog or the number of dogs needed for larger animal groups of the different or both species. Therefore, objectives of this research were to examine spatial and temporal interactions of goats, sheep and guard dogs using GPS collars.

Material and methods

Study site

The study site, located in central Caddo County in Western Oklahoma, was pastureland of the Caddo Nation that had not been grazed in a number of years. The pasture was a slightly irregular polygon with side lengths of 167, 79, 190 and 65 m starting from the northeast corner (35°7′ 1.54″N, 98°15′ 11.57″W) and working clockwise. The total area was approximately 1.3 ha. The study area had been an improved pasture of lovegrass (*Eragrostis curvula*), but its non-use had enabled thickets of smooth sumac (*Rhus glabra*), sand plum (*Prunus angustifolia*) and black locust (*Robinia pseudoacacia*) to become established. Sumac covered approximately 60% of the area and sand plum covered 15%. Under the canopies, there was little lovegrass because of competition with trees for sunlight. Lovegrass in open areas as well as some under the canopy of woody species was being self-smothered by accumulated residue from previous growth. This self-smothering had reduced the vigour of the grass and put it at a competitive disadvantage to sumac. Goats and sheep in combination were used to control the sumac and sand plum and break up accumulated grass residues.

Animals

During the summer grazing seasons of 2002 and 2003, 12 Boer-cross goats (yearling) and 12 Rambouillet-cross sheep (born in the previous fall) grazed the pasture and were accompanied by one guardian dog from the American Institute of Goat Research of Langston University. Different animals, including the guardian dog (Great Pyrenees in 2002 and Anatolian in 2003), were used in the two grazing seasons. Each year, three goats and two sheep were randomly chosen and fitted with GPS collars, along with the dog. In 2002, the average body weight (BW) of goats and sheep at the beginning of the experiment was 37.5 ± 3.98 and 30.3 ± 3.19 kg, respectively. In 2003, the average BW was 31.1 ± 3.64 kg for goats and 39.7 ± 2.36 kg for sheep.

GPS collars

Collars were GPS 3000 lightweight remote tracking collars (Lotek Engineering Inc., Newmarket, Ontario, Canada) with dimensions of $68 \times 48 \times 58$ mm ($L \times W \times H$) and weight, including battery and light duty belt, of 295 g. These very lightweight collars are typically used to track small wildlife and have not been employed often to study smaller domesticated animals. The GPS 3000 is capable of locking onto eight satellites simultaneously to fix location of latitude and longitude, with fixes stored in memory in degrees to eight decimal points. Memory capability is sufficient for storage of approximately 40,000 location fixes. In addition to latitude and longitude, each location fix record contained the corresponding date, time, elevation or height estimate, dilution of precision value (DOP; a numerical value of the expected accuracy of a location fix based on the geometry of satellites used for that location fix), fix status (two and three dimensional; 2D and 3D, respectively), number of satellites used, and ambient temperature. Using a flexible scheduling option, location fixes were recorded every 30 min for approximately 2 weeks (July 2002 and June 2003). Maximum time to acquire a fix was set to 70 s. Scheduling and location fix data transfer between the collars and a personal computer was accomplished by using a download link connecting the two units via a serial port with special cabling and by using proprietary software (Lotek Engineering Inc.).

Calculations

Even with the removal of Selective Availability in 2000, post-processing of the collar files increases the accuracy of the latitudinal and longitudinal location fixes generated by the GPS collars (Adrados et al. 2002; Coyne et al. 2003). Post-differential correction is a process using data collected from a nearby continuously operating reference station (CORS) covering the same time interval as the GPS collar study. The CORS GPS receiver continuously calculates its location based on satellite signals, compares this location fix to its known latitude and longitude and creates an observation file with correction factors. The observation files along with precise satellite navigation files are made available to the public. The CORS closest to the study area was located at Purcell, OK (34°58′47.49577″N, 97°31′09.26486″W), 68.6 km away. Corrected fixes were then imported into ArcMap 9.3 (ESRI, Redlands, CA). Boundaries of the plot including a 7-m external buffer were constructed as shapefiles using a coordinate system of WGS 1984 UTM 14N. The X and Y coordinates in meters were calculated for each fix. Only fixes within the boundary and buffer shapefiles were exported. A grid with 10×10 m squares was overlaid on the shapefiles and a grid analysis (points in polygon) was conducted. Minimum distance travelled between consecutive fixes and distance between any two animals at the same fix time were calculated using Euclidian geometry. The area within pastures did not markedly vary in elevation; therefore, vertical distance travelled was not computed.

The heading from the previous to current fix and turning angle involving three consecutive fixes were calculated using spherical geometry (Jerde and Visscher 2005; Nams 2006; Brooks and Harris 2008). Minimum total distance travelled in a 24-h period and during the day (06:30–21:00 hours) and night was calculated.

Statistical analyses

A repeated measures, mixed model analysis (Littell et al. 1996) was conducted using the SAS (1988) statistical software package. For minimum distance travelled between consecutive fixes and for minimum total distance the statistical model included animal identity (12 individuals), species (dog, goat or sheep), year (2002 or 2003), fix time (0:00, 0:30, . . ., 23:30) and all interactions, with identity nested within species and year as a random effect, although, fix time was excluded from the model for total distance. A second model was similar to the first except for substitution of day and night for fix time as appropriate. For distance between any two animals at the same fix time, the statistical models were similar to the first and second but with species categories of dog–goat, dog–sheep, goat–goat, goat–sheep and sheep–sheep.

Results and discussion

GPS collar weight

The weight of GPS collars was 295 g. The GPS collar ranged from 0.75 (sheep in 2003) to 0.97% BW (sheep in 2002). These percentages are less than half of the 2.2% value in the Hulbert et al. (1998) study and from which it was concluded that collar mass had no significant effect on bite rate, circadian rhythms or BW change. In fact, GPS units as high as 8% of BW have been used in sheep and goats without adversely affecting physical condition or grazing behaviour (Schlecht et al. 2006).

GPS fixes

Over the 2 years, there were 8556 total fixes. Table 1 represents the percentage of fix type and species across the 2 years. As expected, dogs accounted for 16.6% (one out of six collars), goats 50% (three out of six collars) and sheep 33.4% (two out of six collars) of the total fixes. Year 2002 accounted for 52.9% and year 2003 for 47.1% of the total fixes, with this difference due to an approximate 42 h longer time that animals wore collars in 2002. Within species the percentage of fix types differed between years. For goats in 2002, 2D accounted for 29.9%, 3D fixes for 62.2% and no fixes, where collars failed to acquire a fix, for 7.9%. For sheep in 2002, 2D accounted for 17.7%, 3D fixes for 80.9% and no fixes for 1.4%. For the dog in 2002, 2D accounted for 33.0%, 3D fixes

Table 1. Fix type (raw,%) by species within year.

Year	Fix type	Species		
		Goat	Sheep	Dog
2002	2D	7.9	3.1	2.9
	3D	16.5	14.3	4.7
	Failed	2.1	0.2	1.2
2003	2D	6.6	4.6	2.3
	3D	14.6	9.5	4.7
	Failed	2.4	1.6	0.8

for 53.1% and no fixes for 13.9%. In 2003, the relative number of fixes within species was fairly constant, with 2D fixes accounting for 29.4%, 3D fixes for 60.3% and no fixes for 10.3%. In 2003, success fix rate was equal to expected values across species and day/night. However, in 2002, the fix rate success was greater ($p < 0.05$) than expected for the dog, less than expected for sheep and similar to expected for goats.

Overall, the success fix rate was 91.7%, with 27.5% 2D fixes and 64.2% 3D fixes. The majority of previous studies involving GPS collars do not report fix interval, success fix rate or fix type (Cain et al. 2005), and those studies that did used either stationary collars, which have a higher success rate than collars deployed on animals (Janeau et al. 2004), or collars deployed on wildlife (Poole and Heard 2003; Pepin et al. 2004). Few reports concerning use of GPS collars on livestock included a success fix rate or fix type. Of those that do provide such information, Ganskopp (2001) reported a fix success rate of 99.4% in cattle grazing open rangeland, and Turner et al. (2000) reported a fix success rate of 93.5% with a fix interval of 30 min for cattle grazing in an open small pasture. In a study of grazing sheep in the UK, the overall success fix rate was 98.2% utilising an upland pasture (Rutter et al. 1997). Cain et al. (2005) noted a stationary success rate of 98.7% using the same fix interval (30 min) as in the present study. The success fix rate of this study is comparable to or greater than that of previous ones using collars deployed on wildlife. Janeau et al. (2004) reported a success fix rate of 92.5% (39.1% 2D and 53.4% 3D) with red deer in deciduous forest in the leaf-off period (November–April) and 86.5% (48.5% 2D and 38.04% 3D) in the leaf-on period (May–October). Poole and Heard (2003) reported a 76% success fix rate (15% 2D and 61% 3D) for mountain goats in mountainous terrain. Graves and Waller (2006) had a 72% success fix rate tracking bears in coniferous forest in mountainous terrain, even though the attempt-fix length of 3 min was considerably longer than the attempt-fix length of 70 s used in the present study. Sand et al. (2005) realised a success fix rate of 89.8% on wolves in coniferous forest in Scandinavia.

A number of studies have shown that topography (D'Eon et al. 2002; Janeau et al. 2004; Cain et al. 2005) and vegetation cover (Di Orio et al. 2003; Poole and Heard 2003; Frair et al. 2004) can affect fix success rate and DOP. Frair et al. (2004) reported a success fix rate of 94.9% in open field, 94.3% in deciduous forest in the leaf-off period and 87.5% in the leaf-on period, and Di Orio et al. (2003) showed that canopy cover was inversely related to success fix rate and to percentage of 3D fixes. The topography of the area in the present study was fairly flat with gentle slopes; however, the vegetation cover varied and could be the reason why the success fix rate in 2002 was in disagreement with expected values. That is, the fix rate success was greater than expected for the dog, less than expected for sheep and similar to expected for goats. The dog did not move much and seemed to rest in the shade under the tree canopy in the northwest corner of the study area. Being the first year of the study, the goats may have spent time browsing in the thickets of smooth sumac, sand plum and black locust. D'Eon and Delparte (2005) reported that collar angle (degrees from vertical) negatively affected success fix rate and DOP. It is likely goats in 2002 spent more time browsing than sheep in 2002 or goats and sheep in 2003. If a goat stands on hind legs and browses over its head, then the collar angle would be 90° or greater from vertical. Likewise, it is possible that the availability or distribution of plant species preferred by sheep varied less with year than of those preferred by goats and were located more in areas with greater available sky.

After removing fixes outside of the buffer, the data-set had 3922 fix records for 2002 and 3466 for 2003. In 2002, dog had 183 2D (33%) and 372 3D (67%) fixes, and in 2003, there were 179 2D (31%) and 393 3D (69%) fixes. In 2002, goats had 583 2D (30%) and 1329 3D (70%) fixes, and in 2003, there were 504 2D (29%) and 1231 3D (71%) fixes. In 2002, sheep had 248 2D (17%) and 1207 3D (83%) fixes, and in 2003, there were 360 2D (31%) and 799 3D (69%) fixes. Sheep in 2002 had a higher ($p < 0.05$) percentage of 3D fixes than in 2003 and also than other species in either year.

Distance travelled

For distance between any two animals at the same fix time, the data-set included 16,185 observations. Over the 2 years, 2942 observations were dog–goat (between the guardian dog and each of the three collared goats), 2063 were dog–sheep (between the guardian dog and each of the two collared sheep), 3221 were goat–goat (amongst the three collared goats), 1214 were sheep–sheep (between the two collared sheep) and 6745 were goat–sheep (amongst the three collared goats and the two collared sheep).

Average total distances (minimum) travelled in a 24-h period, during the day, and during the night are presented in Table 2. Year-by-species interactions were significant ($p < 0.01$) for each time period. In 2002, the dog travelled less ($p < 0.01$) during the day and in 24 h than did goats or sheep. However, the three species travelled similar distance in 24 h, daytime, and nighttime in 2003. Distance travelled during the day accounted for approximately 80% of the 24-h total, even though fixes during the day represented only 60% of the total, in accordance with 14.5 h of daylight and 9.5 h of nighttime.

Average distance travelled between consecutive fixes is presented in Table 3 for total day-and-night periods and in Figures 1–3 for each 30-min interval. All species travelled more ($p < 0.05$) during day than night. There were year-by-species interactions ($p < 0.05$) for daytime. The dog in 2002 travelled the least between fixes and goats in 2002 travelled the most, with goats and sheep in 2002 and 2003 being intermediate. Distance travelled in 30 min at night was similar for year-species combinations. In 2003, the dog travelled more during the day than did sheep, with goats being intermediate. Conversely, in 2002 distance travelled between 30-min fixes ranked ($p < 0.05$) dog < sheep < goat, with a considerable greater difference between the dog and the small ruminant species. Figure 1 shows that the 2002 dog was less active at some times during the day and tended to be more active at most times during the night than the dog in 2003. However, the dog in 2003 was more active than the dog in 2002, particularly from dawn and until dusk. Goats in both 2002 and 2003 were active from dawn to dusk, with a slight decrease around 12:00 hours (Figure 2). From Figure 3, it is apparent that the sheep in 2003 followed the same activity pattern as goats, with considerable activity from dawn to dusk and a pronounced decrease around noon; however, sheep in 2002 displayed a fairly constant activity level until mid-afternoon. Reasons why distance travelled in 30-min periods differed markedly between years at 06:30–08:30 hours for sheep are unclear, but could relate to varying climatic conditions having different effects on the 2 years.

If in this study there was a 100% success fix rate, entries in Table 2 would be exact multiples of entries in Table 3. Fix interval and fix rate success significantly affect the accuracy of individual-based movement models, especially the calculation of daily distance travelled (Pepin et al. 2004; Jerde and Visscher 2005). Fix rate success would not be a problem if animals travelled in a straight line; however, this is generally not the case. Hebenbrock et al. (2005) noted that the deviation of travel measured by GPS from actual course distance in different gaits of the horse ranged from 1 to 2%. They attributed this residual deviation to the fact that the horse did not run in a straight line but sometimes travelled in a curved path over the course, which was especially true for the canter. The same consideration is of pertinence to the present study in that the travel distances are minimums.

Sheep during the night in 2002 had the highest success fix rate. During that time, sheep travelled 17.0 m in 30 min. Multiplying distance travelled by 19, which is the number of 30-min increments in the 9.5 h night, the total minimum distance travelled during the night in 2002 for sheep is 323 m, which is in very close agreement with 325 m in Table 2. Conversely, the dog during the day in 2002 had the greatest number of no-fixes, relatively. Using the entry in Table 3 and multiplying by 29, which is the number of 30-min increments in the 14.5 h day, the total minimum distance travelled during the day in 2002 for the dog is 789 m, which is considerably greater than 510 m in Table 2.

Pepin et al. (2004) developed a non-linear function to predict the underestimation of daily distance travel due to unsuccessful fixes. For the fix rate of the present study (30 min), Pepin et al. (2004) calculated the underestimation of daily travel to be 20%. Taking a slightly different approach from that of Pepin et al. (2004), Jerde and Visscher (2005) calculated the probability of estimating step lengths (distance between two consecutive fixes) with a success fix rate of 90%, as in the present study, to be approximately 80%. Extrapolating step length to daily distance

Table 2. Average minimum total distance (m) travelled.

	2002			2003		
Time period	Dog	Goat	Sheep	Dog	Goat	Sheep
24 h	$718^{d} \pm 88.2$	$1277^{e} \pm 50.9$	$1298^{e} \pm 62.4$	$1349^{e} \pm 93.9$	$1334^{e} \pm 54.2$	$1280^{e} \pm 66.4$
Day (06:30–21:00 hours)	$510^{b} \pm 56.8$	$1089^{c} \pm 32.8$	$1002^{c} \pm 40.2$	$1103^{c} \pm 60.5$	$1095^{c} \pm 34.9$	$1015^{c} \pm 42.8$
Night (21:30–6:00 hours)	$209^{a} \pm 56.8$	$188^{a} \pm 32.8$	$295^{a} \pm 40.2$	$245^{a} \pm 60.5$	$240^{a} \pm 34.9$	$265^{a} \pm 42.8$

Note: Means with a common superscript do not differ ($p > 0.05$).

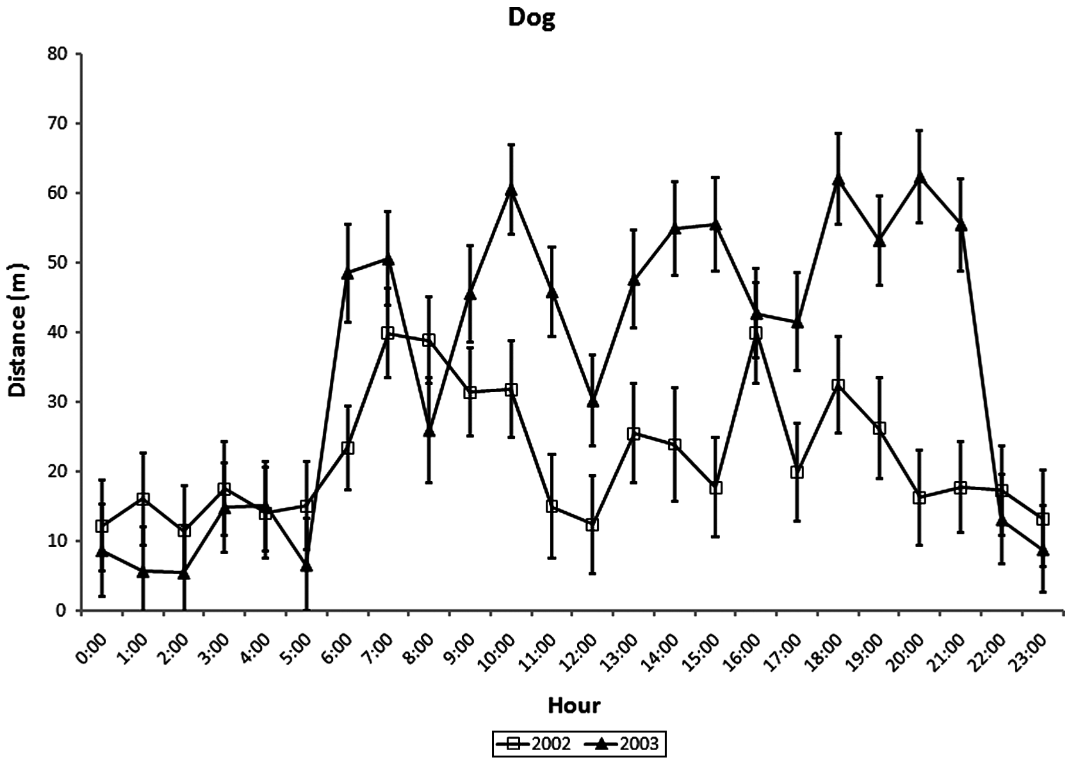

Figure 1. Lsmeans and standard errors for minimum distance travelled between consecutive 30-min fixes for the guardian dog by fix time.

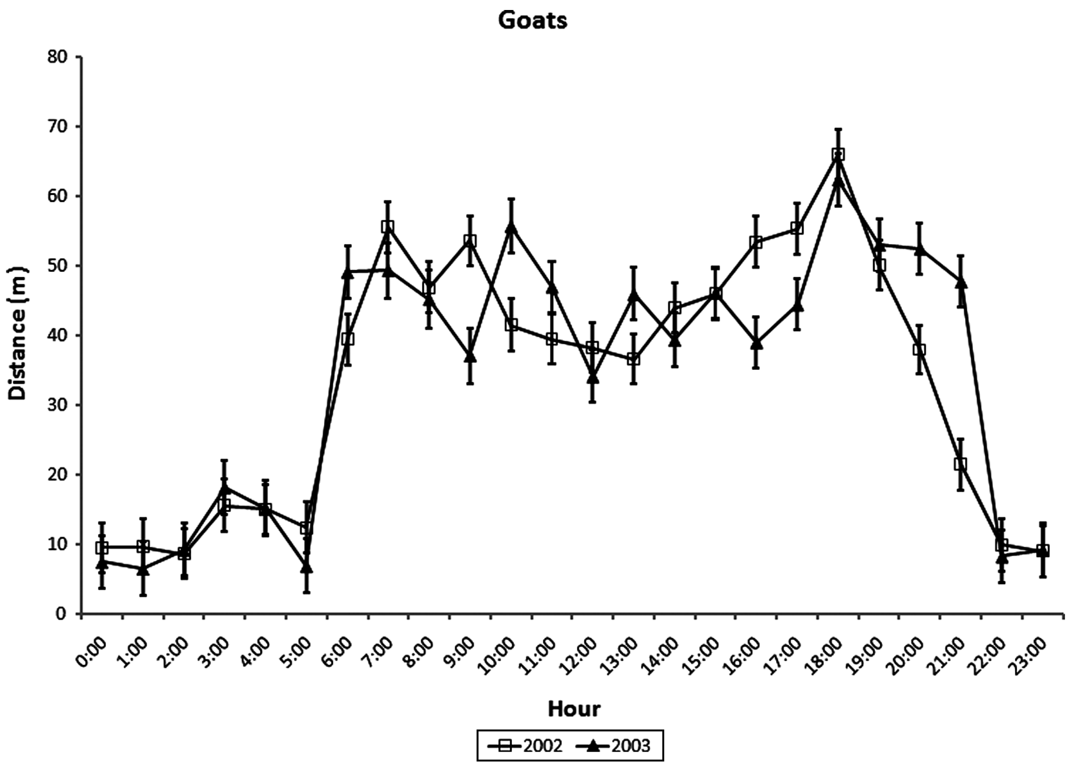

Figure 2. Lsmeans and standard errors for minimum distance travelled between consecutive 30-min fixes for goats by fix time.

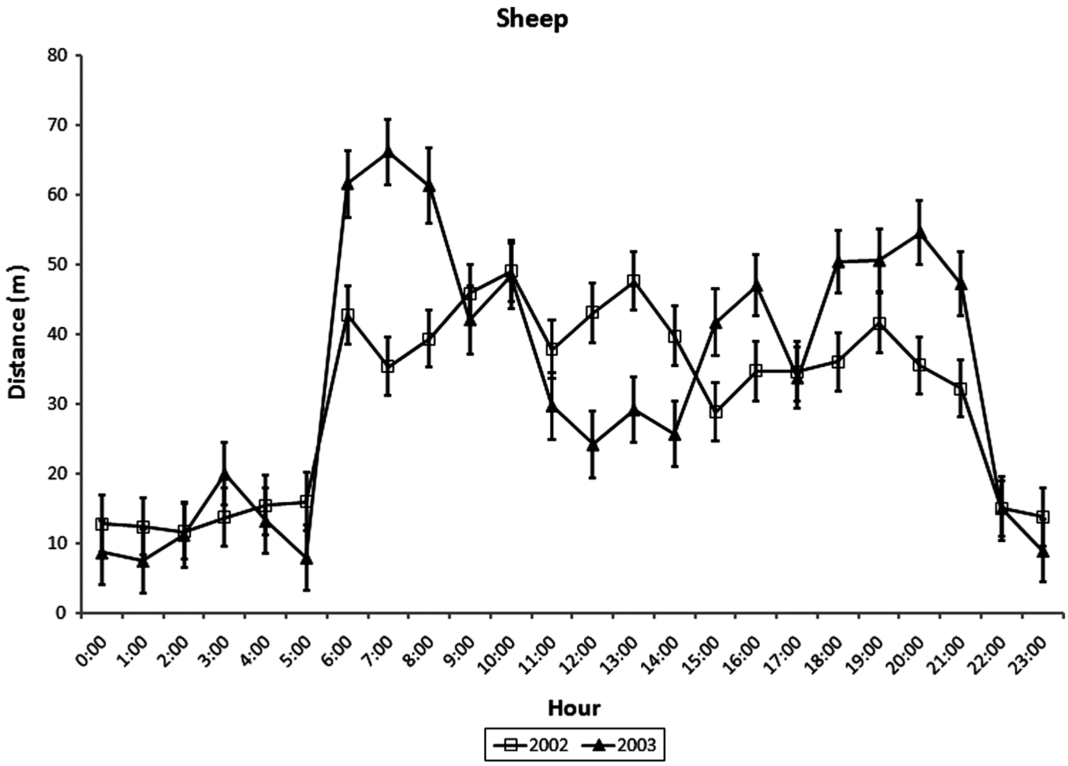

Figure 3. Lsmeans and standard errors for minimum distance travelled between consecutive 30-min fixes for sheep by fix time.

travelled, the estimation of Jerde and Visscher (2005) supports that of Pepin et al. (2004) in an underestimation of daily distance travelled of 20%. Applying Pepin's adjustment factor to values in Table 2 for sheep and goats yields a distance that is similar to values in Table 3 multiplied by 29 for day distance and 19 for night distance and then summed. For example, applying Pepin's adjustment to the sheep in 2003 yields a daily distance of 1536 m (1280×1.2) compared with the value calculated from Table 3 of 1605 m ($44.2 \times 29 + 17.0 \times 19$). For goats in 2002, Pepin's adjustment yields a daily distance of 1532 m and the value calculated from Table 3 is 1629 m. Unfortunately, this does not work as well for dog, especially in 2002. The dog in 2002 yields a daily distance of 862 m for Pepin's adjustment compared with the value calculated from Table 3 of 1076 m. This may be because of the relatively high incidence of no-fixes with the dog in 2002. If the 24-h totals in Table 2 are divided by the combinations in Table 3, the resulting underestimation for dog in 2002 was 1.50, goat in 2002 was 1.28, sheep in 2002 was 1.13, dog in 2003 was 1.28, goat in 2003 was 1.31 and sheep in 2003 was 1.25. This would indicate that an underestimation of total distance travelled due to missed fixes was about 25%, excluding dog in 2002.

In a 4 km^2 pasture, three British hill sheep were selected from within different sub-flocks (Rutter et al. 1997). They were then fitted with GPS units and returned to the study area. Each ewe maintained a non-overlapping, distinctive home range, presumably that of the sub-flock, which were 500–1000 m apart. One GPS unit malfunctioned; however, the other two ewes utilised areas of 2 and 7 ha, representing 0.5 and 1.75% of the total study area, respectively. The total area in the present study is smaller than either of these

Table 3. Average distance travelled (m) in 30 min by year, species and time.

	2002			2003		
Time period	Dog	Goat	Sheep	Dog	Goat	Sheep
Day (06:30–21:00 hours)	$27.2^{b} \pm 2.00$	$47.8^{de} \pm 1.07$	$39.5^{c} \pm 1.25$	$49.3^{e} \pm 1.96$	$46.8^{de} \pm 1.11$	$44.2^{d} \pm 1.37$
Night (21:30–6:00 hours)	$15.1^{a} \pm 2.30$	$12.8^{a} \pm 1.29$	$17.0^{a} \pm 1.47$	$15.6^{a} \pm 2.30$	$15.9^{a} \pm 1.35$	$17.0^{a} \pm 1.63$

Note: Means with a common superscript do not differ ($p > 0.05$).

two animal-defined home ranges and the sheep utilised all of the study area even though there were definite preferred areas.

Sheep and goats tended to travel about the same distances at day and night in both years. Schlecht et al. (2006) reported that free-grazing sheep and goats travelled the same daily distance of 6.7 km during the dry season and only slightly more during the rainy season (9.3 km). When goats and sheep were herded, they still travelled a similar distance, which increased to 10.1 km/day. Barbari et al. (2006) noted that the spatial distribution of grazing cattle was much wider at night than during the day, which may correspond to a greater distance travelled at night than during the day. These researchers also noted a bimodal distribution over the 24-h clock. However, cattle tended to increase activity from dawn until noon, and then decrease until late afternoon at which time activity increased until near midnight (Barbari et al. 2006). This differs from the goats and sheep on this study by a lag of 4 h in the morning and a longer time interval between peaks.

There are no known data available concerning distance travelled by small ruminant guardian dogs. Results of the present experiment suggest that guardian dogs do not protect small ruminants in pastures of relatively small size by exhibiting greater movement than the grazing animals, such as frequent circling or travelling around the perimeter. Relatively, in 2002, the dog was older than the one in 2003. However, the 2002 dog was as healthy as the 2003 dog and was in the prime of his guarding years. This age difference might explain the greater distance travelled by the 2003 dog during the day. Although given the greater experience of the older 2002 dog, this does not necessarily reflect a lower level of protection. That is, perhaps the dog in 2002 realised a relatively low degree of dangerous predator risk during the day and took the opportunity for minimal movement.

Separation distance

Average distances amongst species at the same fix-time are presented in Table 4 for day-and-night periods and in Figures 4–8 for each 30-min period. In both years and during day and night, distance between the dog and goats was less than between the dog and sheep. However, distance in 2003 between the dog and both small ruminant species was less than in 2002 in both day and night. There was less distance amongst goats than between sheep. Similarly, in all but one case (2002 goats) distance amongst or between the same species was less at night than during daytime. Goats and sheep in both years and throughout the day were spatially separated more than within species, although the magnitude of difference varied with year and time of day. Figures 4 and 5 show how spatial relationships during different times of day between the dog and goats and sheep varied markedly with year. For example, in 2002 the distance between the dog and goats was considerably greater during much of the day than at night, whereas the separation distance in 2003 varied little with time. In general, opposite differences existed for the dog–sheep distance, although differences amongst times of the day in 2003 were less than for dog–goat differences in 2002. In Figure 6, the goat–goat distance remained fairly constant at around 10 m throughout the day and night for both years. The sheep–sheep distance (Figure 7) was small in the early morning hours and then increased until late morning, with a decrease in early afternoon, a subsequent increase in early evening and then a decline toward nighttime hours. The goat–sheep distance in 2002 was greatest during nighttime hours and averaged around 60 m during the day (Figure 8). Conversely, in 2003, the goat–sheep distance was greatest during daylight hours, but also averaged around 60 m during those times.

The intra-species distance indicated that the goats preferred to be close to one another regardless of time of the day. Sheep desired much greater separation distance particularly during the daytime but also at night. In fact, goats only bedded at night a little closer to one another than they grazed. Fairly small differences between years in separation differences suggest relatively little effect of forage or environmental

Table 4. Average distance (m) between species at same fix time during day and night.

Item	Dog–goat	Dog–sheep	Goat–goat	Goat–sheep	Sheep–sheep
2002					
Day (06:30–21:00 hours)	$64.0^{i} \pm 1.15$	$93.7^{l} \pm 1.34$	$13.3^{bc} \pm 1.04$	$67.4^{j} \pm 0.70$	$28.4^{f} \pm 1.63$
Night (21:30–6:00 hours)	$14.2^{c} \pm 1.37$	$90.7^{kl} \pm 1.57$	$9.3^{ab} \pm 1.32$	$88.5^{k} \pm 0.88$	$13.6^{bc} \pm 1.96$
2003					
Day (06:30–21:00 hours)	$22.2^{d} \pm 1.12$	$58.0^{h} \pm 1.40$	$10.2^{ab} \pm 1.09$	$58.5^{h} \pm 0.78$	$35.1^{g} \pm 1.92$
Night (21:30–6:00 hours)	$10.9^{bc} \pm 1.35$	$27.0^{ef} \pm 1.64$	$7.1^{a} \pm 1.36$	$24.7^{de} \pm 0.96$	$17.7^{cd} \pm 2.32$

Note: Means with a common superscript do not differ ($p > 0.05$).

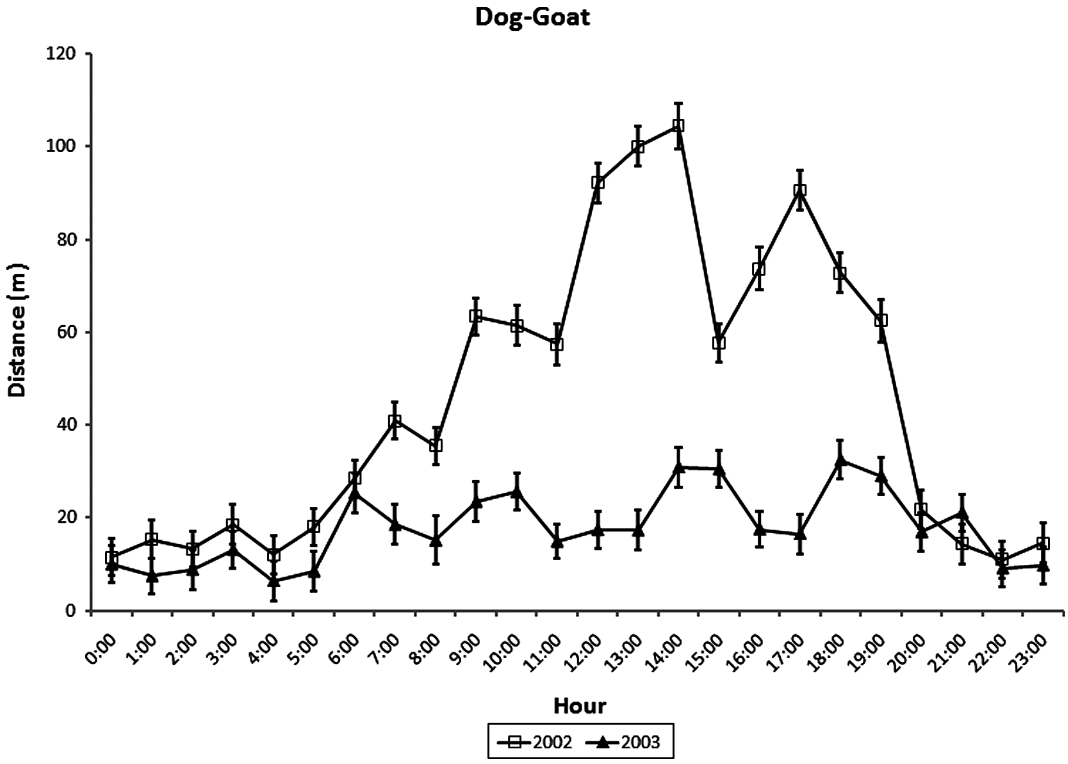

Figure 4. Lsmeans and standard errors for distance between guardian dog and the average of the three collared goats at the same fix time.

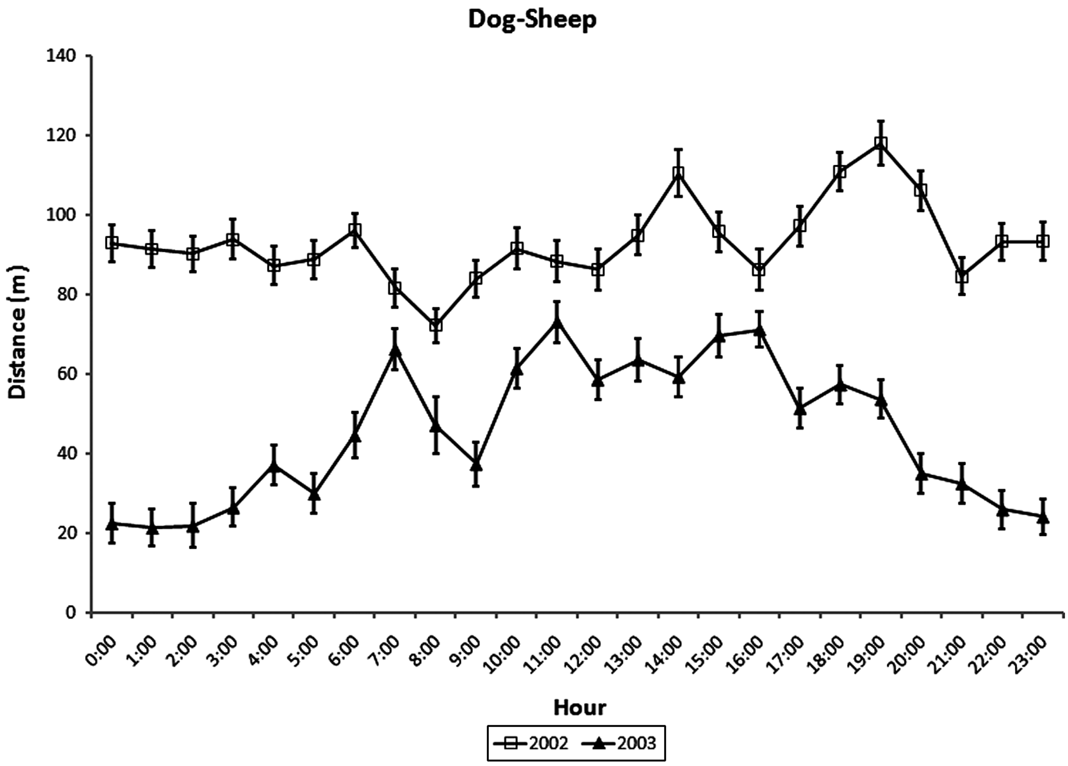

Figure 5. Lsmeans and standard errors for distance between guardian dog and the average of the two collared sheep at the same fix time.

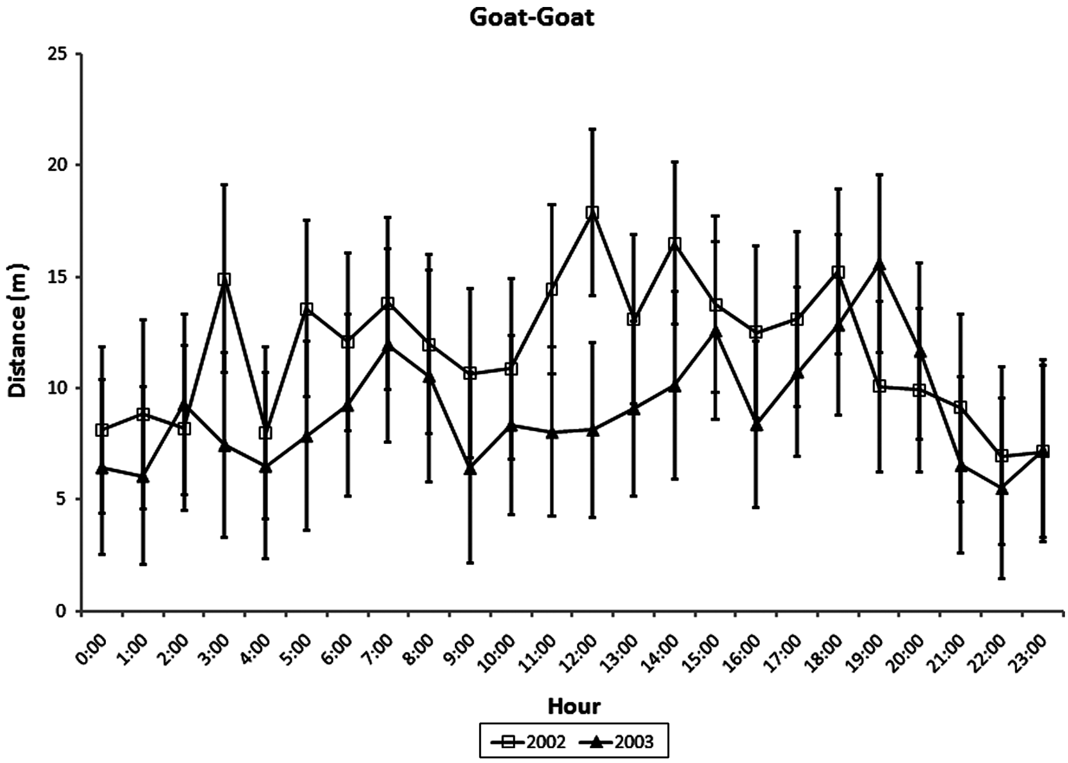

Figure 6. Lsmeans and standard errors for distance between the three collared goats at the same fix time.

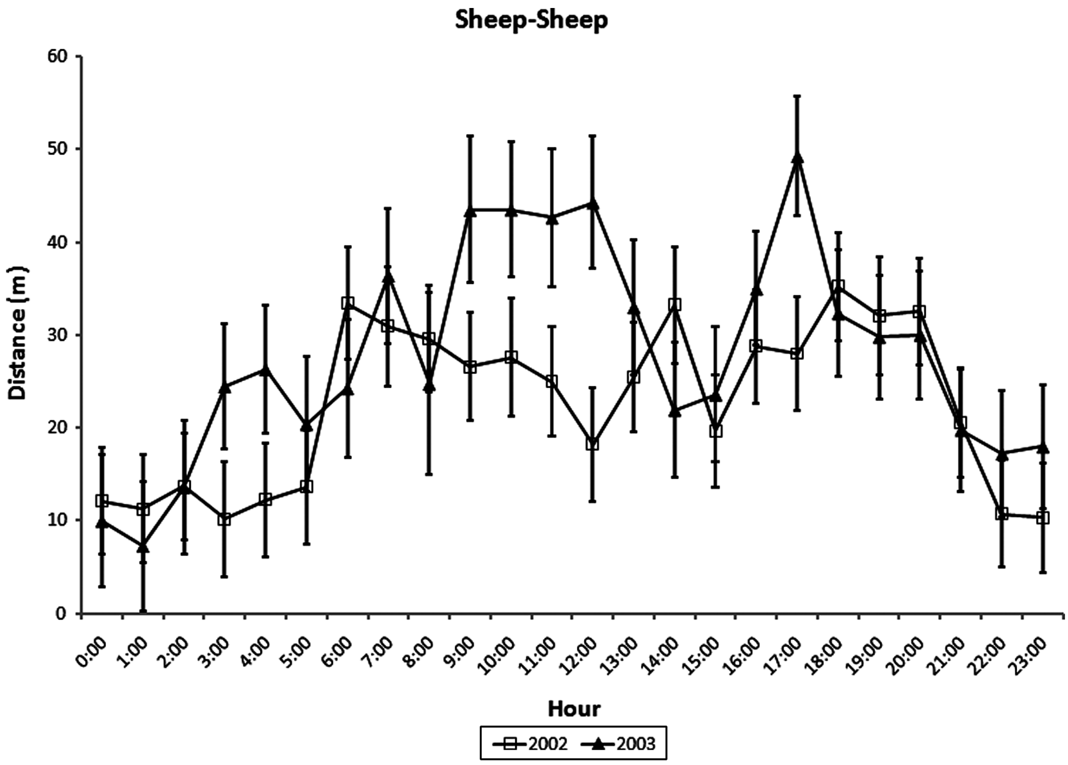

Figure 7. Lsmeans and standard errors for distance between the two collared sheep at the same fix time.

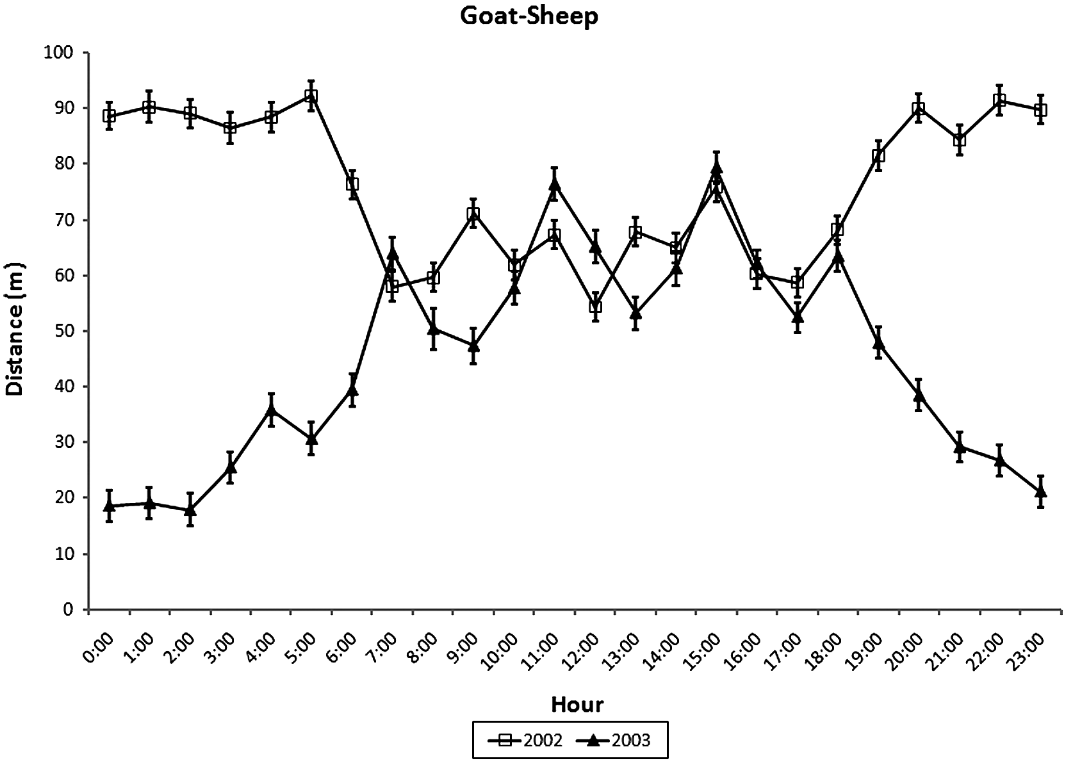

Figure 8. Lsmeans and standard errors for distance between the average of the three collared goats and the average of the two collared sheep at the same fix time.

conditions on how closely goats and sheep stay to others of the same species.

That goats and sheep appeared to graze and behave as separate groups could have resulted from different forage conditions and(or) local environmental preferences. This segregation may have also arisen from the recent social mixing of these two species. Alternatively, goat–sheep distance in 2002 greater at night than day suggests a social influence rather than primarily effects of forage conditions and species preferences. Even though the goat–sheep distance in 2003 was less at night than day, a greater goat–sheep than goat–goat and sheep–sheep distances supports appreciable influences of social preferences on distances between species.

For dog–small ruminant species distances, it also appears that the dog in 2002 was not well bonded with sheep. A similar dog–sheep distance in 2002 between day and night may indicate that the dog was not overly concerned where the sheep were regardless of conditions influencing predation or theft risk. Although, this might have also involved the distances between goats and sheep. That is, in 2002 the dog could have maintained a close proximity with goats and the high distance from sheep was simply a function of the separate locations of the two ruminant species, particularly at night. Based on the within and between ruminant species distances, sheep could be more challenging for a guard dog to protect compared with goats and with larger animal groups a greater number of guard dogs would be required with sheep in a mono-species group. Concomitantly, more than one guard dog would seem advantageous for mixed versus mono-species animal groups, with efforts expended to ensure that at least one or a minimum number of dogs are well bonded to each or both ruminant species.

Turning angle was computed and then categorised into four quadrants and is presented in Table 5. If turning angle was between –45° and 45°, then direction was forward; between –135° and 135°, backward; between 45° and 135°, right and between –45° and –135°, left. For day periods with at least three consecutive fixes each spaced 30 min apart

Table 5. Turning angle direction by species (number; percentages shown in parentheses).

	Turning angle direction			
Species	Backward (315–45°)	Forward (135–225°)	Left (225–315°)	Right (45–135°)
Dog	66 (8.8)	389 (52.0)	147 (19.7)	146 (19.5)
Goat	253 (9.4)	1262 (46.8)	591 (21.9)	590 (21.9)
Sheep	155 (7.1)	1057 (48.6)	483 (22.3)	480 (22.1)

(5619 observations), 48% of the movements were forward, right and left movements were equal at 22% and backward movements were 8%. There was no greater probability ($p > 0.05$) of turning left or right across species, but goats had a higher probability of turning backward than did the dog or sheep.

Preferred locations

Figures 9–12 are digital orthophotograph maps depicting the study area taken early in the 2003 grazing period and preferred pasture locations of the three species during the day and at night for the 2 years. Preference for a location was obtained from a point in polygon analysis. In Arcmap, a grid with 10×10 m squares was overlaid on the boundary (fence) and fence buffer shapefiles. Originally, 280 squares (20×14) were present in the grid due to the computation algorithm that constructs a regular (square or rectangular) grid. The squares that did not intersect the fence or fence buffer were eliminated, resulting in 193 squares. The number of fixes was computed within each square. A square with at least 3% of the fixes for that year–species–time combination was considered to indicate preference for that location.

Figure 9 is the preferred pasture locations in 2002 during the day. There were five squares (locations) preferred by the guardian dog, which are predominately in the northern part of the pasture and represented by the letter D within the square. These five squares accounted for 65% of all the daytime fixes for the dog in 2002. This area of the paddock was the location of the water tub and dog feeder, and was endowed with adequate shade. For sheep, there were three preferred locations in the centre of the

Figure 9. Preferred locations of the three species during the day of 2002.

pasture denoted by the letter S, which accounted for 29% of all the daytime fixes for sheep in 2002. This area of the paddock had abundant grass cover. Goats had four squares designated by the letter G that are located near preferred locations of the dog, accounting for 16% of the total daytime fixes for goat in 2002. Figure 10 is the preferred pasture locations in 2002 during the night. There were eight squares preferred by the guardian dog, which are in the northwestern part of the pasture. The locations in the northwest corner marked by the letter D accounted for 86% of all the nighttime fixes for the dog in 2002. For sheep, there were six preferred locations in the centre of the pasture denoted by the letter S that accounted for 66% of all the nighttime fixes for sheep in 2002. These squares are either the same squares for daytime fixes for sheep or adjacent to them. Goats are represented by the five squares in the northwest corner of the pasture near preferred locations of the dog. The location in the northwest corner of the pasture denoted by the letter G accounted for 82% of all the nighttime fixes for goats in 2002. Figure 11 is the preferred pasture locations in 2003 during the day. There were two locations preferred by the guardian dog, which were situated in opposite corners of the pasture and represented by the letter D. The location in the northwest corner accounted for 18% of all the daytime fixes for the dog in 2003 and the location in the southeast corner accounted for 7%. For sheep, there were three preferred squares in the northwestern corner of the pasture and represented by S squares. The locations in the northwest corner of the pasture accounted for 24% of all the daytime fixes for sheep in 2003. Goats are represented by the five G squares, with most in the corners of the pasture near the dog and sheep preferred locations. The location in

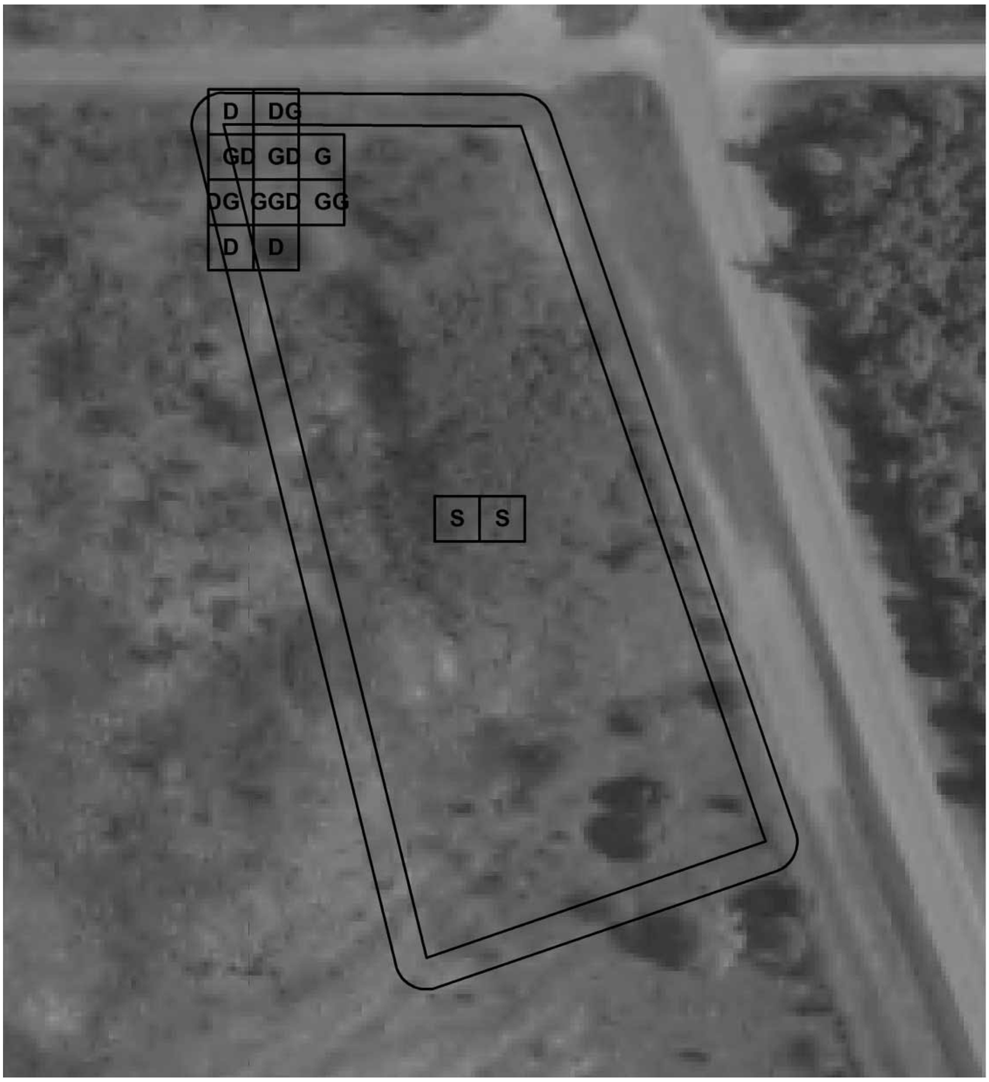

Figure 10. Preferred locations of the three species during the night of 2002.

the northwest corner of the pasture accounted for 18% of all the daytime fixes for goats in 2003 and the squares in the southeast corner, 9%.

Figure 12 is the preferred pasture locations in 2003 during the night. There were nine squares preferred by the guardian dog, which were mainly in the corners of the pasture and are represented by D squares. The location in the northeast corner accounted for 39% of all the nighttime fixes for the dog in 2003; the location in the northwest corner, 23% and the two squares in the southeast corner, 12%. For sheep, there were seven preferred squares also largely in the northern corners of the pasture and represented by S squares. The locations in the northeast corner of the pasture and in the northwest corner of the pasture accounted for 39 and 19%, respectively, of all the nighttime fixes for sheep in 2003. The two squares in the southeast corner accounted for 7% of the nighttime fixes. Goats are represented by the eight G squares, with most in the corners of the pasture near the dog and sheep. The location in the northeast corner of the pasture accounted for 43% of all the nighttime fixes for goats in 2003; the location in the northwest corner, 16% and the squares in the southeast corner, 17%.

Conclusions

Though distances travelled by all species were greater during the day than night, each species did travel at night and were not stationary. The greater distance amongst goats and between sheep during the day than night indicates a more relaxed herd/flock instinct when the animals are apt to be grazing than at night when the animals may be bedded down. The greater distance between goats and sheep than within the two species

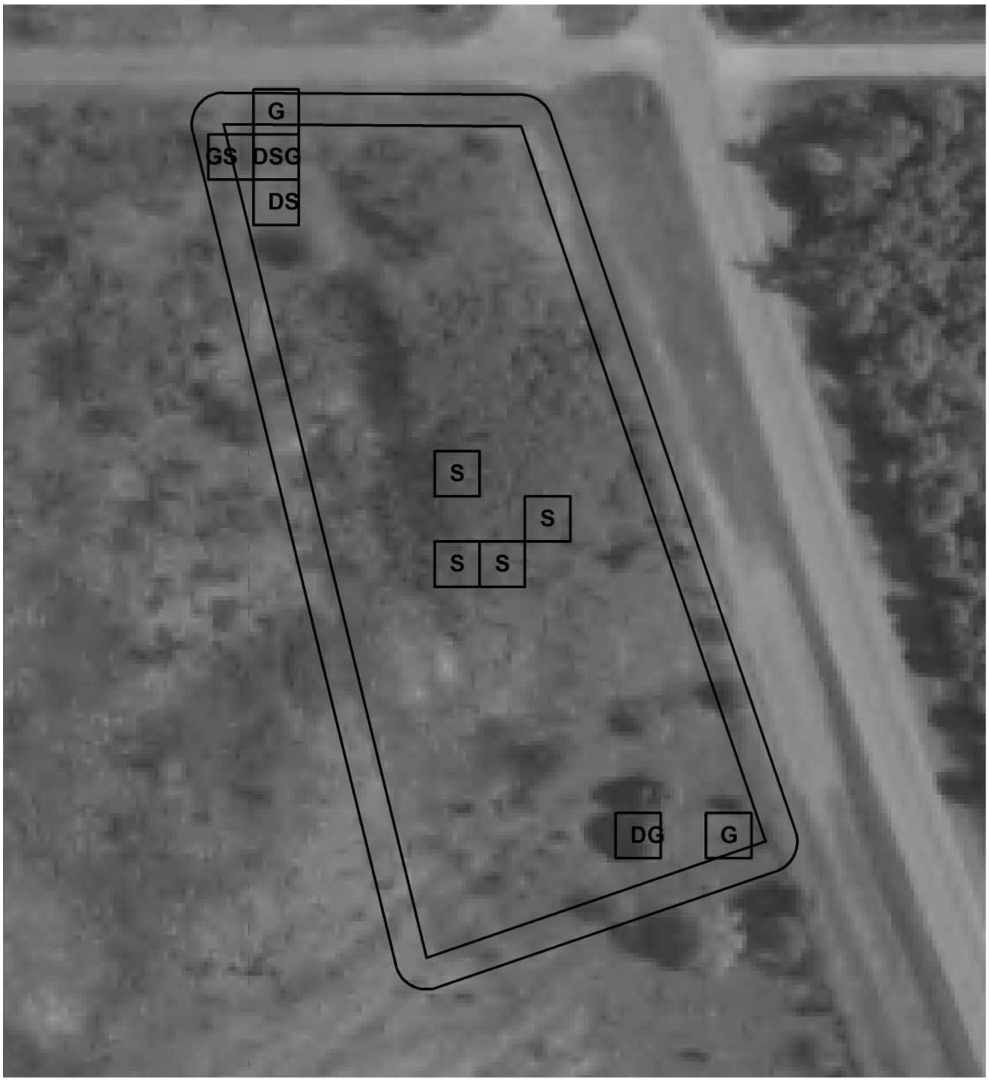

Figure 11. Preferred locations of the three species during the day of 2003.

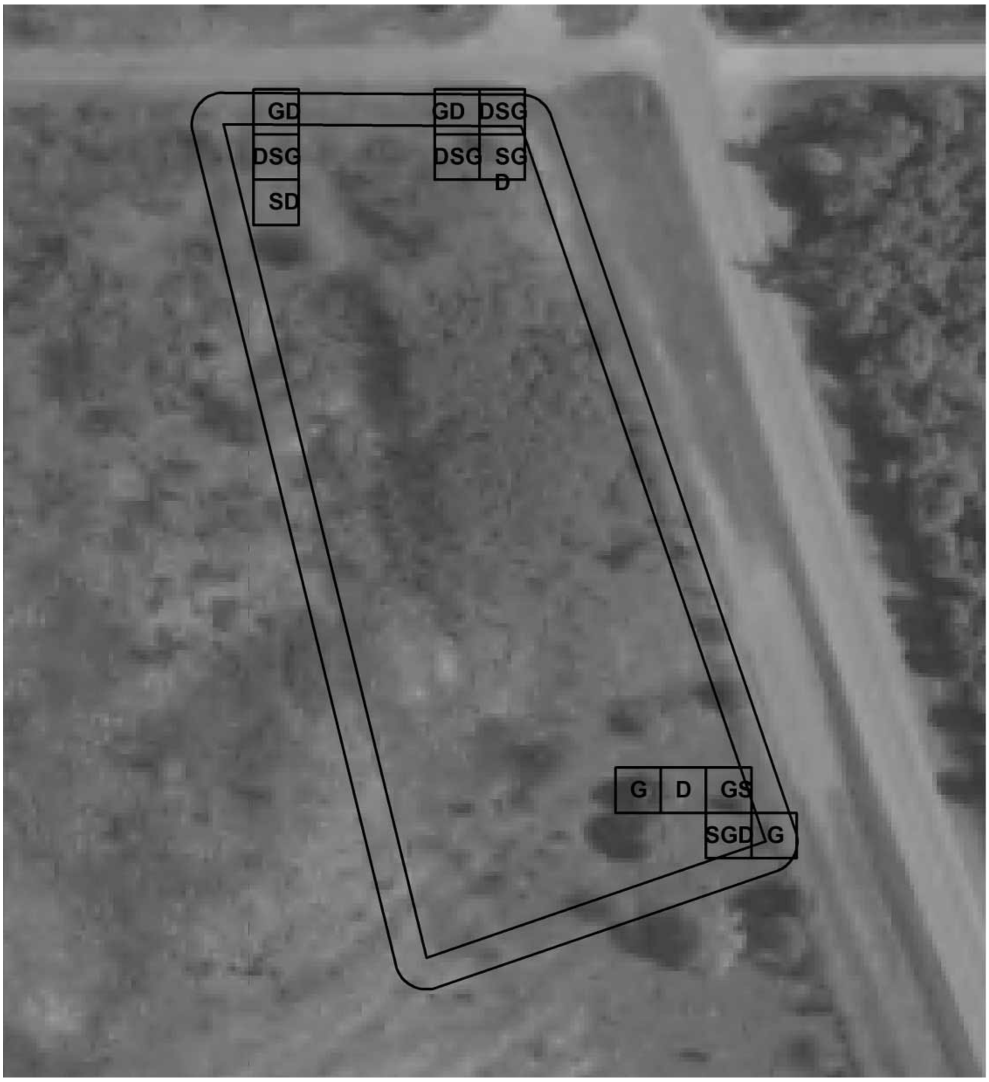

Figure 12. Preferred locations of the three species during the night of 2003.

indicates that goats and sheep interacted as two separate entities rather than as on large herd/flock. The closer distance between the dog and goats than between the dog and sheep indicates a clear preference of the dog for goats over sheep, which could be the result of greater habituation with goats.

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