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ESCAPE DECISIONS BY DALL'S SHEEP EXPOSED TO HELICOPTER OVERFLIGHTS

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ABSTRACT

High rates of helicopter disturbance potentially may affect the fitness of Dall's sheep (*Ovis dalli dalli*), but the species' behavioural responses to helicopters are not well known. Dall's sheep were exposed to experimentally controlled helicopter overflights in the Yukon Territory, Canada. The probability that sheep would escape (run/walk away) from the helicopter decreased as the smallest distance between sheep and helicopter during an overflight became greater. The relationship, however, was strong only when sheep were inside or near rocky slopes, in small groups, or when groups had a large proportion of lambs. Otherwise, sheep always had a high escape probability when the helicopter was within 3 km. Escape probability also decreased when the helicopter was below the sheep. The distance from the helicopter at which sheep initiated their escape increased as the sheep's distance to terrain block (ridge that blocks the line of sight between sheep and helicopter until the latter is past the ridge) became larger. Sheep escaped farther if terrain blocks were closer, but the relationship weakened if most group members were bedded. Escape probability models are provided to determine setback distances and elevations that reduce disturbance.

INTRODUCTION

Ungulates may suffer energetic costs when running or walking away from aircraft, vehicles, or human-caused noises that disturb them (e.g. Berger et al. 1983; Krausman & Hervert 1983; Bleich et al. 1994; Bradshaw 1994; Côté 1996). Even when the energetic costs of these movements are negligible, disturbance may reduce foraging efficiency (Berger et. al 1983; Stockwell, Bateman & Berger 1991), disrupt activity budgets (Maier et al. 1998), and cause stress-related increases in heart and metabolic rates (MacArthur, Geist & Johnston 1982). While ungulates may suffer no substantial fitness costs when disturbance rates are low, some studies suggest that high disturbance rates could reduce reproductive success (Joslin 1986; Yarmoloy, Bayer & Geist 1988; Harrington & Veitch 1992; Bradshaw 1994).

In this paper I quantify escape decisions by Dall's sheep (*Ovis dalli dalli*) exposed to experimentally controlled helicopter overflights. My purpose is not to address whether helicopters can cause population declines, but rather to present new insights on behavioural responses. This is an essential first step towards understanding which disturbance rates could affect population dynamics (see Bradshaw 1994; Sutherland 1996).

Disturbed sheep behave as if helicopters were a perceived threat by making at least three escape decisions. First, sheep decide whether they should interrupt maintenance activities and give up a feeding or resting site to escape (run or walk away) from a helicopter. Second, if they escape, sheep decide at what distance from the helicopter they should initiate movement and, finally, how far they should move before resuming maintenance activities. These decisions, like those regarding antipredator behaviour, are important for animals attempting to make optimal trade-offs between energetics and risk avoidance (Lima & Dill 1990; Kramer & Bonenfant 1997).

Based on preliminary observations and the literature (Harrington & Veitch 1991; Côté 1996; Frid 1997; Kramer & Bonenfant 1997), I asked the following questions:

1) Are escape decisions affected by the directness of the helicopter's approach (as quantified by the nearest distance between sheep and the helicopter: Fig. 1), the helicopter's relative elevation, and distances between sheep and the nearest terrain block (ridge that blocks the line of sight between sheep and helicopter until the latter is past the ridge)? Do these variables act independently (additively) or do they interact (multiplicatively) with each other (see Frid 1997)?
2) Do variables related to the pre-disturbance condition of sheep (group size, distance to security cover, proportions of lambs and of bedded animals in a group) affect escape decisions? If so, do these variables interact (multiplicatively) with helicopter-related variables?

METHODS

Study sites, animals and season

I collected data between mid June and early August, 1997, in the southwest Yukon Territory, Canada. I made 49 observations at Hoge Pass (ca. 61 °19' N, 139° 33' W), Kluane National Park Reserve (KNPR), 7 observations at Nines Creek (ca. 61° 11' N, 138° 50' W), Kluane Wildlife Sanctuary, and 1 observation at Vulcan Creek (ca. 60° 55'N, 138° 29' W), KNPR. All sites contained >200 sheep, were roadless, rugged, and harboured large carnivores.

Helicopter traffic at all sites occurs almost exclusively between May and September. At Hoge Pass and Nines Creek, where I collected almost all observations, there rarely were more than 25 helicopter flights/year prior to my study (R. Breneman [KNPR] and K. Hattie [Inco], personal communication). (More precise records are unavailable.) I collected 86 % of observations at Hoge Pass not because helicopters threatened sheep there, but because that site provided excellent observation conditions for my experimental study. To maximise sample sizes, I pooled observations of female-young groups (N = 39) and of all-male groups (N = 18).

Field methods and Variables

Sheep were exposed to overflights by a single helicopter (Bell 206B) flying at a mean ± SD air speed of 165 ± 31 km/h. The helicopter had a sling only during three observations.

My assistants and I observed sheep from the ground, from distances of >1km and using spotting scopes and/or binoculars. We simultaneously observed 1 to 4 focal groups (1/observer), and recorded continuous sampling of their behaviour (Martin & Bateson 1993) into tape recorders. These records started several minutes prior to the overflight and continued until animals stopped reacting overtly to disturbance. Female-young groups tend to be large, and often we could not observe all group members at once. Thus, I quantified the timing of responses to disturbance based on the behaviour of the first animal or animals to respond in the group (most responses involved >50 % of the group, see Results). Variables are described in Table 1 and Fig. 1.

At Hoge Pass I designed *a priori* and communicated to the pilot (via radio) the helicopter trajectory. For 45 of 49 observations at this site (79 % of the data set), the helicopter trajectory and its relation to the timing of sheep responses was recorded as follows. Synchronised with the behavioural tape records and through a radio operated by observers on the ground, the pilot read into a tape recorder his GPS location (coded by a 3 digit number), speed, and elevation several times per minute (usually 2-3). An observer on the ground supplemented these data by mapping the helicopter trajectory (including elevations based on adjacent topography) on a 1:50,000 map. Points required for analyses that were between GPS locations were later estimated from the helicopter's speed and climbing/dropping rates. These records later allowed reconstruction of the timing of sheep behaviour relative to helicopter locations.

For all data at Nines Creek (where I had no radio communication with the pilot), four observations for which the helicopter GPS was unavailable at Hoge Pass, and the one observation at Vulcan Creek, the helicopter trajectory and its relation to the timing of sheep responses were recorded as follows. An observer picked *a priori* distinct points in the landscape, and numbered them on the 1:50,000 map. When the helicopter flew over these points, he spoke the number identifying them into a tape recorder. This observer also mapped the helicopter trajectory, including elevations based on adjacent topography. The taping of sheep behaviour and helicopter locations were synchronised in time, which later allowed for reconstruction of the timing of sheep behaviour in relation to helicopter locations. Points on the helicopter's trajectory that were not recorded in the field but that were required for analyses were later estimated using the helicopter's speed and climbing/dropping rates. At Hoge pass and Vulcan creek, these were obtained from the pilot, and at Nines creek they were estimated from the time the helicopter took to travel between mapped locations.

We used 1:50,000 topographic maps and known points on the landscape to estimate the sheep's distances to security cover and to the nearest terrain block (both defined in Table 1), and the distances sheep escaped. When these distances were <100 m, however, we made estimates using the torso lengths of adult sheep (representing approximately 1 m) as reference points.

Because groups often were spread out over a wide area, all distances were measured from the group's "centre of gravity". The latter is the imaginary balance point of the horizontal plane contained by the perimeter of the group, with the distribution of animals within that perimeter determining the weight of the plane.

Independence between observations

Multiple flights during the same day are not independent of each other, and here I present only data on the first flight of the day. When >1 group were simultaneously observed during the same overflight, these groups were almost always several km apart or separated by ridges. Thus, it was very unlikely that groups responded to each other's behaviour rather than to the helicopter.

Sheep were not marked. To reduce the problem of groups contributing more than one observation to the data set (Machlis, Dodd & Fentress 1985), I considered observations to be independent only if they involved different groups that could be temporarily distinguished by their position in the landscape or if they occurred on different days.

Model building and statistical analyses

I built multiple regression models, a task involving subjective intuition (Neter, Waserman & Kutner 1989; Wilkinson, Blank & Gruber 1996), with an approach centred around my *a priori* prediction that escape responses are affected by interactions between sheep and helicopter variables. I also heeded the guideline that the number of independent variables available for model building should be no more than 1/6 of the sample size (Neter et al. 1989). Thus, I built models in three stages, with each stage reducing the model to its most significant form with backward stepping procedures (see details below). The first stage reduced one model testing the independent effects and two-way interactions of all helicopter-related variables (Table 1). The second reduced 3-4 models, one for each independent sheep-related variable (Table 1), testing two-way interactions between each sheep variable and each helicopter variables in the reduced model of Stage 1. If additional variables were added to the model of Stage 1, during a third stage the variables of each reduced model from Stage 2 were tested with a single model, which I reduced to its most significant form.

The two exceptions to this approach were as follows. First, I excluded least distance from analysis of escape initiation distance because the latter can be only greater than or equal to least distance, which would cause a statistical artifact. This reduction in the number of variables allowed me to consider all sheep-related variables except proportion of lambs in a single model during the second stage of model building. (Proportion of lambs was analysed separately because I excluded male groups from its analysis). Second, during the first stage of model building for analysis of distance escaped, no helicopter variables were significant. Thus, for Stage 2 I chose the helicopter variable that was significant for escape initiation distance, and intuitively decided to include least distance.

For analyses of escape probability, I used logistic regression, and reduced models to their most significant form following the criteria described in Trexler & Travis (1993). Using JMP (SAS Institute 1996), I specified one subset of independent variables at the time, and compared Rho^2 values, whole model tests, lack of fit tests and effect-likelihood ratio tests between the models that included different variable subsets. Models could not become significant unless the lack of fit test had a Chi-square probability >0.05, and variables could not remain in the model unless the effect likelihood ratio probability was <0.05. Function plots were generated with the equation (symbols are defined in Trexler & Travis 1993):

$$\text{Escape probability} = 1-[(EXP(\alpha+\beta_1X_1+\beta_iX_i\ldots))/(1+(EXP(\alpha+\beta_1X_1+\beta_iX_i\ldots)))]$$

For analyses of escape initiation distance and distance escaped, I used linear regression models, which I reduced with backward stepping procedures (Neter et al. 1989; Wilkinson et al. 1996) using SYSTAT (SPSS 1996). Stepping was interactive, and independent variables were excluded from the model unless their P-values were <0.05.

To avoid collinearity problems in both logistic and linear regressions, variables could not remain in the model unless they had tolerance values >0.1 (Wilkinson et al. 1996). (Tolerance is 1 minus the multiple correlation between a predictor and the remaining predictors in the model.) These values were calculated for both regression types with SYSTAT (SPSS 1996).

To check regression assumptions, I examined scatter plots of residuals and leverage, and probability plots of residuals (Neter et al. 1983; Wilkinson et al. 1996), and checked normality with density function plots (SPSS 1996). Residuals and leverage values were calculated with LOGIT (Steinberg & Colla 1991) for logistic regression and SYSTAT for linear regression. I used arcsine square-root or logarithmic (base 10) transformations to normalise continuous variables (Zar 1984).

RESULTS

Sheep escaped from helicopters in 43 of 57 (75 %) groups exposed to helicopter disturbance. In the remaining groups, all sheep either became vigilant only or did not respond overtly. Animals ran (sometimes combined with walking) in 37 of 43 (86 %) escape events, and walked during remaining escape events. In general, sheep first stared at the helicopter and then alternated movement with vigilance bouts.

Most group members escaped in relative synchrony. The initial run or walk away from the helicopter included >50 % or 100 % of the group, respectively, during 62% and 48 % of escapes (N = 42 [one observation had missing data]). Even when sheep delayed their initial escape relative to other group members, most sheep escaped at some point during the disturbance event. The maximum percent of group members escaping was >50 % or 100 %, respectively, in 88 % and 76 % of observations (N = 42). It is noteworthy, however, that at times some group members escaped while a small proportion of sheep did not move.

To escape or not escape

The probability that sheep would escape was affected strongly by the helicopter's least distance and its interactions with sheep-related variables. The helicopter's relative elevation also had an effect (Tables 2, 3).

Sheep were more likely to escape as least distance (Fig. 1) became smaller, but the strength of this relationship depended on the sheep's distance to security cover. The relationship was strong when sheep were inside or near security cover. When sheep were farther from cover, however, they had a high probability of escaping (e. g. ≥ 0.6 at 75 m from cover, Fig. 2a), regardless of least distance (within a 3 km range). In fact, a model considering the interaction between least distance and distance to security cover and the independent effects of the helicopter's relative elevation (see below) best predicted the probability of escape ($Rho^2 = 0.64$, Model 1 of Table 3, Fig. 2).

Whether the sheep's decision to escape was affected by the helicopter's least distance also depended on group size. Sheep in very large groups always had a high probability of escape (e. g. ≥ 0.5 for groups with 40 sheep), regardless of least distance (within a 3 km range), whereas sheep in smaller groups became substantially less likely to escape as least distance became larger (Model 2 of Table 3; Fig. 3). Likely due to low statistical power (see Thomas & Juanes 1996), this interaction was excluded from a model that considered multiple sheep and helicopter variables.

The effect of least distance on escape probability of female groups also depended on the proportion of lambs in the group (Model 3 of Table 3; Fig. 4). For groups with a high proportion of lambs, escape probability decreased strongly as least distance became larger. Groups with a low proportion of lambs, however, always had a high probability of escape (e. g. ≥ 0.6 for groups with lamb proportion of 0.1: Fig. 4a).

When the helicopter was below them, sheep were substantially less likely to escape than when the helicopter was at their elevation or above. This effect was independent of other variables (Model 1 of Table 3). I found no significant effect of the sheep's distance to terrain block (defined in Table 1) and the proportion of bedded animals on escape probability.

Escape initiation distance

Escape initiation distance ranged from 100 m to 3 km, and had a mean ± SD value of 1.04 ± 0.67 km (N = 42 [one observation had missing data]). According to the reduced regression model, it increased as distance to terrain block became larger ($R^2 = 0.22$; Fig. 5), but all other variables had no significant effect. Larger groups, however, had a weak but nearly significant tendency to have greater escape initiation distances than smaller groups ($R^2 = 0.08$; $P = 0.07$).

Distance escaped

The distance sheep escaped ranged from approximately 15 m to 2.2 km (mean ± SD = 253 ± 438 m, median = 100 m; N = 43). It decreased as distance to terrain block became larger, but the relationship was relatively strong only when the proportion of bedded animals was large, and weakened as this proportion decreased ($R^2 = 0.25$; Table 4). According to the reduced regression model, all other variable had no significant effect (proportion of lambs was not tested because of low sample size). However, sheep generally escaped towards security cover, and though weakly and not quite significantly, distance escaped increased with the latter ($R^2 = 0.09$; $P = 0.05$). Also, larger groups had a weak tendency to escape farther than smaller ones, but not quite significantly ($R^2 = 0.07$; $P = 0.08$).

DISCUSSION

I found that, although factors related to the helicopter influenced escape decisions made by sheep, these factors did not always act in isolation of the sheep group's size, distance to security cover, and proportion of lambs and bedded animals. Attempts to mitigate disturbance, however, will be based primarily on factors controlled by pilots. Thus, it is useful to summarise the effect of helicopter variables as if they did act in isolation.

Least distance was the most important helicopter variable. The smaller the least distance (i.e., the more direct the helicopter's approach), the greater the probability that sheep would escape. (This effect depended on sheep-related variables.) I found no effect of least distance on the distance sheep escaped.

The sheep's probability of escape decreased as relative elevation became lower. (This relationship was independent of sheep-related variables.) Likely there is an upper elevation threshold above which escape probability would decrease. I could not test this prediction because my observations did not include overflights that were >350 m above the sheep. I found no effect of relative elevation on escape initiation distance and distance escaped.

The sheep's distance to a terrain block also affected escape decisions. The closer this block, the smaller the escape initiation distance because sheep cannot see (and perhaps hear) the helicopter until it is past this block. (This relationship was independent of other variables). Sheep escaped for greater distances if terrain blocks were nearby. (This relationship depended on the proportion of bedded animals.) Perhaps this response occurs because the sudden appearance of a helicopter from behind a nearby ridge is more disturbing than when sheep can see the helicopter approaching gradually. I found no effect of distance to terrain block on escape probability.

Interactions between multiple factors

Sheep inside or near security cover, where natural predation risk is lower (Frid 1997 and references cited within), became substantially less likely to escape as least distance increased. Sheep farther from cover always had a high probability of escape, regardless of least distance (within a 3 km range). This relationship suggests that natural predation risk influences the strength of disturbance responses. However, smaller groups were substantially less likely to escape as least distance became smaller, but larger groups always had a high probability of escape, regardless of least distance (within a 3 km range). Given that predation risk decreases with increasing group size (review in Roberts 1996), these relationships are intriguing and require further investigation.

Female groups with a large proportion of lambs were substantially less likely to escape as least distance became larger, but groups with a small proportion of lambs always had a high escape probability throughout the range of least distances. These relationships suggest an escape cost that is specific to mothers. Escaping may cause mother-young separation, which could decrease young survival (Côté & Beaudoin 1997). Further, lambs straying behind a group escaping from a helicopter can be taken by golden eagles (*Aquila chrysaetos*) (Nette, Burles & Hoefs 1984).

Implications for conservation

Ungulates populations may be highly variable due to predation (Ross, Jalkotzy & Festa-Bianchet 1997) and forage availability (Caughley & Gunn 1993). Thus, rigorous quantification of the effects of helicopter disturbance on population dynamics requires multi-year studies of radio-collared individuals exposed to experimentally determined disturbance rates (see Harrington & Veitch 1992). Such expensive projects rarely will be an option, and my study was no exception. My logistic regression models, however, are useful for conservation because managers can use them to generate setback distances and elevations between sheep and helicopters that result in an "acceptably low" escape probability. Exactly what the latter probability is would ultimately be determined by models of how different disturbance rates affect fitness (e. g. Bradshaw 1994), which was outside the scope of this paper.

I suggest that Model 1 of Table 3 provides the best choice for generating setback distances and elevations for populations in which distance to security cover is well studied. It explained the most variability (64 %) in the animals' decisions to escape, and illustrates how distance to security cover has a dramatic effect on escape probability. For example, when a helicopter is at the same elevation as the sheep and at a least distance of 1 km, the chances of escape are <10 % for sheep inside security cover, but almost 100 % for sheep at 75 m from cover (Fig. 2a). I suggest that predictions of this model be based on distances to cover that are *no smaller* than the 75 % quartile for the population (weighted by group size: see Jarman 1974). Predictions could be adjusted according to seasonal and diurnal variation in distance to security cover. Model 1 of Table 3 also accounts for how escape probability decreases as the helicopter's relative elevation becomes smaller. Thus, if the altitudinal range of sheep is known (Fig. 6), horizontal setback distances can be adjusted according to the helicopter's elevation (Fig. 7).

When data on distances to cliffs are lacking but the altitudinal range of animals is known, the model presented in Table 2 will be the best choice. This model accounts only for least distance and relative elevation and has a poorer fit ($Rho^2 = 0.28$) than Model 1 of Table 3. As exemplified in Fig. 7, however, it can be an important management tool and its poorer fit may be compensated by basing guidelines on lower escape probabilities. If altitudinal ranges are unknown, I suggest being conservative and using the model of Table 2 to calculate setback distances based on a relative elevation of +300 m.

One simple way of reducing disturbance is to be aware that, as suggested by the relationship between escape initiation distance and distance to terrain block, sheep appear to not perceive a helicopter that is hidden by a ridge. Thus, as much as possible helicopter routes should be planned such that a ridge blocks the line of sight between the helicopter and where most animals are likely to be.

My study provides one example of how behavioural ecology can be applied to the conservation of animals exposed to motorised disturbance. An important next step is to link the behavioural responses that I quantified to how different disturbance rates may affect population dynamics (Harrington & Veitch 1992; Bradshaw 1994; Sutherland 1996).

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Table 1. Variable definitions.

Variable	Definition
	Dependent variables
Escape	Binomial variable recorded only when sheep were not travelling prior to helicopter overflights. It describes whether ≥ 1 group members (almost always >50 %) interrupted feeding (as defined in Frid 1997) or bedding (occasionally standing inactive) to run and/or walk away ≥ 10 m from a helicopter flying <4 km from them. While 10 m seems like a small escape distance, Côté (1996) considered it a threshold indicating moderate disturbance, and even short escape distances likely reflect increased heart rates (MacArthur et al. 1982), reduced foraging efficiency (Stockwell et al. 1991), and disrupted activity budgets (Maier et al. 1998).
Escape initiation distance	Continuous variable describing the distance (km) from the helicopter at which ≥ 1 group members (almost always >50 %) began to escape.
Distance escaped	Continuous variable describing the maximum distance (m) ≥1 group members (almost always >50 %) escaped before ≥ 90 % of the group resumed feeding or bedding.
	Helicopter-related independent variables (all continuous)
Least distance	Measured in km and explained in Fig. 1.
Relative elevation	The helicopter's elevation minus the sheep's elevation (analysed in feet and subsequently converted into m for graphs/text). The value is negative when the helicopter is below the sheep.
Distance to terrain block	Distance (km) between sheep and nearest ridge that blocks the line of sight between sheep and helicopter until the latter is past the ridge.

Table 1, cont.

Variable	Definition
	Sheep-related independent variables(all continuous)
Distance to security cover	The pre-disturbance distance (m) between sheep and steep (>30°) rocky slopes.
Group size	The number of non-lambs in a group. I excluded young of the year from group size values because infant ungulates appear to recognise potential threats less readily than older conspecifics (FitzGibbon & Lazarus 1995), and their responses to risk likely are dependent on the responses of their mothers. I used the same rationale for *proportion bedded* (see below). Group boundaries were defined as in Frid (1997).
Proportion of lambs	The proportion of lambs in a group; male groups were excluded from analyses.
Proportion bedded	Proportion of non-lambs in a group that was bedded just prior to disturbance.

Table 2. Reduced logistic regression model estimating the effect of helicopter variables on escape probability. Independent variables were transformed as $Log_{10}(x+1)$. Elevations were analysed in feet.

Variables tested	**Effect likelihood ratio test of variables included (DF = 1)**			**Whole model test (N = 57)**				
	Estimate ± SE	χ^2	***P***	***-log-likelihood***	χ^2	***DF***	***P***	***Rho²***
Whole model test				22.89	17.78	2	<0.001	0.28
Intercept	-3.74 ± 1.04							
Least distance	9.68 ± 3.32	11.08	<0.001					
Relative elevation	-0.40 ± 0.18	5.92	0.02					

Table 3. Reduced logistic regression models estimating the effect on escape probability of interactions between helicopter variables and each sheep variable. Distances, elevations, and group size were transformed as $Log_{10}(x+1)$. Proportions were arcsine square root transformed. Elevations were analysed in feet.

Variables tested and sample sizes for each model	**Effect likelihood ratio test of variables included (DF = 1)**			**Whole model test**				
	Estimate ± SE	χ^2	***P***	***-log-likelihood***	χ^2	***DF***	***P***	***Rho²***
Model 1 (N = 57)								
Whole model				11.51	40.54	3	<0.001	0.64
Intercept	-7.00 ± 2.45							
Relative elevation	-0.63 ± 0.31	5.99	0.01					
Least distance	29.60 ± 9.56	29.81	<0.001					
Dist. to security cover * least dist.	-9.89 ± 3.13	22.75	<0.001					
Model 2 (N = 57)								
Whole model				20.21	23.14	2	<0.001	0.36
Intercept	-4.85 ± 1.35							
Least distance	29.00 ± 8.10	20.69	<0.001					
Group size * least distance	-13.04 ± 4.43	11.27	<0.001					
Model 3 (N = 39)								
Whole model				17.47	11.46	1	<0.001	0.25
Intercept	-3.59 ± 1.12							
Proportion of lambs * least distance	17.62 ± 6.50	11.46	<0.001					

Table 4. Reduced linear regression model estimating effects of interactions between proportion bedded (arcsine square root transformed) and distance to terrain block (log_{10} [x+1] transformed) on distance escaped.

Variable	**P**	**Regression coefficient ± standard error**	**ANOVA SUMMARY FOR REDUCED MODEL**				
			F	*DF*	*P*	R^2	*SEE*
Intercept	<0.001	2.34 ± 0.13					
Proportion bedded * distance to terrain block	0.001	-0.80 ± 0.23	12.10	1, 37	0.001	0.25	0.52

Figure captions

Fig. 1. Trigonometry of a helicopter trajectory. The smallest distance between the sheep group (filled circle) and the helicopter trajectory (arrow), or least distance, determines the angle formed by the line of distance *x* and the helicopter trajectory. If *x* is held constant, this angle is smaller when least distance is (a) small than when least distance is (b) large. Because this angle and least distance are interchangeable measures, least distance measures the directness of the helicopter's approach from the perspective of the sheep's location.

Fig. 2. Effect of the interaction of least distance and the sheep's distance to security cover on escape probability. The family of curves in Fig. 2a was generated with parameters of Model 1 of Table 3, with relative elevation held constant at 0 m. Sheep groups at distances to security cover of 75 m (the mean distance), 20 m (the median distance), and 0 m (inside security cover), are represented, respectively, by the short-dashed line, the solid line, and the long-dashed line. Fig. 2b is an example of the relationship described by this family of curves. Solid circles represent sheep inside security cover or within 10 m of it, and open circles represent sheep >10 m from cover. Data points are jittered so that overlapping points can be read. Because I had to categorise continuous three-dimensional data to show it in two dimensions, Fig. 2b is descriptive only and significant trends are in Fig. 2a.

Fig. 3. Effect of the interaction of least distance and the sheep's group size (lambs excluded) on escape probability. The family of curves in Fig. 3a was generated with parameters in Model 2 of Table 3. The long-dashed line, the solid line, and the short-dashed line represent groups with sizes of 40, 18 (the mean group size), and 2, respectively. Fig. 3b is an example of the relationship described by this family of curves. Dark circles represent groups with ≤ 20 sheep, and light circles represent groups with >20 animals. Data points are jittered so that overlapping points can be read. Because I had to categorise continuous three-dimensional data to show it in two dimensions, Fig. 3b is descriptive only and significant trends are in Fig. 3a.

Fig. 4. Effect of the interaction of least distance and the proportion of lambs in the group (male groups excluded) on escape probability. The family of curves in Fig. 4a was generated with parameters in Model 3 of Table 3. Groups with proportions of lambs of 0.1, 0.3 (the mean proportion), and 0.5, are represented, respectively, by the long-dashed line, the solid line, and the short-dashed line. Fig 4b is an example of the relationship described by this family of curves. Dark circles represent groups with a proportion of lambs ≥ 0.3, and lighter circles representing groups with a proportion of lambs <0.3. Data points are jittered so that overlapping points can be read. Because I had to categorise continuous three-dimensional data to show it in two dimensions, Fig. 4b is descriptive only and significant trends are in Fig. 4a.

Fig. 5. Relationship between escape initiation distance and distance to terrain block. Regression line is generated from the reduced model $y = 0.13 + 0.30[\log_{10}(x+1)]$ ($F = 11.33$; $DF = 1,40$; $P = 0.002$; $R^2 = 0.22$, $SEE = 0.012$).

Fig. 6. Example of how to include the sheep's' altitudinal distribution in the design of guidelines for helicopters. Relative elevations are based on the range where most animals are likely to be, and are converted to actual elevations that helicopter pilots can refer to. For each of these elevations there is a corresponding setback distance, as exemplified in Fig. 7.

Fig. 7. Example of setback distances and elevations generated with the logistic regression model of Table 2. Solid lines represent distances and elevations based on escape probabilities of 0.1, and dashed lines are based on escape probabilities of 0.2. I suggest grouping elevations into categories encompassed by the vertical dot lines (including the right y-axis), and using the setback distance that corresponds to the upper range of each elevation category. For example, for an escape probability of 0.2, a setback distance of 3.5 km corresponds to the elevation category of ≥ 0 and ≤300 m.

Fig. 1

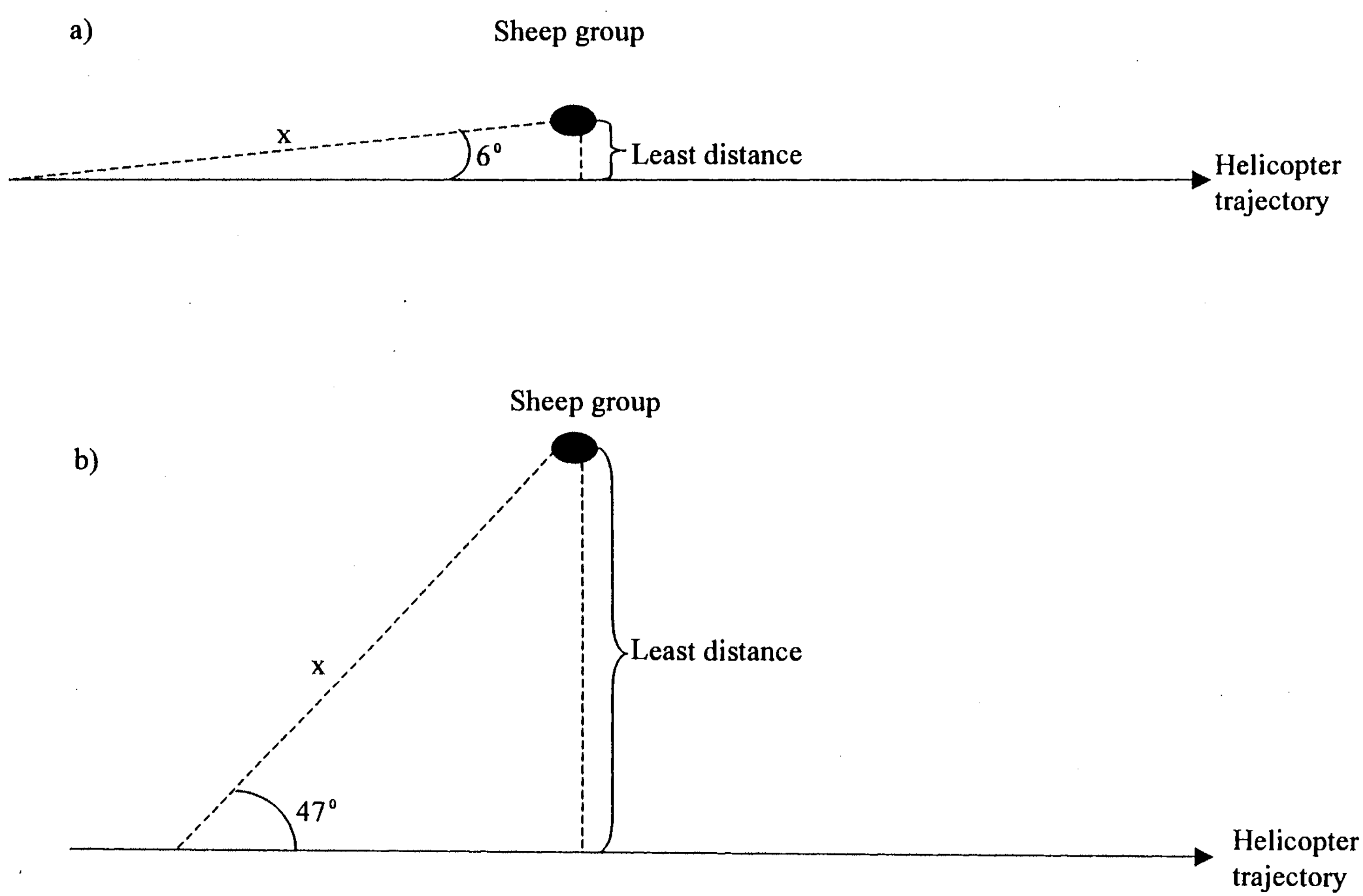
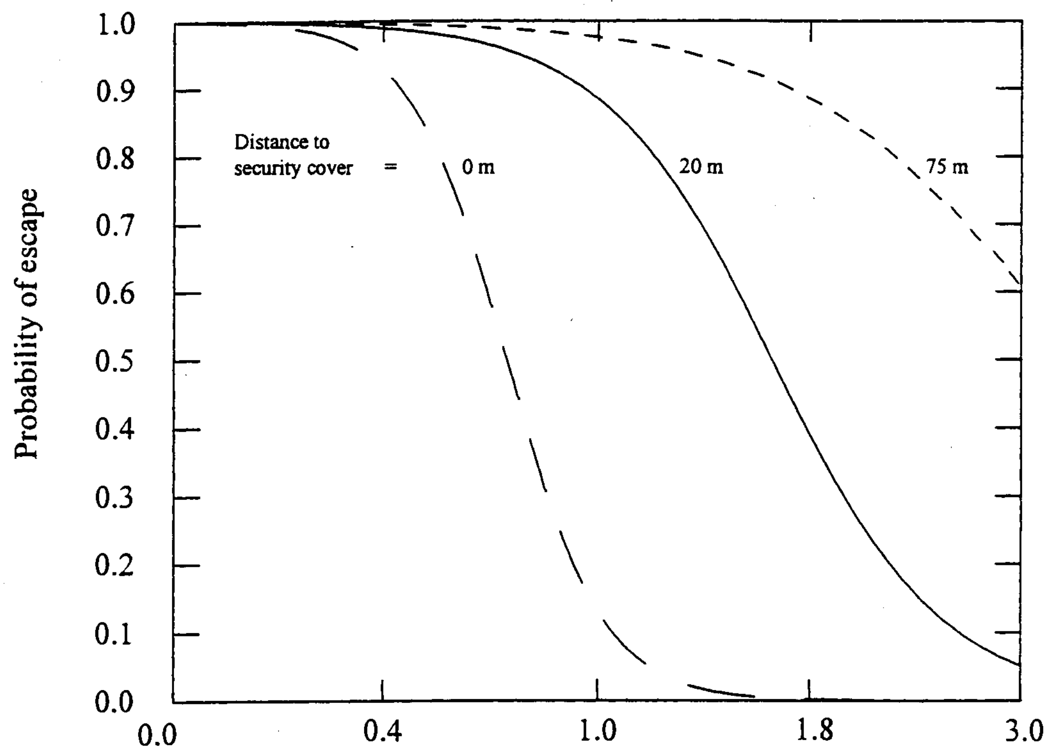

a)
Sheep group
x
6°
Least distance
Helicopter
trajectory
b)
Sheep group
x
47°
Least distance
Helicopter
trajectory

Fig. 2

a)


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Probability of escape
Distance to security cover =
0 m
20 m
75 m
0.0
0.4
1.0
1.8
3.0

b)

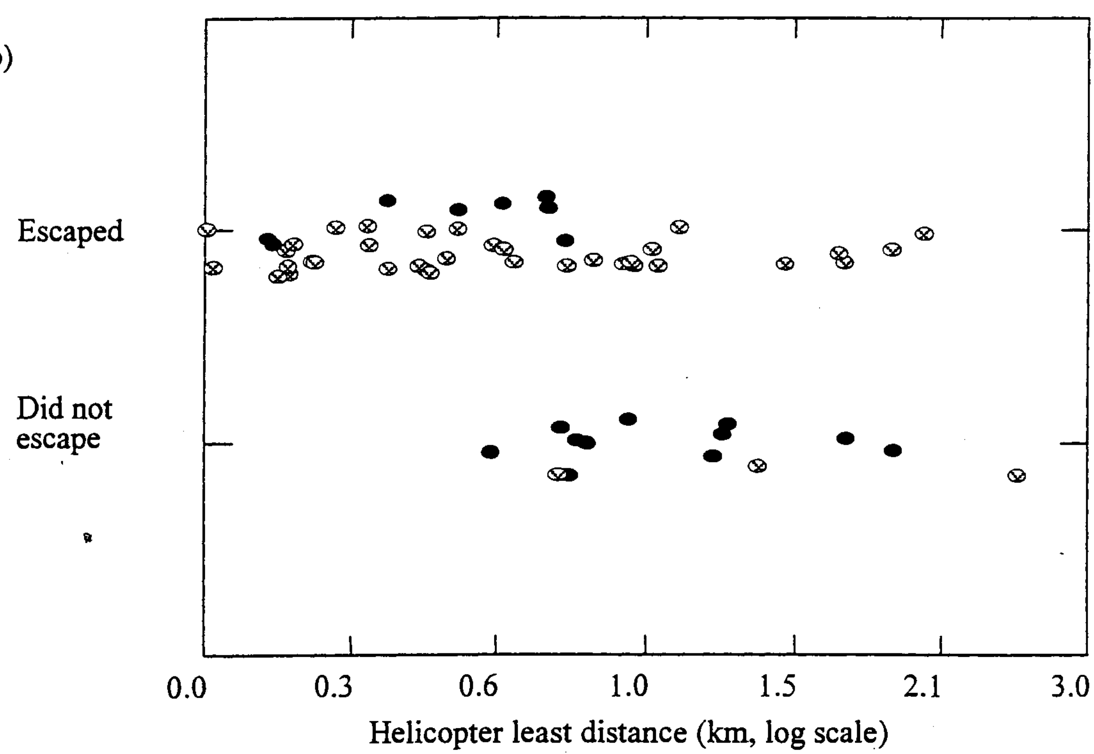

Escaped
Did not escape
0.0
0.3
0.6
1.0
1.5
2.1
3.0
Helicopter least distance (km, log scale)

Fig. 3

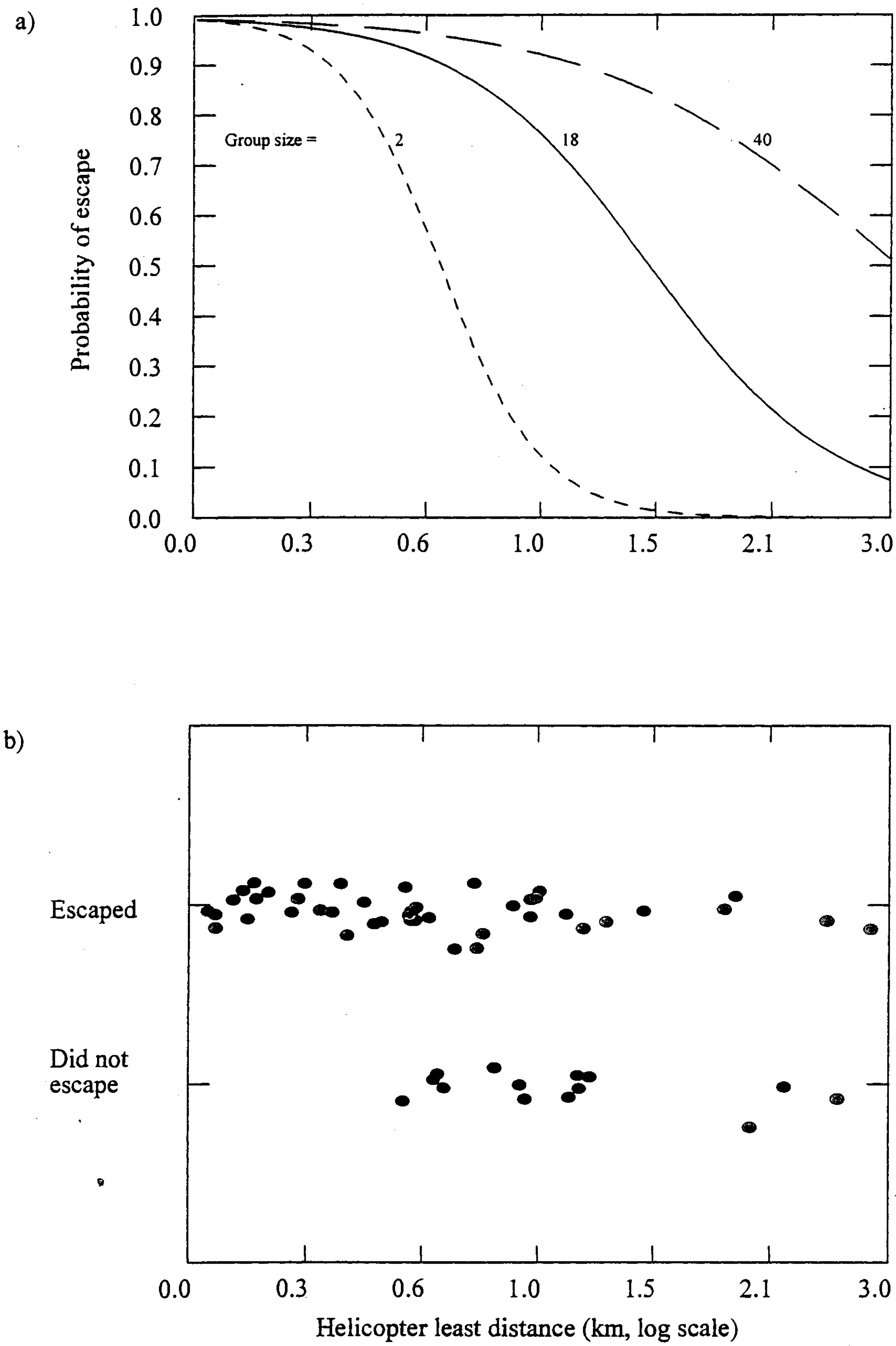

a)
Probability of escape
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Group size =
2
18
40
0.0
0.3
0.6
1.0
1.5
2.1
3.0
b)
Escaped
Did not escape
0.0
0.3
0.6
1.0
1.5
2.1
3.0
Helicopter least distance (km, log scale)

Fig. 4

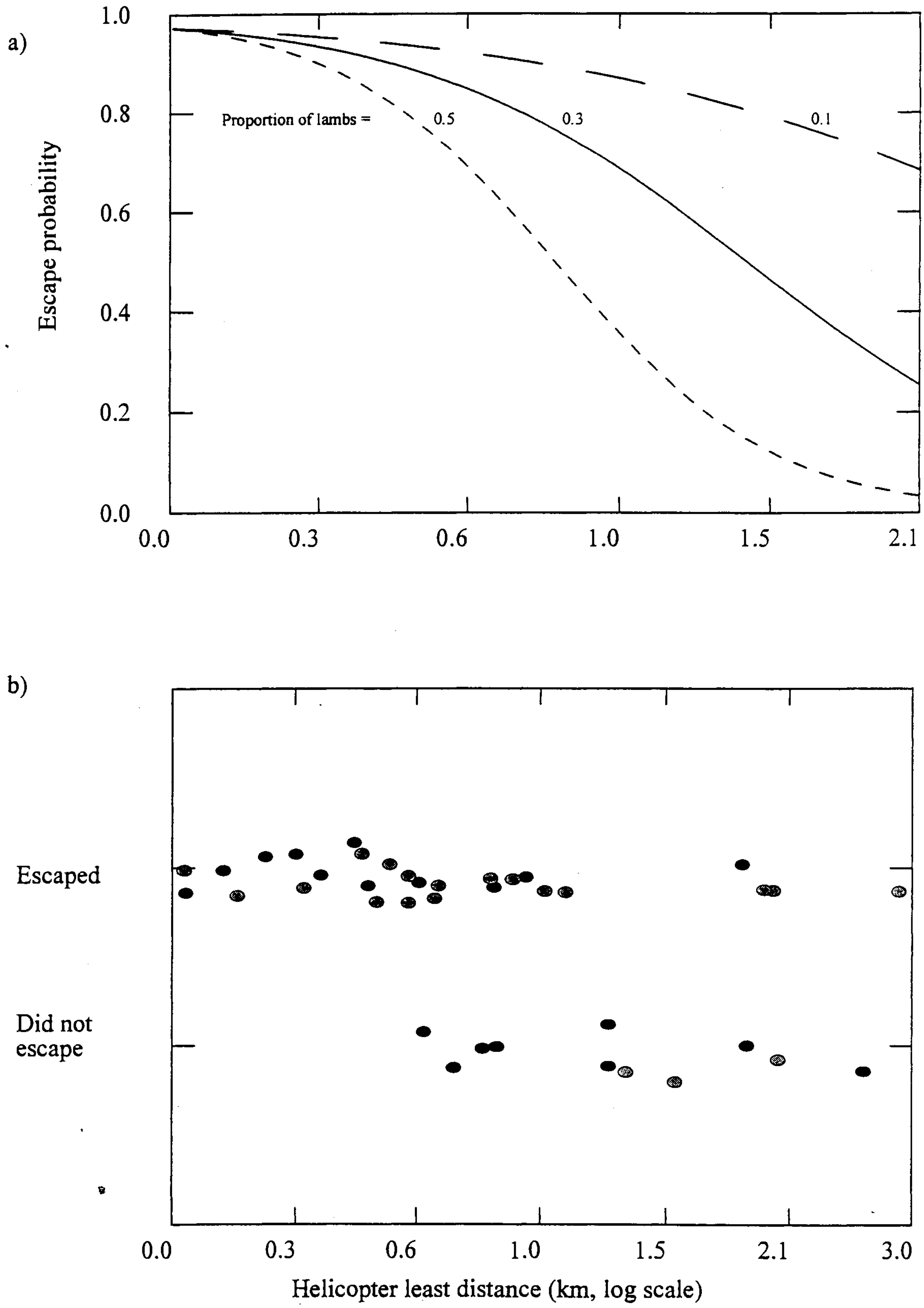

a)
Escape probability
1.0
0.8
0.6
0.4
0.2
0.0
Proportion of lambs =
0.5
0.3
0.1
0.0
0.3
0.6
1.0
1.5
2.1
b)
Escaped
Did not escape
0.0
0.3
0.6
1.0
1.5
2.1
3.0
Helicopter least distance (km, log scale)

Fig. 5

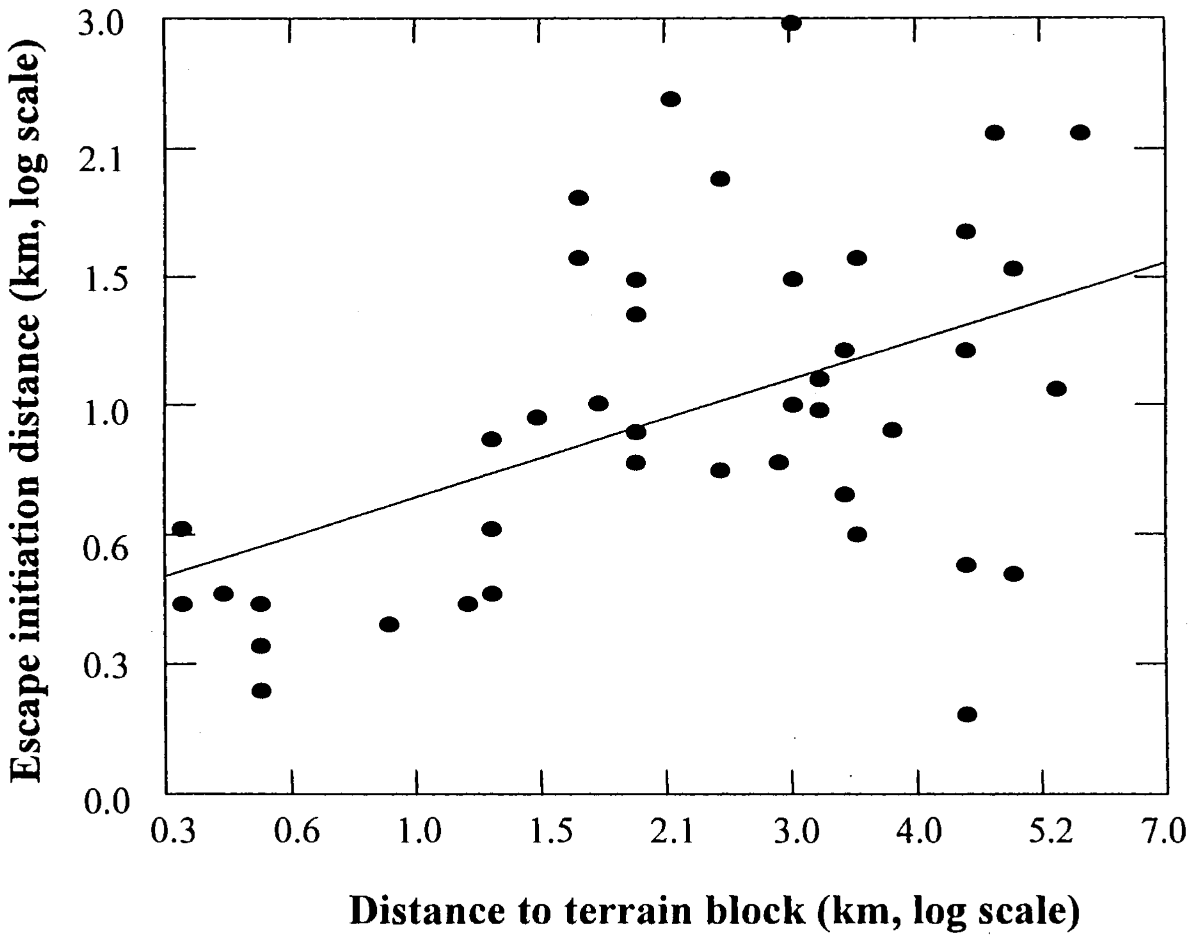
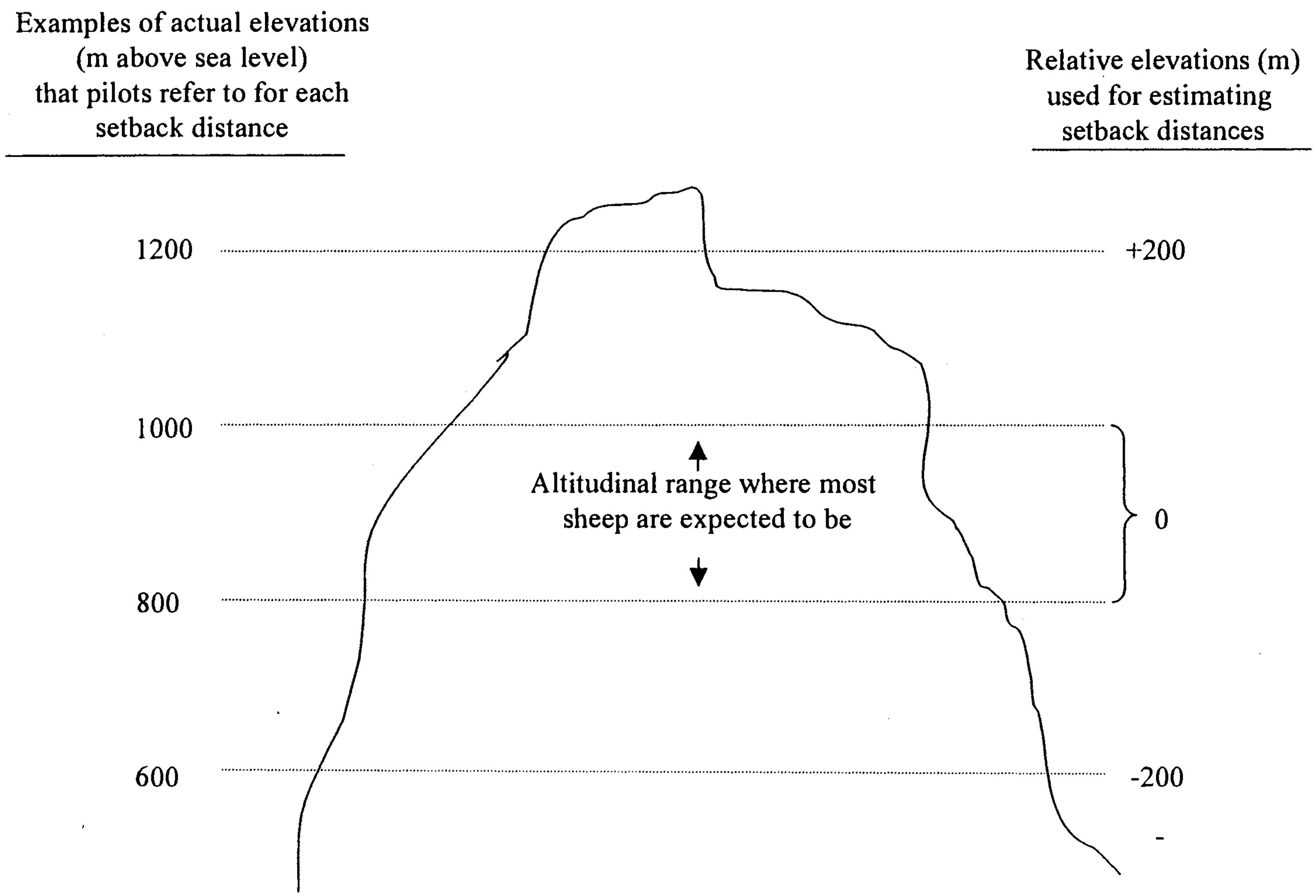
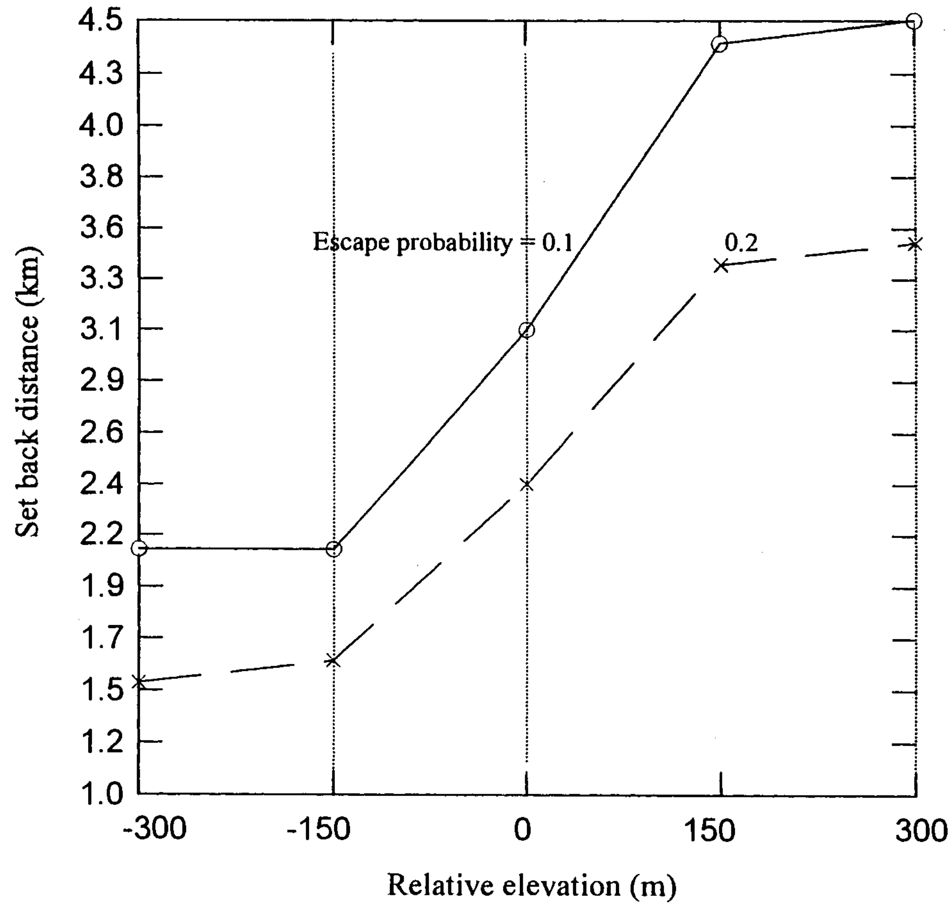

3.0
2.1
1.5
1.0
0.6
0.3
0.0
Escape initiation distance (km, log scale)
0.3
0.6
1.0
1.5
2.1
3.0
4.0
5.2
7.0
Distance to terrain block (km, log scale)

Fig. 6



Examples of actual elevations
(m above sea level)
that pilots refer to for each
setback distance
Relative elevations (m)
used for estimating
setback distances
1200
+200
1000
Altitudinal range where most
sheep are expected to be
0
800
600
-200

Fig. 7


Set back distance (km)
4.5
4.3
4.0
3.8
3.6
3.3
3.1
2.9
2.6
2.4
2.2
1.9
1.7
1.5
1.2
1.0
Escape probability = 0.1
0.2
-300
-150
0
150
300
Relative elevation (m)