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Determining the factors causing variation in traffic accidents both in space and time are important for management, as it can help in designing mitigation efforts. The annual harvest of red deer *Cervus elaphus* in Norway has increased from 2,695 in 1971 to 23,597 in 2001, while the number of car-killed red deer increased from 27 to 443 over the same period. I analysed how the temporal variation in the annual number of car-killed red deer along the west coast of Norway varied with population density and climate. The increase in the number of car-killed red deer was mainly an effect of increasing population size (as evidenced from harvest records). The parameter estimate for the population size effect was 1.722 and 1.025, respectively, before and after adding the (non-significant) effect of 'year' (as a continuous term). An increase in population size therefore led to an increase in the proportion of the number of car-killed red deer only when excluding the year effect which was likely due to an increase in traffic volume. Spring conditions, as measured by the March-May value of the North Atlantic Oscillation (NAO), correlated with the number of car-killed red deer, but winter, summer or autumn NAO did not. I argue that the consequences of an increasing number of car-deer collisions with increasing population density should be incorporated into future modelling of harvesting strategies if the aim is to maximise the economic outcome at a national scale.

Key words: accidents, climate, density, harvesting, traffic, North Atlantic Oscillation

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Cervid populations have been increasing in density and distribution during the last decades in most areas of the U.S.A. (McShea & Underwood 1997) and Europe (Gill 1990). In parallel, the number of cars and human infrastructure such as roads have also increased. In some urban areas, traffic accidents have become the most common proximate cause of death of deer (Lopez, Vieira, Silvy, Frank, Whisenant & Jones 2003, see also Vincent, Bideau, Cibien & Quéré 1988). Costs related to human and deer injury and mortality as well as vehicle damage arising from road or railway accidents involving deer now amount to a very significant and increasing annual total (Putman 1997, Finder, Roseberry & Woolf 1999, Schwabe & Schuhmann 2002, Nielsen, Anderson & Grund 2003). To determine which factors cause the variation in such accidents, both in space and time, is important for management, as it can help in designing mitigation efforts (Schaefer & Penland 1985, Romin & Bissonette 1996a, Ujvari, Baagøe & Madsen 1998).

At a fine temporal scale, it has been shown that collisions with deer were most frequent at dawn and dusk (e.g. white-tailed deer *Odocoileus virginianus*; Allen & McCullough 1976, Haikonen & Summala 2001). On a seasonal basis, moose *Alces alces* and white-tailed deer accidents are frequent in May and June (Fraser 1997), but typically moose accidents are most common during winter or during rut (October-December; see review in Lavsund & Sandegren 1991). Some studies report peaks in accident numbers in autumn (e.g. fallow deer *Dama dama*, Geissler 1981; white-tailed deer, Allen & McCullough 1976; roe deer *Capreolus capreolus*, Madsen, Strandgaard & Prang 2002), while others report peaks in number of car-deer collisions both during spring and autumn (white-tailed deer; Hubbard, Danielson & Schmitz 2000). Evidence suggests that the long-term trend is closely related to harvest size and traffic volume (white-tailed deer; McCaffery 1973), but, generally, much less attention has been paid to determining the causes of long-term trends and (annual) variation in number of car-killed deer.

The annual harvest of red deer *Cervus elaphus* in Norway has increased from 2,695 in 1971 to 23,597 in 2001, and the number of car-killed red deer increased from 27 to 443 over the same period (Statistics Norway 1972, Statistics Norway 2002a). Although one study has listed the total number of red deer killed in traffic accidents in Norway for the period 1987-1993 (Groot Bruinderink & Hazebroek 1996), there has been no study analysing which factors in space and time affect the annual number of car-killed red deer in Norway. Indeed, very few studies on cervids in general consider annual variation in the distribution of such accidents. In this study, I analyse the official statistics of the annual number of red deer killed in traffic accidents in Norway (during 1971-2001), and test the following hypotheses:

(H_1): The number of car-killed red deer correlates positively with population densities of red deer (as evidenced from harvest records), i.e. that the slope is > 0. More precisely, I test whether the number of car-killed red deer is a constant proportion (H_{1a}, slope = 1) or an increasing proportion (H_{1b}, slope > 1) with increasing population size (based on the assumption that the density index based on harvest reflects the population size linearly).

(H_2): The number of car-killed red deer correlates positively with increasing traffic (km of roads and number of cars).

(H_3): The number of car-killed red deer correlates with climate. The North Atlantic Oscillation (NAO) refers to a north-south alternation in atmospheric mass between the subtropical atmospheric high-pressure center over the Azores and the atmospheric subpolar low-pressure center over Iceland (Hurrell, Kushnir, Ottersen & Visbeck 2003). It measures the strength of the westerly winds blowing across the North Atlantic Ocean between 40°N and 60°N. Variability in the direction and magnitude of the westerly winds is responsible for interannual and decadal fluctuations in wintertime temperatures and the balance of precipitation and evaporation across the Atlantic and the adjoining landmasses. During positive phases of the NAO the prevailing westerly winds are strengthened and move northwards causing increased precipitation and temperatures over northern Europe. The winter-NAO is well known to strongly affect winter conditions for red deer at the west coast of Norway, influencing both temperature, precipitation and snow depth (Mysterud, Yoccoz, Stenseth & Langvatn 2000). I used the NAO as it can be considered a 'package of weather' which represents better the climate than any single local weather variable (Stenseth, Ottersen, Hurrell, Mysterud, Lima, Chan, Yoccoz & Ådlandsvik 2003). The body weight of red deer generally increases with increasing NAO index (Mysterud, Stenseth, Yoccoz, Langvatn & Steinheim 2001b). Deer condition may in turn affect ranging behaviour, and I therefore predict a negative correlation between the number of car-killed red deer and the NAO winter index.

Material and methods

The number of car-killed deer is listed in the annual hunting statistics from Statistics Norway (Statistics Norway 2002a). By law, all car-killed deer in Norway must be reported either to the police or to the municipality wildlife authorities, who in turn send the data to Statistics Norway for processing and quality control, and this system has been maintained for the entire period. Data were available on a national scale for the period 1971-2001, and on a county scale from 1978 to 2001. Year is defined from 1 April to 31 March the following year, i.e. what is termed year 1980 covers the period 1 April 1980 - 31 March 1981 (Statistics Norway 2002a).

I focussed on the counties along the west coast of Norway, i.e. Rogaland, Hordaland, Sogn and Fjordane, Møre and Romsdal and Sør-Trøndelag, as these counties constitute the main distribution range for red deer in Norway, and as accidents were rare outside these counties (Fig. 1). The vegetation on the west coast of Norway

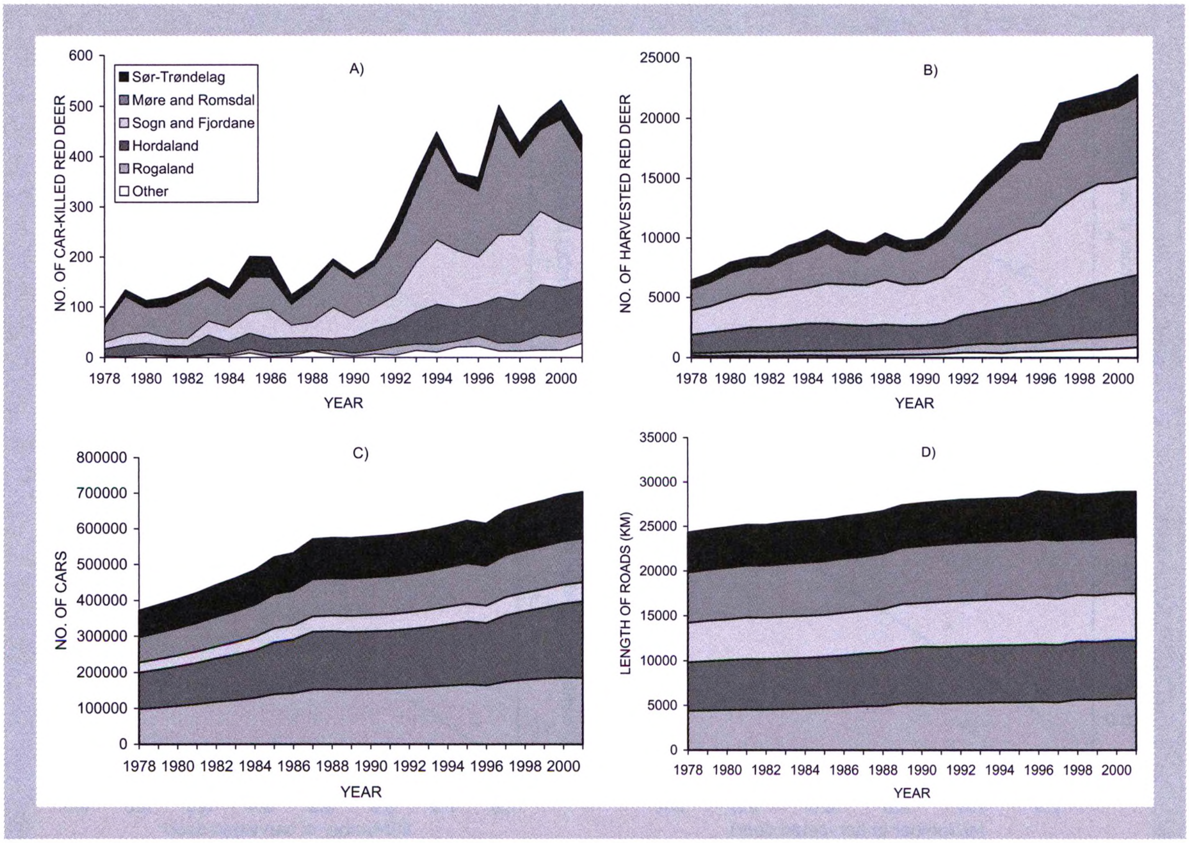

Figure 1. Numbers of car-killed red deer in Norway during 1978-2001 for the five main counties and the other counties pooled (A), of harvested deer for the same period and areas (B), of cars registered (C) and of the total length of roads in the five main counties (D).

is mostly boreo-nemoral (Abrahamsen, Jacobsen, Kalliola, Dahl, Wilborg & Påhlsson 1977). A detailed description of the habitat (Mysterud, Langvatn, Yoccoz & Stenseth 2002) and topography (Mysterud, Langvatn, Yoccoz & Stenseth 2001a) is given elsewhere. I also derived data for indices on population size, traffic volume and climate.

Considering the population size index, the number of harvested deer (available from Statistics Norway 2002a) is regarded to be a fairly reliable index of population density over longer time spans such as those considered in my study (Mysterud, Yoccoz, Stenseth & Langvatn 2001c, Yoccoz, Mysterud, Langvatn & Stenseth 2002, Mysterud et al. 2002), although the year-to-year variation in harvest may also depend on harvest quotas. For a further discussion of this index, see Mysterud et al. (2001c).

Considering the traffic volume indices, the length of roads as well as the number of cars registered in each county was available from the statistical yearbook from Statistics Norway (Statistics Norway 2002b). The total number of cars included passenger cars, busses, vans and lorries. The length of roads included a number of state roads ('riksvei'), county roads ('fylkesvei') and municipality roads ('kommunevei'). The length of roads and the number of cars were correlated, and for analysis the total number of cars was used as an index for traffic volume.

Considering the climate indices, the seasonal (winter: December-February; spring: March-May; summer: June-August; autumn: September-November) indices of the North Atlantic Oscillations (NAO) were used (Hurrell et al. 2003 and obtained from http://www.cgd.ucar.edu/~jhurrell/nao.pc.html). The best indices are regarded as those based on principal component analysis (Hurrell et al. 2003), and they were therefore preferred to the station-based indices which are more commonly used (see Stenseth et al. 2003). As the red deer data were from April one year to March the next year (see above), I used spring, summer and autumn indices from year t and winter index from year t+1. As the NAO for spring also includes March, I furthermore tested the average monthly (station-based) index for April and May using data from http://www.cgd.ucar.edu/~jhurrell/

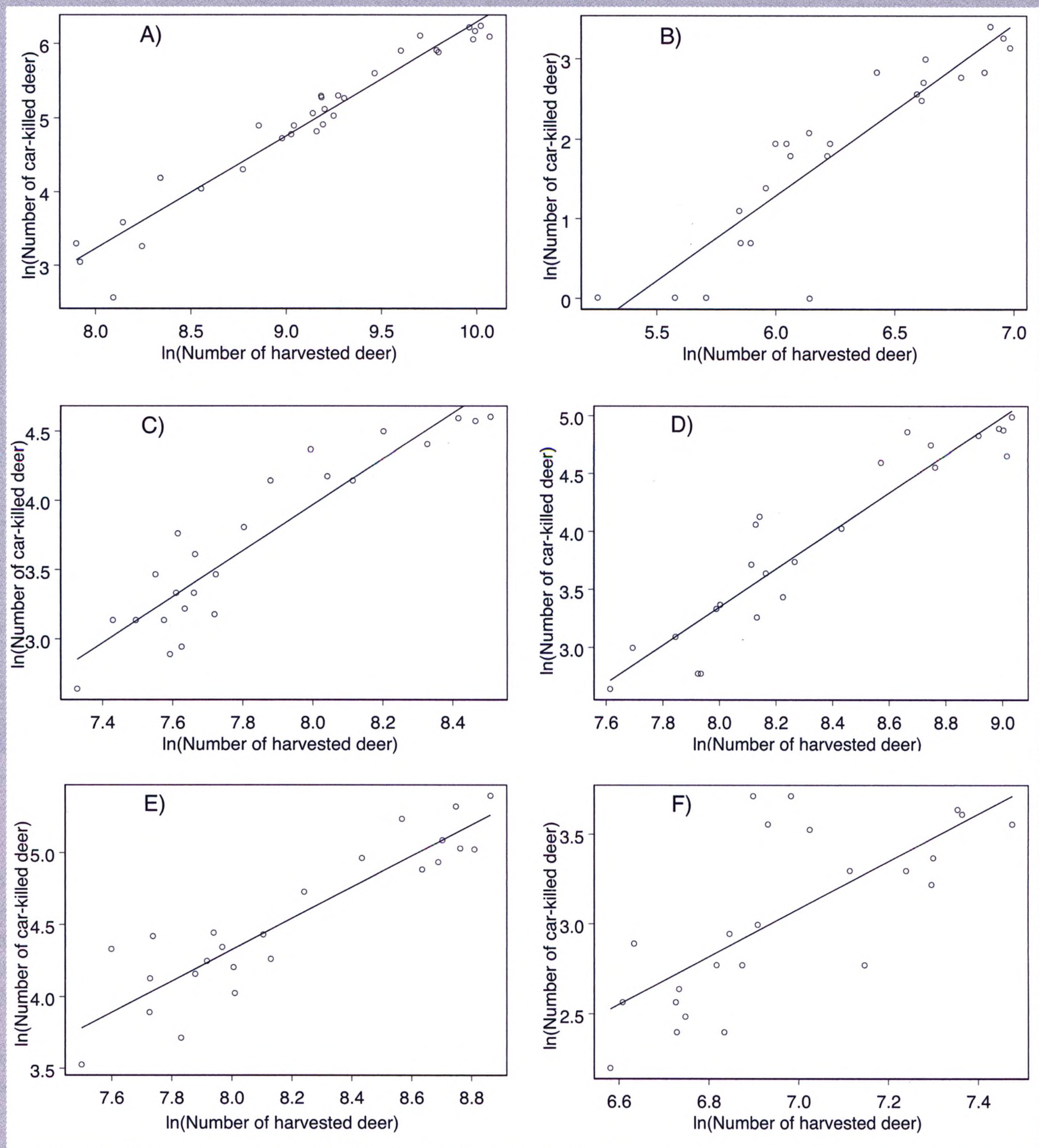

Figure 2. Relationship between the number of car-killed red deer and the size of harvest (an index for population size) for: A) the whole of Norway during 1971-2001, and for the counties of B) Rogaland, C) Hordaland, D) Sogn and Fjordane, E) Møre and Romsdal and F) Sør-Trøndelag during 1978-2001.

nao.stat.other.html#monthly. In general, high NAO values are correlated with much precipitation and high temperatures along the west coast of Norway, in particular during winter. A more detailed description of these indices is given elsewhere (Hurrell et al. 2003), and so are their major impacts on ecological systems (Stenseth, Mysterud, Ottersen, Hurrell, Chan & Lima 2002, Mysterud, Stenseth, Yoccoz, Ottersen & Langvatn 2003) including red deer along the west coast of Norway (Post, Stenseth, Langvatn & Fromentin 1997, Mysterud et al. 2001b).

Table 1. Results from linear mixed models of annual variation in (ln) number of car-killed red deer at the west coast of Norway during 1978-2001; A) with year effect, B) with number of cars and C) with only population size index included in the model.

Parameter	L.S. mean	SE	df	T	P
A) Model including a 'year' effect (AIC = 149.9595)					
Intercept	-76.807	41.578	83	-1.847	0.068
ln (number of harvested deer)	1.025	0.457	83	2.242	0.028
Year	0.036	0.023	18	1.617	0.123
NAO - winter	-0.041	0.033	18	-1.248	0.228
NAO - spring	0.116	0.041	18	2.872	0.010
NAO - summer	-0.037	0.044	18	-0.854	0.404
NAO - autumn	0.023	0.039	18	0.596	0.559
County (Møre and Romsdal vs Hordaland)	72.071	65.020	83	1.108	0.271
County (Rogaland vs Hordaland)	-136.424	102.493	83	-1.331	0.187
County (Sogn and Fjordane vs Hordaland)	32.539	90.833	83	0.358	0.721
County (Sør-Trøndelag vs Hordaland)	143.069	52.701	83	2.715	0.010
ln (number of harvested deer)*County (Møre and Romsdal vs Hordaland)	0.060	0.627	83	0.095	0.924
ln (number of harvested deer)*County (Rogaland vs Hordaland)	-0.501	0.863	83	-0.581	0.563
ln (number of harvested deer)*County (Sogn and Fjordane vs Hordaland)	0.340	0.809	83	0.421	0.675
ln (number of harvested deer)*County (Sør-Trøndelag vs Hordaland)	1.309	0.690	83	1.898	0.061
Year*County (Møre and Romsdal vs Hordaland)	-0.036	0.035	83	-1.034	0.304
Year*County (Rogaland vs Hordaland)	0.070	0.054	83	1.291	0.200
Year*County (Sogn and Fjordane vs Hordaland)	-0.018	0.049	83	-0.367	0.715
Year*County (Sør-Trøndelag vs Hordaland)	-0.076	0.029	83	-2.656	0.010
B) Model including number of cars (AIC = 124.0615)					
Intercept	-15.279	5.140	82	-2.972	0.004
ln (number of harvested deer)	1.350	0.372	82	3.631	0.001
ln (number of cars)	0.702	0.620	82	1.134	0.260
NAO - winter	-0.046	0.033	19	-1.414	0.174
NAO - spring	0.110	0.041	19	2.650	0.016
NAO - summer	-0.025	0.043	19	-0.585	0.566
NAO - autumn	0.023	0.038	19	0.605	0.553
County (Møre and Romsdal vs Hordaland)	15.571	8.171	82	1.906	0.060
County (Rogaland vs Hordaland)	-10.049	10.822	82	-0.929	0.356
County (Sogn and Fjordane vs Hordaland)	0.767	7.254	82	0.106	0.916
County (Sør-Trøndelag vs Hordaland)	12.330	7.054	82	1.748	0.084
ln (number of harvested deer)*County (Møre and Romsdal vs Hordaland)	-0.063	0.453	82	-0.140	0.889
ln (number of harvested deer)*County (Rogaland vs Hordaland)	0.182	0.535	82	0.341	0.734
ln (number of harvested deer)* County (Sogn and Fjordane vs Hordaland)	0.052	0.479	82	0.108	0.915
ln (number of harvested deer)*County (Sør-Trøndelag vs Hordaland)	0.257	0.532	82	0.483	0.630
ln (number of cars)*County (Møre and Romsdal vs Hordaland)	-1.251	0.942	82	-1.327	0.188
ln (number of cars)*County (Rogaland vs Hordaland)	0.776	1.162	82	0.668	0.506
ln (number of cars)*County (Sogn and Fjordane vs Hordaland)	-0.072	0.940	82	-0.077	0.939
ln (number of cars)*County (Sør-Trøndelag vs Hordaland)	-1.153	0.847	82	-1.361	0.177
C) Model with only population size index (AIC = 125.856)					
Intercept	-9.806	1.516	87	-6.470	<0.001
ln (number of harvested deer)	1.722	0.193	87	8.906	<0.001
NAO - winter	-0.045	0.030	19	-1.468	0.158
NAO - spring	0.120	0.037	19	3.258	0.004
NAO - summer	-0.028	0.041	19	-0.682	0.504
NAO - autumn	0.023	0.037	19	0.625	0.540
County (Møre and Romsdal vs Hordaland)	5.310	1.857	87	2.860	0.005
County (Rogaland vs Hordaland)	-1.522	1.666	87	-0.913	0.364
County (Sogn and Fjordane vs Hordaland)	-0.164	1.846	87	-0.089	0.930
County (Sør-Trøndelag vs Hordaland)	3.212	2.188	87	1.468	0.146
ln (number of harvested deer)*County (Møre and Romsdal vs Hordaland)	-0.621	0.233	87	-2.667	0.009
ln (number of harvested deer)*County (Rogaland vs Hordaland)	0.382	0.226	87	1.691	0.095
ln (number of harvested deer)*County (Sogn and Fjordane vs Hordaland)	-0.059	0.230	87	-0.259	0.796
ln (number of harvested deer)*County (Sør-Trøndelag vs Hordaland)	-0.341	0.300	87	-1.135	0.260

Statistical analyses

The time series of both the number of car-killed deer, harvested red deer and traffic volume (number of cars and length of roads) show a strong temporal trend and are autocorrelated (see Fig. 1). The correlation between year (as a continuous variable) and the traffic index was so high ($r > 0.95$ for all counties included in the analyses) that it was not possible to reliably differentiate between them. For further analysis, a time trend will indicate an increase in length of roads and the number of cars (and possibly other factors), and they were not entered in the same model. To remove (or estimate) the time trend, I entered 'year' as a continuous covariate. Entering 'year' as a factor solved most of the autocorrelation problems for the number of harvested deer. Although the number of harvested deer reflects main trends in population size (Mysterud et al. 2001c), the year-to-year increase or decrease in harvest is also affected by harvest quotas. I therefore did not further 'break up the series', as the very fine-scaled details of this density measure may not be reliable.

I used linear mixed-models (LME) to analyse variation in number of car-killed red deer. As I used the time series from five counties in the same model, I used 'year' as random factor to avoid pseudoreplication. Numbers of car-killed red deer, harvested deer and cars were ln-transformed to stabilise the variance. For Rogaland, there was no car-killed deer in the years 1978-1980, and a small positive value (0.1) was inserted before transformation, which is a common approach to deal with zeros when log-transforming (e.g. Bjørnstad, Falck & Stenseth 1995). Parameter estimation and type III testing was used for inference, so that the order in which the factors were entered did not play a role. The AIC criteria was used when comparing models (Burnham & Anderson 1998), and all models were run in S-Plus (Venables & Ripley 1994).

Results

Regressing the (ln) number of car-killed red deer directly to the (ln) number of harvested deer in Norway and for the five counties along the west coast (Fig. 2), gave parameter estimates larger than 1 (not significant for the county of Møre and Romsdal) which is in agreement with H_{1b}. In a global linear-mixed model for the five counties along the west coast (with 'year' as a random factor), the effect of number of harvested deer remained significant after having controlled also for a linear 'year' effect (Table 1) or for the (ln) number of cars (see Table 1). However, the parameter estimate (1.025 when including year and 1.350 when including (ln) number of cars; see Table 1) was not significantly different from 1, suggesting that a constant proportion of the population was killed in accidents which supported H_{1a}. Removing the non-significant effect of year (and (ln) number of cars) gave a parameter estimate for the effect of population density index of 1.722 (SE = 0.193), which supported H_{1b}. The model using year (AIC = 149.960) was less parsimonious than the model using (ln) number of cars (AIC = 124.062), which in turn was fairly similar to the model using only harvest (AIC = 125.856). There was not a significant effect of (ln) number of cars, but this variable entered the model with the lowest AIC value (see Table 1), and thus provided ambiguous evidence for H_2. In the models, the effects of 'county', as well as the interaction between 'county and year' or 'county and (ln) number of cars' and 'county and number of harvested deer' were also included (see Table 1). There was a positive relationship between number of car-killed deer and the spring NAO (see Table 1) which therefore gave some support of H_3. This result remained significant when using the average monthly (station-based) value from April-May (l.s. mean = 0.130, SE = 0.057, df = 19, T = 2.276, P = 0.035). There was no effect of the NAO during winter, summer or autumn (see Table 1).

Discussion

Roads can have major impacts on ecological systems (Forman & Alexander 1998, Trombulak & Frissell 2000). Roads and the related traffic affect the behaviour of cervids (Rost & Bailey 1979, Lyon 1983, Putman 1997), and accidents are fairly frequent and cause injury and death (see introducing section of this paper). My analysis of the annual variation in the number of car-killed red deer in Norway suggests that the increase in population size (as evidenced from harvest records) is the main factor behind the large increase in car-killed red deer. My study therefore is in agreement with the reported long-term trends of white-tailed deer accidents in the U.S.A. which were closely related to harvest size (McCaffery 1973). I found no significant main effect of the number of cars, but this variable entered the most parsimonious model providing at least some support for H_2. Previous studies have found clear (McCaffery 1973) or no effects (Gleason & Jenks 1993) of traffic volume. At fine spatial scales, the exact location of roads relative to feeding sites (Carbaugh, Vaughan, Bellis & Graves 1975) and the distance of roads to forest cover (Bashore, Tzilkowski & Bellis 1985, Finder et al. 1999) are important for white-tailed deer collisions, whereas another study failed to find a relationship with habitat or topography (Feldhamer, Gates, Harman, Loranger & Dixon 1986). Further, more accidents may occur at roads where cars drive fast (for white-tailed deer see Allen & McCullough 1976, Bashore et al. 1985; for mule deer see Romin & Bissonette 1996b).

Even when ignoring the emotional/ethical costs to humans (and animals) involved in such accidents, the economic costs are substantial (e.g. Schwabe & Schuhmann 2002), and should be incorporated as a cost in any economic modelling of harvesting strategies if the aim is to maximise the economic outcome at a national scale. Most focus when modelling harvesting strategies of cervids has been on how to increase harvest size (and determine the variance), e.g. as was done for moose in Norway (Sæther, Engen & Solberg 2001) and red deer in Scotland (Milner-Gulland, Coulson & Clutton-Brock 2000, Clutton-Brock, Coulson, Milner-Gulland, Thomson & Armstrong 2002). In order to move a step further, the relationship between population size and number of car-killed deer must be determined. In the absence of direct estimates of population size, I have used size of harvest, as has been used in previous studies as a fair approximation of long-term trends in population size (see Forchhammer, Stenseth, Post & Langvatn 1998, Mysterud et al. 2001c, Mysterud et al. 2002). There was a very close relationship between the number of car-killed red deer and the number of harvested deer (see Fig. 2), but the exact parameter estimate depended on whether a non-significant year term (1.025) was added or not (1.722). The latter estimate will more strongly affect harvesting models, as it suggests an increase in the proportion of deer killed in accidents with increasing population density. The highest estimate came from the best model (as judged by the AIC). Sæther et al. (2001) showed that when performing threshold harvesting compared to proportional harvesting for moose, the mean harvest increased slightly (but also the variance increased). It will be interesting to see how costs related to traffic accidents will affect such conclusions in future harvest modelling.

That there was no effect of winter climate on the number of accidents at the west coast of Norway was somewhat unexpected. Train collisions with moose increased with severity of winter (snow depth and temperature) as well as with train speed (Andersen, Wiseth, Pedersen & Jaren 1991, Gundersen & Andreassen 1998). The winter NAO is well known to strongly affect winter conditions for red deer at the west coast (Mysterud et al. 2000), so the lack of a correlation between the winter NAO and the number of accidents is likely not related to the use of this coarse scale index. Less attention has been paid to the correlation between the NAO at other seasons than winter (Mysterud et al. 2003), but the NAO in May was reported to affect body weight of red deer calves along the west coast of Norway (Post, Langvatn, Forchhammer & Stenseth 1999). The analyses found an effect of the NAO in spring. Many accidents occurred during spring in some studies on other deer species (Fraser 1997, Hubbard et al. 2000). My analysis suggests that there may be inter-annual variation in the number of deer killed in the traffic during spring which may be related to the condition of the deer.

I conducted my study at a coarse spatial ('county') and temporal ('annual') scale. The scale may be important for the patterns observed (in general: e.g. Wiens 1989, and for red deer in Norway see Mysterud et al. 2000). Though some clear patterns emerged at the coarse scales I used, a closer look at the patterns on finer spatial and temporal scales are warranted before deciding on the most efficient mitigation efforts. In particular, whether such accidents are concentrated in time and space should be used to decide whether a regional decline in population size of red deer or rather local fencing or supplementary feeding to keep animals away from traffic arteries could solve the problem. From a broader society perspective, managers should at least take into account the local losses in traffic and the associated costs when deciding whether or not the red deer population should be allowed to increase further.

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