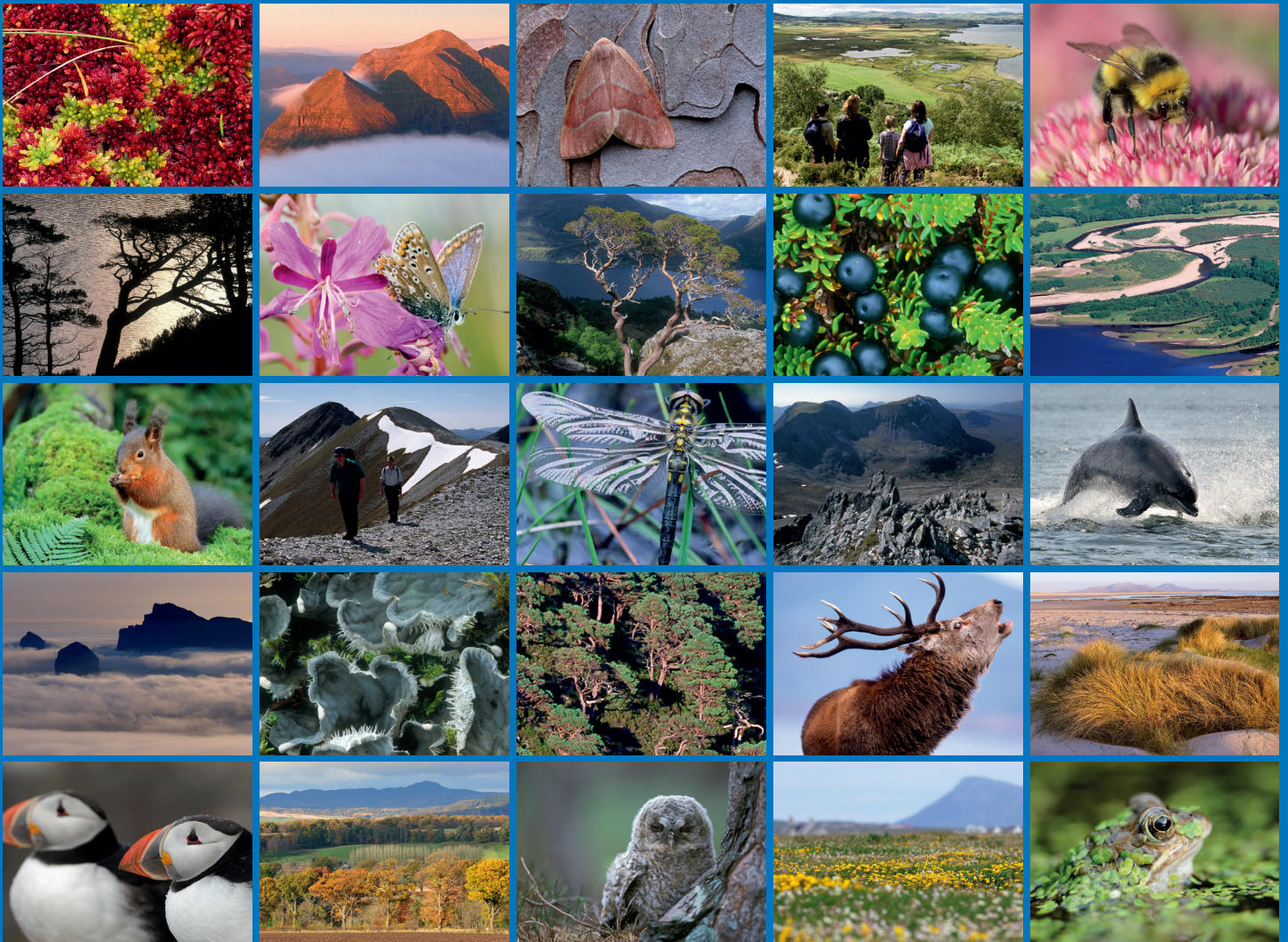# Estimating national trends and regional differences in red deer density on open-hill ground in Scotland: identifying the causes of change and consequences for upland habitats

COMMISSIONED REPORT

Commissioned Report No. 981

Estimating national trends and regional differences in red deer density on open-hill ground in Scotland: identifying the causes of change and consequences for upland habitats

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COMMISSIONED REPORT
Summary

Estimating national trends and regional differences in red deer density on open-hill ground in Scotland: identifying the causes of change and consequences for upland habitats

Background

For many decades there has been a debate about the number of red deer in Scotland and the extent of deleterious impact by herbivores on the natural heritage. This report describes the overall trend in red deer density on open-hill ground in the Highlands and Islands of Scotland, and regional variation, since systematic censuses began in 1961. Forestry Commission Land was excluded, because of the difficulty of estimating numbers in largely wooded areas. The analysis was undertaken to provide a comprehensive exploration of existing evidence to SNH on population status and trends. The temporal and spatial variation in population density is explored in terms of two major drivers: culling effort and the levels of sheep stocking. Investigating the impact of climate change, on deer density, and its interaction with culling and changing sheep stocks, was beyond the scope of this report. However, the impact of deer and sheep on the natural heritage is investigated by analysing the probability that features in protected areas are in 'favourable' condition using the available Site Condition Monitoring records.

Since our preliminary findings on status and trends in density were published in the SNH Report, *Deer Management in Scotland,* submitted to the Cabinet Secretary, and published by the Scottish Government on 18 November 2016, the statistical models have been refined to give more robust estimates. This means that there are some differences from the earlier results. In particular, the estimate of overall density in winter 2016 is somewhat lower. However, the trends within some Deer Management Groups have been revised to better describe recent changes.

Main findings

– After four decades of steady increase since 1961, national mean densities of red deer on open-hill ground in the Highlands and Islands of Scotland in the last 15 years have been around 10 to 10.5 deer per km^2. Densities appear to have stopped increasing in the core range, despite a reduction in competition from sheep, and the more favourable climate in recent years.

– Since 2000 deer densities have decreased in a number of Deer Management Areas (DMAs) with maximum densities reducing from over 30 deer per km^2 to around 17 deer per km^2. This varies depending on the region, with evidence that deer densities have declined in Eastern areas; are stable in the North West, but with some increases in other areas. Where densities were high in 2000, many DMAs have shown reductions. However, in areas with low densities in 2000, there have been some increases.

– As expected, there is evidence that population change is related to deer density and the percentage cull. The latter has increased from about 16% to around 22% compared to the 1960s. The most likely explanation for the cessation of overall growth in the population since 2000 is that this higher culling effort is now sufficient to balance recruitment with offtake. However, the culling percentage varies substantially between DMAs from less than 10% to more than 30%, and there is strong evidence of culling driving the recent trends.

– There is no evidence that deer densities are related to sheep densities when analysing data at the DMA scale. However, a parish level analysis of the spatio-temporal variation in deer density showed that high density sheep stocks tended to be associated with lower deer densities, independently from the impact of culling. The highest deer densities tended to occur in locations with few sheep and relatively low levels of culling.

– Site Condition Monitoring within the DMAs showed that woodland features in particular, were less likely to be in favourable condition than other types of features considered. Not surprisingly where herbivore pressures were identified by surveyors, features were less likely to be in 'favourable' condition. Considering the estimated densities of sheep and deer directly in the analysis, suggested weak but consistent impact of sheep more than deer on the probability of 'favourable' condition.

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Acknowledgements

1. THE STATUS AND TRENDS IN THE OVERALL RED DEER POPULATION IN THE HIGHLANDS & ISLANDS

1.1 Approach

Changes in the overall population density of red deer on open-hill range in the Highland and Islands, the species' stronghold in Scotland, were estimated from 'official' counts of areas coordinated by SNH, and its predecessors, the Deer Commission for Scotland and Red Deer Commission, between 1961 and 2016 (Box 1, page 3). Forestry Commission land was excluded because of the difficulties of counting deer on predominantly wooded land. Since the counts need to be done in a consistent way, we did not use the estimates from locally-commissioned censuses undertaken by individual Deer Management Groups (DMGs).

Even when the counts are conducted in the same way in space and time, what proportion of animals actually present in an area of land that is counted is unknown, as is the extent to which the number of animals present at the time of the count is representative of the number animals present over longer time periods. While some counts are thought to be under-estimates, others may involve some double-counting. Thus the 'total' count method has an unquantified error. However, it should be possible to use data from consistently-conducted counts over multiple years to estimate trends in deer densities - whether a given population is increasing, decreasing or unchanged, with more confidence, accepting that underlying, long-term trends will be at least partially hidden due to short-term fluctuations in the location of animals and other uncontrolled sources of variation in the counts.

Ideally counts would be conducted annually, and also repeated, for each spatial unit of interest, since this should permit the most precise detection of trends. As the intervals between consecutive counts increase, estimation of what has happened in the intervening period is likely to become less accurate.

Here we analyse deer densities for Deer Management Areas (DMAs – these are equivalent to DMGs but we use this term to allow us to include areas where some DMGs have lapsed e.g.: Cabrach & Glenbuchat, or to include all parts of the area counted when some of this area might be outside a DMG boundary e.g.: Islay). DMAs are similar to the Deer Count Areas identified historically. The median number of counts for any individual DMA was 10, and the most 50 (Rum), while the number of DMAs counted per year varied from four to 23, with the median 10.

The statistical model we used (see Box 2, page 4) estimates the underlying trend line \over the years which are represented by density estimates derived from the number of deer counted in each of the Deer Management Units (DMUs - the properties/estates), which make up a DMA.

1.2 Results

Having refined the analysis as far as possible within the limitations of the data, the results show that the overall mean density of red deer on open-hill range in the Highlands and Islands increased by approximately 55% from 6.8 deer per km^2 (95% confidence intervals (CI) 5.6 - 8.3 deer per km^2) in 1961 (Figure 1), reaching a peak around 2001 of 10.6 deer per km^2 (95% CI 8.8 - 12.7 deer per km^2). Since the Millennium the density has remained more or less constant with an estimated 10.2 deer per km^2 (95% CI 8.7 - 12.4 deer per km^2).

The 55% increase between 1961 and 2016 is very similar to the 60% in our preliminary analysis documented in the SNH Report *Deer Management in Scotland* (2016). However, while the trends are similar, the specific density estimates are 15-20% lower, because we now use both a weighted approach to allow for the 10-fold difference in the area of DMAs,

and an improved, and more appropriate, method of back-transforming the predictions from the model output, which is on the log scale (see Box 2).

1.3 Discussion

After four decades of steady increase since 1961, densities in the last 15 years appear to have stopped rising in the core range. The apparent levelling-off in the population growth was first noted by Clutton-Brock and colleagues in 2004 when analysing the Deer Commission for Scotland count data up to 2000 (Clutton-Brock, Coulson & Milner 2004). These researchers attributed a slowing in population growth in the 1990s to 'density dependence' in response to grazing competition for food. However, given that there has been a 40% reduction in sheep stocks across the Highlands & Islands since the early 1990's (SAC 2008, Thomson 2011), many of which in summer, at least, competed for the hill grazing, this is surprising. At the same time climate warming has seen earlier springs, longer growing seasons, and hence higher plant productivity, as well as more benign winters, all of which should enhance birth rates and survival (Albon & Clutton-Brock 1988, Clutton-Brock & Albon 1989). We discuss the possible reasons for this cessation of growth later in the Report (see Section 3.).
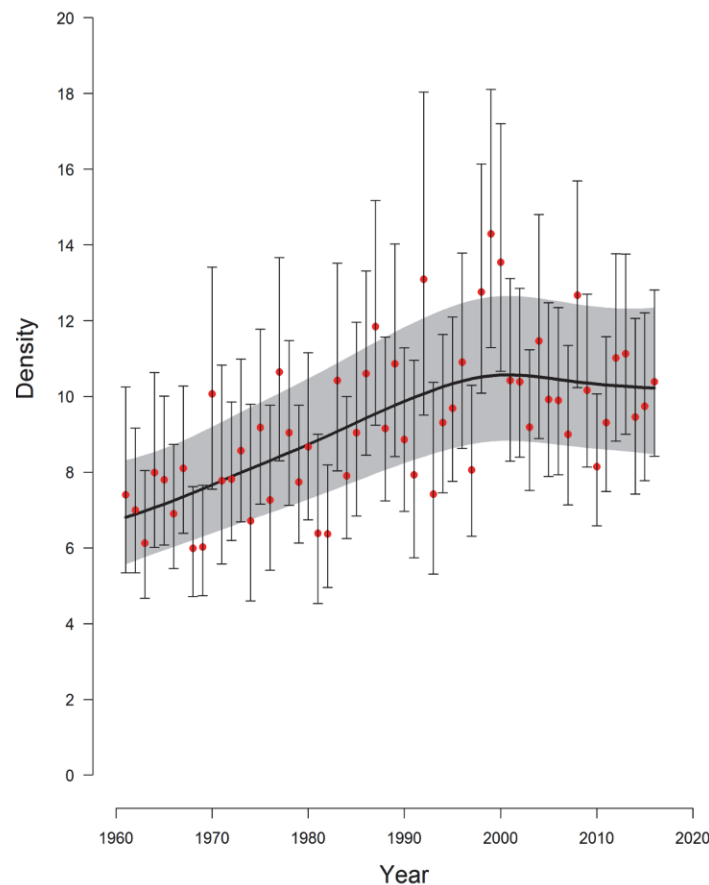

Figure 1. The overall trend (black curve – grey shading shows the 95% confidence intervals) in red deer (stags, hinds, calves) density estimated across the Highlands and Islands, since records began in 1961 until 2016. The red dots show the annual estimates and the thin lines the 95% confidence intervals based on the subset of DMAs counted in each year.

BOX 1: The 'official' count data

The data used were all the historical 'foot' counts conducted since 1961, by the Red Deer Commission for Scotland and its successor the Deer Commission for Scotland, as well as subsequent counts by SNH. The maps used to record deer by the counters were digitised by the Macaulay Land Use Research Institute. After 2001 the majority of the counts were done by helicopter or, in some cases, a combination of 'foot' counts and helicopter counts. Counts undertaken by local Deer Management Groups (DMGs) including four digitised by SNH have been excluded from the analysis.

Over the 56 years a total of 596 'official' counts of 51 Deer Management Areas (DMAs rather than the DMG *per se*) were conducted, mainly in winter (Jan – Apr), but also more recently in Summer and Autumn. The analysis took account of the 'season' of the count. Some of these counts were partial counts, covering only a proportion of the Deer Management Units' (DMUs) land-holdings, within the DMA. To enable inclusion of such partial counts we calculated and analysed red deer densities at the level of individual DMUs (see below).

The number of DMAs has increased over time either because new ones were formed (e.g.: South Uist first counted in 2000) or some of the larger ones have been subdivided, recently (e.g.: East Grampian & South Ross). We have used these sub-divisions over the entire period. The number of counts per year varied from four to 23 with the median 10. Two DMAs, South Uist and West Loch Lomond, were counted only twice, and excluded from the analysis because there was no information on the intervening trend. Of the 49 DMAs with at least three counts the median number of counts was 10, and the most 50 (Rum).

Within each DMA we excluded all Forestry Commission for Scotland land holdings because of the difficulty of estimating deer in parcels of land which are predominantly wooded. For all other DMUs the counts were calculated as densities of all deer (stags, hinds and calves) per km^2, on the basis of the land area, excluding large bodies of water but not woodland. Typically DMUs are individual estates/properties, though some of the largest estates are made up of two or more DMUs. In total there were 718 DMUs used in the analysis. There were substantially more DMAs counted each year after 2001 than between 1961 - 2000 (mean 14.5 compared to 9.1).

Recent concerns expressed by a number of individuals and organisations[1] about the reliability of estimates from 'foot' counts versus helicopter counts are unfounded. Two independent studies suggest that there is no systematic difference in the estimates of numbers from the two methods. A study on Letterewe Estate found variable results, with helicopter counts giving higher estimates than foot counts only on very rugged, high ground on a particular part of the area (Milner et al 2002). While the Deer Commission for Scotland demonstrated that in two of three test sites, ground counts were 10% higher than helicopter counts. In the third site on Rum, the helicopter counts averaged just 4% higher. In each of the three test sites the variability between the repeat counts (coefficient of variation) was similar for both methods (Daniels 2006). However, the latter study showed that when groups of more than 100 deer are observed from a helicopter, a digital image gives a higher number than the immediate visual estimate.

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[1] http://www.parliament.scot/S5_Environment/General%20Documents/(005)_20161205_BASC.pdf
http://www.parliament.scot/S5_Environment/General%20Documents/(009)_20161206_The_British_Deer_Society.pdf
http://www.parliament.scot/S5_Environment/General%20Documents/(025)_Professor_Rory_Putman.pdf

BOX 2: Statistical Methods

Approach: The deer densities calculated from the counts for each DMU from the years in which counts were performed show considerable fluctuation. Some statistical analysis of these densities is required to separate underlying trends which are of interest from unrealistic, short-term, fluctuations which we have considered to be random noise. The trends will be most robustly estimated where we have many counts. The presence of both long-term trends and short-term fluctuations can be seen in the data from Rum, a DMA which, being an island some distance from the mainland, has a self-contained population. For Rum, we know some counts must be under-estimates, and/or others may involve an element of double-counting, because the observed increases in counts between two pairs of consecutive years is not possible given the level of the cull. A similar effect is likely to occur in other DMUs and DMAs where any one count may be an under-estimate or over-estimate and as a result may not fit very well with the long term trend.
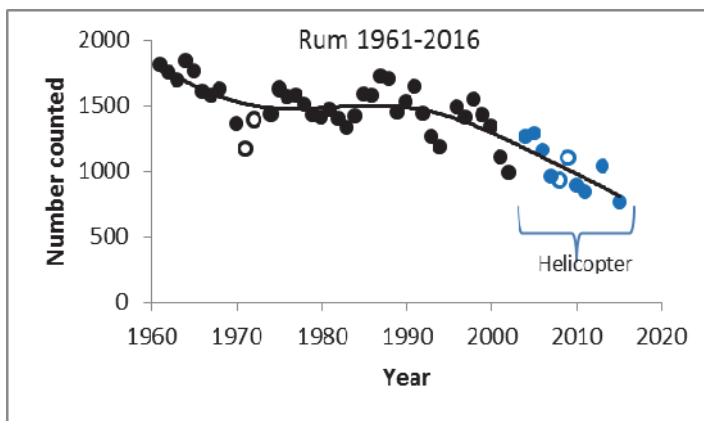

Figure B2. The trend in red deer counts on Rum since 1961. Open circles show consecutive counts (1971 & 1972, and 2008 & 2009) where the apparent increases (>18%) were unlikely given the size of the cull. Individual counts can be anomalous but statistical analysis smooths these out to produce the estimates trend line.

Fitting models to estimate the trend: We have estimated long-term trends in red deer densities at both the national level and at the DMA level from the DMU-level data, making allowance for differences between the DMUs and, in the case of national trends, for differences between DMAs. Densities take into account differences in DMU area, which are used as weights so that trends are representative of changes in the overall population size. As counts were not available for every DMU in every year, we use a statistical model to estimate densities. These modelled values provide predictions in cases where there is no count as well as fitted values in cases where there is a count. 'Good' practice in analysing density data such as these is to convert the values to the log scale so that they have a less skewed (i.e. a more 'normal') frequency distribution and can be analysed using linear models. The estimates from these models are therefore on the log scale and were then back-transformed (anti-logged) so that the scales displayed in the figures represent density estimates that in more conventional units and therefore more accessible to the reader.

Technical details: The procedure for fitting the models was to fit a Generalized Additive Model (GAM), with a smoothing spline for year, to the log-transformed estimates of annual densities either from all Deer Management Units (DMUs) or from DMUs within a particular Deer Management Area (DMA) using the Mixed GAM computation vehicle, 'mgcv', statistical package (Wood, 2006) in R (R Core Team, 2016). In addition to the smooth trend term that was present in all models, the models for particular DMAs each contained a categorical fixed effects to account for differences between DMUs, whilst the national level analysis contained categorical random effects to account for differences between DMUs and for differences between DMAs.

BOX 2: Statistical Methods (continued)

The DMU land areas were used as weights. In the case of DMAs that had been counted, completely or partially, in less than 8 separate years a penalized regression spline was fitted with the degree of smoothness estimated as part of the fitting. For DMAs counted 8 or more times a smoothing spline with fixed degrees of freedom (set to 5 to avoid over-smoothing) was used.

Procedure for back-transformation: In order to obtain predicted densities (in deer km^{-2}) for each DMA in each year, we first formed back-transformed modelled values for each DMU and year combination for which a count had been made. As modelling on a log-transformed scale followed by back-transformation to the density scale introduces some bias, a bias correction factor was calculated for each DMA so as to ensure that the area-weighted average of the modelled densities when a count was present (fitted values) equalled the equivalent value for the observed densities. Modelled log transformed densities were then calculated for every combination of DMU and year, back-transformed and scaled by the bias correction factor, after which an area-weighted average for the DMA was calculated for each year.

An overall national area-weighted average on the back-transformed scale was calculated for each year in a similar way to the DMA averages. To obtain upper and lower confidence limits for each area-weighted average, we obtained the standard error for the corresponding annual prediction and two times these standard errors was added or subtracted from the predictions of log density formed from both the fixed and the random effects. A weighted average over DMUs of the back-transformed and bias-corrected confidence limits was calculated. A model with a categorical fixed effect for each year instead of a smooth term for year was also fitted and confidence limits were calculated similarly. In calculating the standard errors we ignored the contribution of random effect estimates because output from 'mgcv' did not readily allow their inclusion. In our judgement this is not a problem because errors in the random effect estimates will tend to average out, such that the dominant term is the uncertainty in the year effects, which are allowed for in the methodology.

There are two reasons why the bias correction factor at the national level is now better estimated than in our preliminary analysis documented in the November 2016 SNH Report *Deer Management in Scotland*. First, the earlier analysis ignored the random effects when forming the modelled values. The mean of the random effects would be zero for a balanced data set, but as the DMUs have not been counted an equal number of times this resulted in an estimate of the bias correction factor that was biased towards the results of DMUs with many counts. Second there was some additional bias due to the fact that in the preliminary analysis the comparison between the observed densities and fitted values was done on the basis of unweighted means. Subsequent inspection has shown that the unweighted mean of the densities for individual DMUs is higher than the area-weighted mean: the latter being considered more appropriate.

2. DIFFERENCES IN STATUS AND TRENDS IN RED DEER DENSITY ACROSS THE HIGHLANDS & ISLANDS
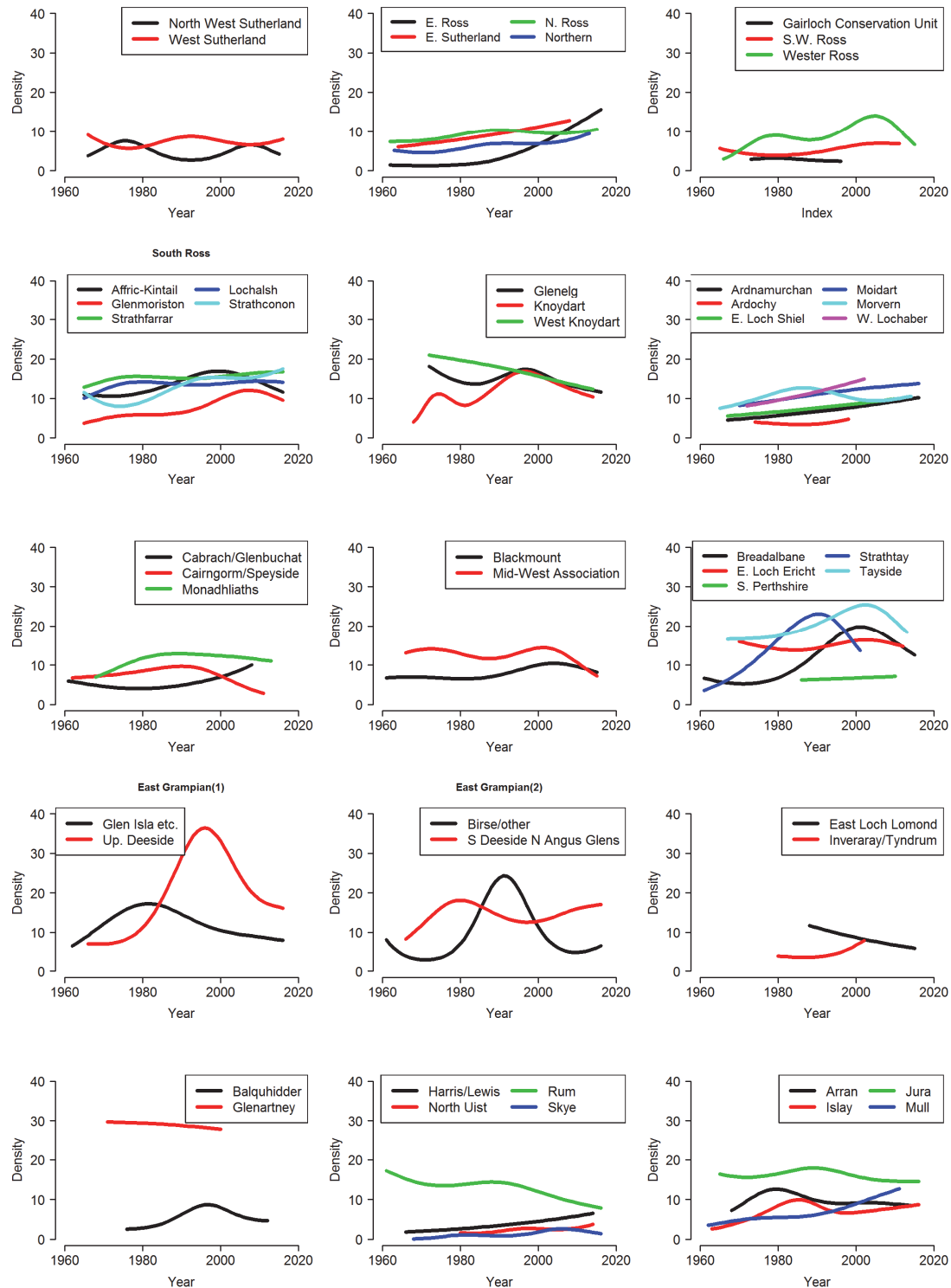

Figure 2. The temporal trends (smoothing splines) in red deer (stags, hinds, calves) density (deer per km^2) between the first and last counts of each DMA. Adjacent DMAs are grouped from the north-west mainland (top-left panel) moving south and east ending with the Islands (bottom-right). The actual densities in the years the counts were conducted are shown in Appendix 1.

2.1 Approach

Wherever a DMA had three or more 'official' counts (Box 1, page 3) we used the smoothing spline (Generalised Additive Model – GAM: see Box 2) to predict the trend over time for each DMA (Figure 2, Annex 1) and from this a density estimate can be extracted for any one year. This permits the comparison of densities across space at the same time, as if the DMAs were all counted in the same year(s). For example, in 2000 (Figure 3: left-hand panel) or using relatively recent data to predict the status in 2016 (Figure 3: right-hand panel), we can estimate the regional variation in deer density.
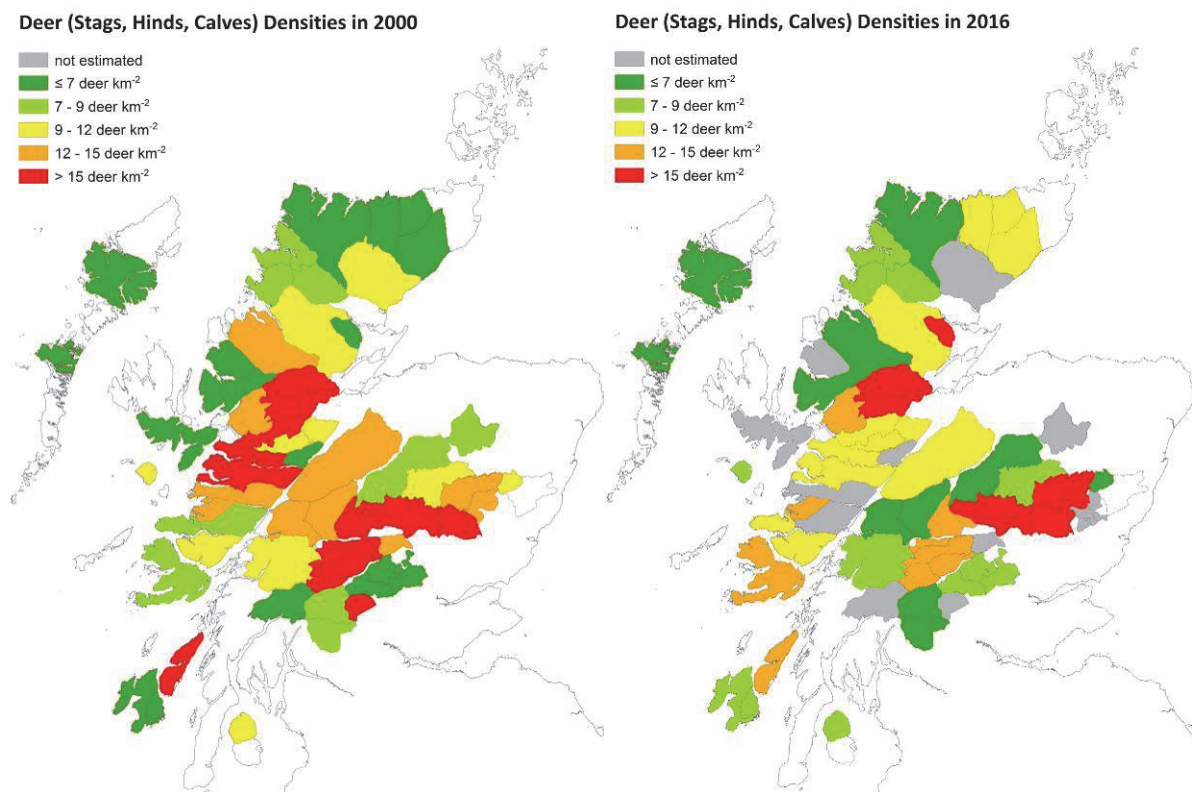

Figure 3. The spatial variation in red deer (stags, hinds, calves) density between DMAs in 2000 (left-hand panel) and in 2016 (right-hand panel) estimated from the temporal trends (smoothing splines – see Figure 2). If the DMA had not been counted since 2010 we made no extrapolation (grey shading).

2.2 Spatial variation in red deer density between DMAs

Red deer (stags, hinds and calves) density estimates across Scotland differ markedly (Figure 3). Densities are typically lower in the Outer Hebrides (Harris/Lewis, North & South Uist) and Skye, and the North-West Highlands, than in much of Ross-shire, West Inverness-shire, and much of Eastern Scotland.

In 2000 there was a 15-fold difference from Skye and Gairloch Conservation Unit (1.8 & 2.3 deer per km^2, respectively), to Glenartney and Glen Isla, East Grampian, (28 & 33 deer per km^2, respectively). At this time 12 (24%) DMAs, amounting to approximately 19% of the Highlands & Islands of Scotland, had estimated densities >15 deer per km^2. However, targeted culling, often under 'Section 7 agreements', reduced the highest densities, so that by 2016 there were only six (15%) of the 39 DMAs assessed (12% of the area of the Highlands & Islands of Scotland with estimated densities of >15 deer per km^2 (Figure 3).

This meant that by 2016 there was now only a 10-fold difference between the lowest and highest density DMAs, with the lowest densities being in Cairngorm-Speyside where concerted culling effort in Abernethy and Glenfeshie in particular, has markedly reduced numbers to an estimated 1.7 deer per km^2. In contrast to 2000, the highest densities were now estimated to be much lower at around 17 deer per km^2 in areas such as South Deeside/North Angus, East Grampian, and both Strathconon and Glenstrathfarrar in South Ross.

2.3   Differences between DMAs in the pattern of change in density

Although, we used all the data since counts formally began in 1961 to estimate trends (see Figure 2 above: Annex 1 shows the detailed fit to the density data for each DMG), we have concentrated on describing the changes since 2000, the period over which the average population density in the Highlands & Islands has remained unchanged (Figure 1). At a regional scale, red deer densities west of the Great Glen/Glen Shiel are largely stable or continuing to increase to the north (Figure 4), whereas to the south the trends contrast greatly between DMAs. For example, Ardnamurchan, Moidart and Morvern are all increasing, while Glenelg, Knoydart and West Knoydart, are all declining (Figure 4). East of the Great Glen densities are generally declining across the Grampian Mountains. Densities on the Hebridean Islands are typically lower but the trends are variable.
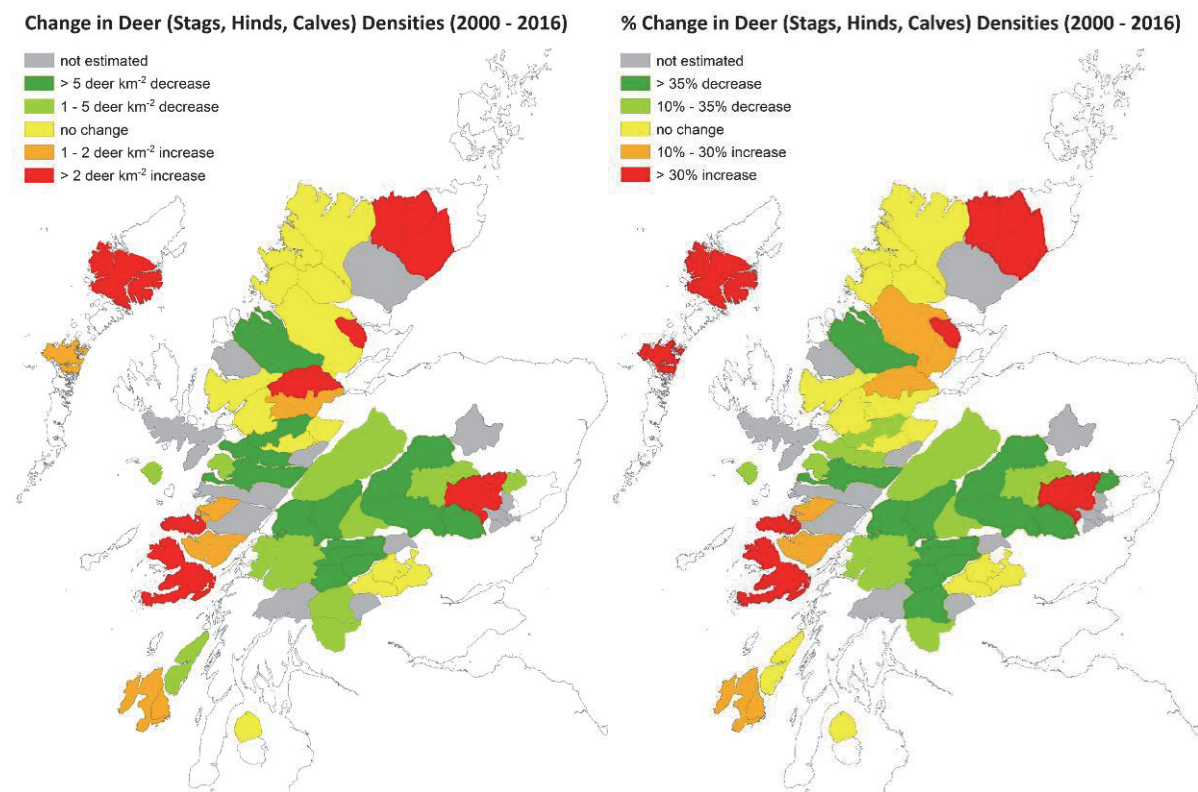

Figure 4. Differences in the magnitude of change in red deer density (stags, hinds, calves) between 2000 and 2016 derived from the trends (smoothing splines – see Figure 2), Left-hand panel - absolute change in density, right-hand panel - the % change in density. If the DMA had not been counted since 2010 we made no extrapolation (grey shading).

Of the 39 DMAs for which we had a count from within the last five years, and therefore, were prepared to use the model estimate of the 2016 density, the trends for 22 (56%) showed a decline since 2000. Of those DMAs that had densities higher than the median in 2000 (from Figure 4), 14 out of 19 had declined by 2016 (Figure 5 right hand pair of columns). In contrast, for DMAs with densities lower than the median in 2000 (from Figure 4), 12 out of 20 showed increased densities (Figure 5 left hand pair of columns). A statistical assessment for this association between initial density and subsequent trend indicates weak evidence for an underlying effect (Fisher's Exact probability test, $P = 0.054$).
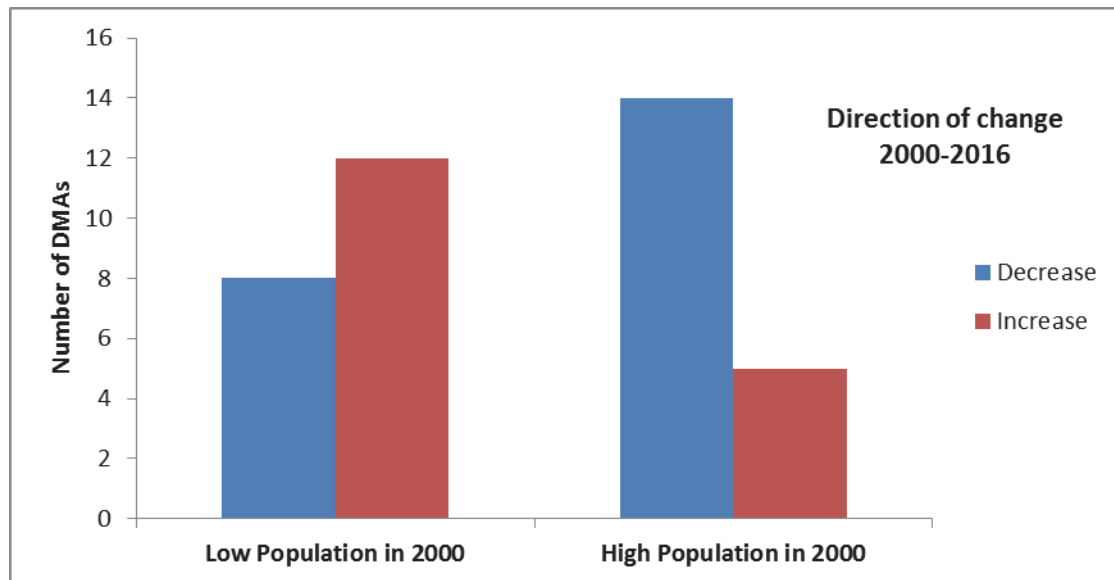

Figure 5. Comparison of the number of DMAs where densities either decreased or increased between 2000 and 2016 in relation to whether their starting densities were lower or higher than the median in 2000.

3. THE DRIVERS OF OVERALL AND REGIONAL TRENDS IN DEER DENSITY

3.1 Approach

Here we explore the relationships between red deer density and two potential drivers of change: first the level of culling (see Box 3), and second, changes in sheep stocks, which, in summer at least, may compete with red deer for hill-grazing. Previously, both of these drivers have been found to have negative impacts on deer density in the Highlands and Islands (Clutton-Brock & Albon 1989). Now 30 years on, we analyse the association between spatial and temporal variation in culling and sheep stocks and the overall deer density in the Highlands and Islands, as well as, between and within Deer Management Areas (DMAs). Finally, this section considers the effects of changes in both culling and sheep, simultaneously, on deer density. Unfortunately, finite resources precluded investigating explicitly the likely contribution of changes in the productivity of hill vegetation given recent climate warming.

3.2 Variation in culling levels

3.2.1 Overall trends in culling

The mean total number of red deer culled per km^2 has more than doubled in the last 50 years, increasing from around 1 deer per km^2 in the early 1960s to 2.3 deer per km^2 in the last decade (Figure 6 – left-hand panel). Since the total red deer population over the same period is estimated to have increased by only 55% the estimated proportion culled has increased from 16 to 22% (Figure 6 – right-hand panel).

Historically, it was suggested that a cull of 1/6th (17%) was the cull rate at which numbers in a population will remain stable (Lowe 1969). This was based on a calf-hind ratio of around 33 (both sexes) per 100 hinds. In practice, across Scotland the calf-hind ratio has been around 40, though this has declined significantly to about 37 per 100 hinds since densities peaked in 2000 and is consistent with density dependence (see Clutton-Brock, Coulson & Milner 2004). Thus, the recent higher cull rate of around 22%, across the Highlands and Islands is consistent with a cessation in the growth of the population and the stable densities observed since 2000 (Figure 1).
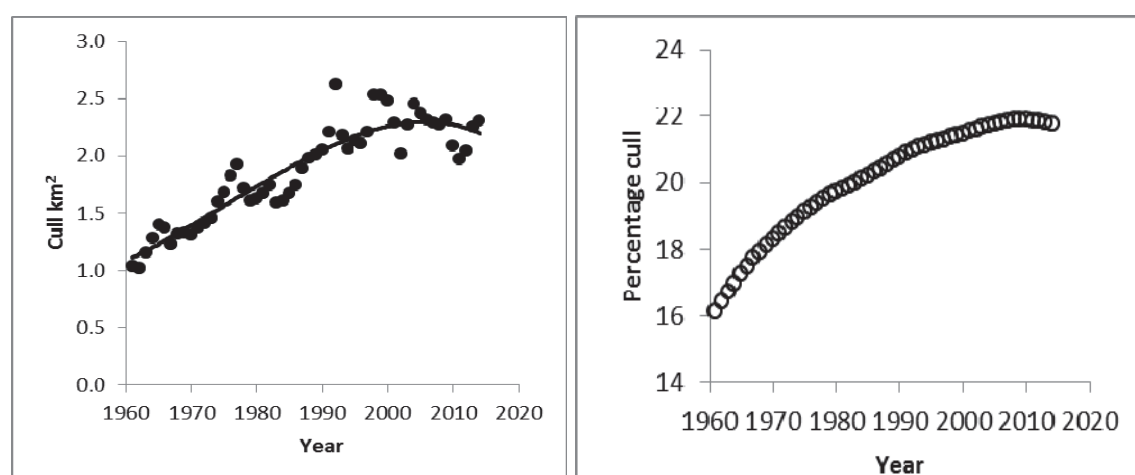

Figure 6. Trends in culling 1961/62 - 2014/15, left-hand panel: total number shot (Cull per km^2), the smoothing spline (3 knots) is shown fitted through the annual estimates; right-hand panel: the proportion of the estimated population (see Figure 1) culled each year.

BOX 3: Cull data

Approach: Not all Deer Management Units (DMUs – estates/properties) make cull returns every year, and some historical data appears to have been lost in transfer between computer software systems within and between the different statutory institutions. Nonetheless there was a reasonable coverage of most Deer Management Areas (DMAs - see Map below), though this also varied between years within DMAs.

% of DMUs Making Cull Returns (2000 - 2016)

- > 97%
- 89% - 97%
- 84% - 89%
- 75% - 84%
- ≤ 75%
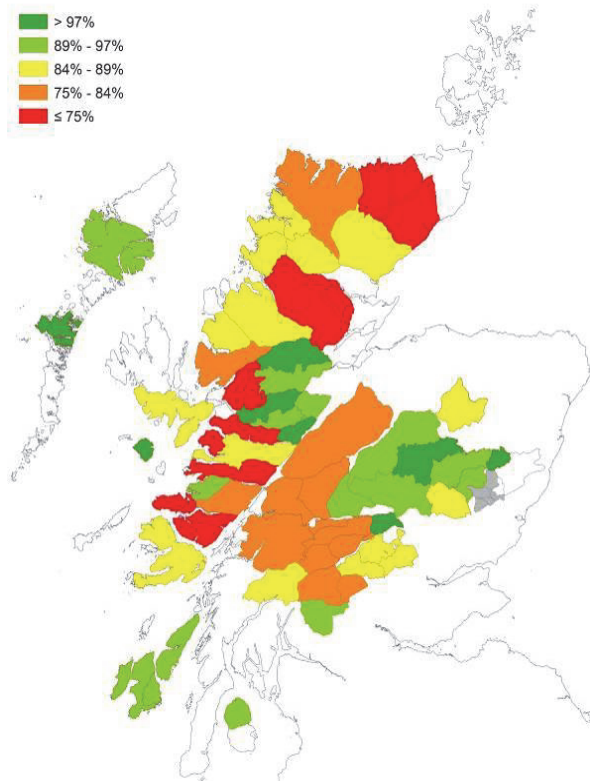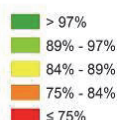
Between 2005/6 and 2014/15, on average 82.5% of DMUs reported culls (range 80.0% to 84.6% between years). This amounts to an average 90.7% of the land area (range 88.4 – 92.9 between years). This suggests smaller estates/properties are less likely to make returns. While many of these non-returns may be from properties that are not deer stalking estates, and which cull very few or no deer, among those DMUs that do make regular returns there was strong statistical evidence of a negative relationship between the numbers culled per km^2 and land area (b = -0.0051 ±0.0013 SE, P < 0.001). This under-reporting means that calculations based on apparent absolute numbers culled, as used in the SNH Deer Management in Scotland 2016 Report, need to be treated as minimal estimates. Consequently, this analysis used the numbers culled per km^2, weighted by the area of each DMU.

3.2.2 Regional variation in culling and impact on deer densities across Scotland

The temporal changes in numbers culled per km^2 since the 1960s, for all DMGs are shown in Annex 1. Over the period 2000 to 2016 differences in the absolute cull rate - the cull density (expressed as total deer shot per km^2), explained 27% of the variation in the relative change in population density across 40 DMAs (Figure 7).
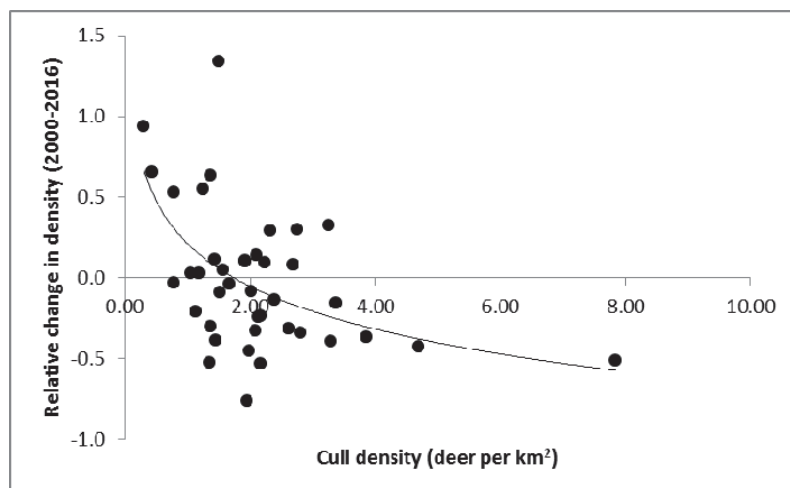

Figure 7. The relative change in deer density between 2000 and 2016 in each of 40 DMAs plotted against the mean cull density (deer culled per km^2) each year. Positive values indicate increases with +1.0 equal to a doubling. The regression line shows the underlying trend in deer density = 0.212 - 0.381(Log_e cull density).

% of Estimated Deer Population Culled (2000 - 2016)

- not estimated
- ≤ 14%
- 14% - 16%
- 16% - 20%
- 20% - 30%
- > 30%

Mean Sheep Densities (2000 - 2016)

- no sheep
- ≤ 15 sheep km^{-2}
- 15 - 25 sheep km^{-2}
- 25 - 40 sheep km^{-2}
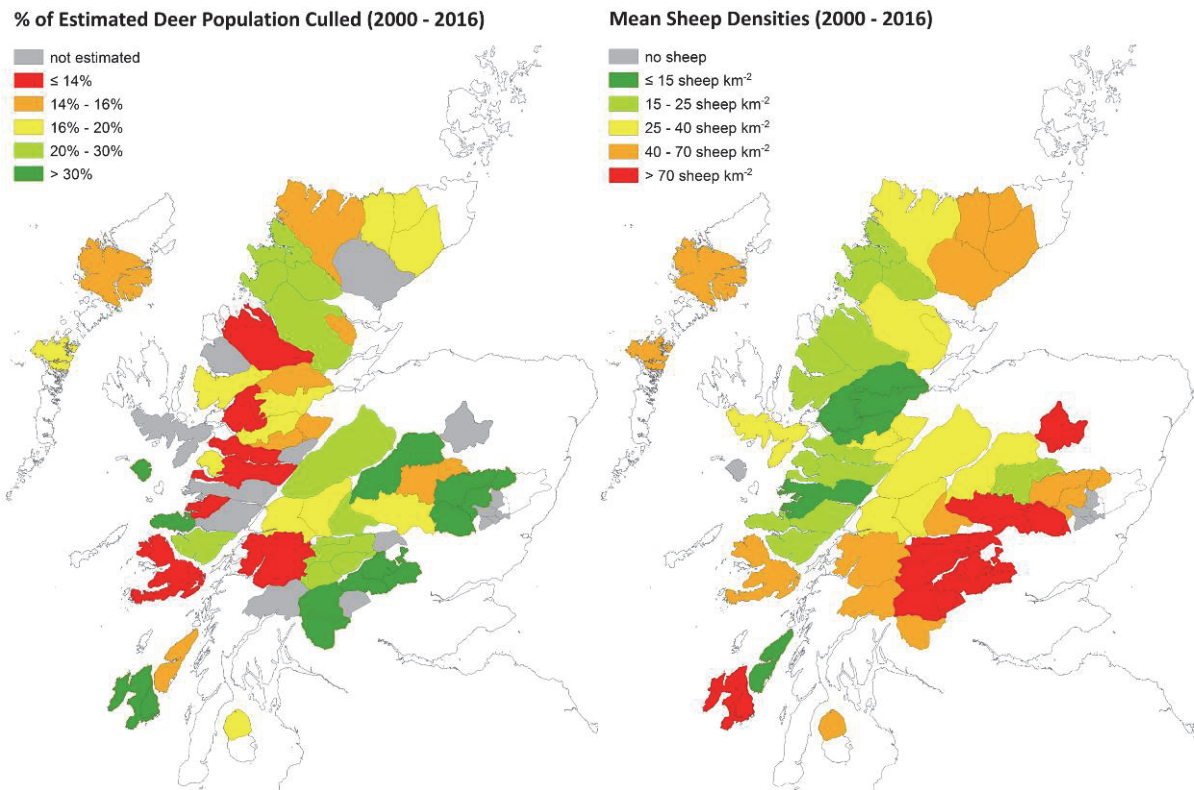- 40 - 70 sheep km^{-2}
- > 70 sheep km^{-2}

Figure 8. Variation in the mean percentage of the estimated population culled between 2000 and 2016 (left hand panel) and mean sheep densities between 2000 and 2016 (right-hand panel) across the DMAs in the Highlands and Islands.

The percentage of the estimated population culled varied markedly across the DMAs from as little as 10% in South Ross-Lochalsh and Glenelg to more than 30% in most parts of East Grampian (Glenisla – the section 7 area, South Deeside-North Angus, and Birse subgroups), Cairngorm-Speyside, East Loch Lomond, Balquhidder, South Perthshire, Ardnamurchan, Islay and Rum (see Figure 8, left-hand panel).

Although populations which were culled lightly tended to increase between 2000 and 2016 compared to those culled heavily (Figure 7), some of the change in population density may reflect density-dependence (Clutton-Brock, Coulson & Milner, 2004) where low density populations have higher recruitment. Therefore, we analysed population change in terms of both mean estimated population density and mean percentage cull (to take account that large populations could have higher absolute numbers culled) over the period. There was strong statistical evidence that both drivers have a negative effect (Table 1, Figure 10), and together explained 25% of the overall variance in population change. The estimated slope of the density-dependent effect is adjusted as if the percentage cull was constant (set to the mean) in all DMAs. Likewise, the estimate of the percentage cull effect is adjusted, as if the population density was constant.

Table 1. The estimates of the slopes, standard errors and 95% confidence intervals of the mean density and mean percentage cull in the model of population change 2000-2016, with t-tests and associated statistical significance levels.

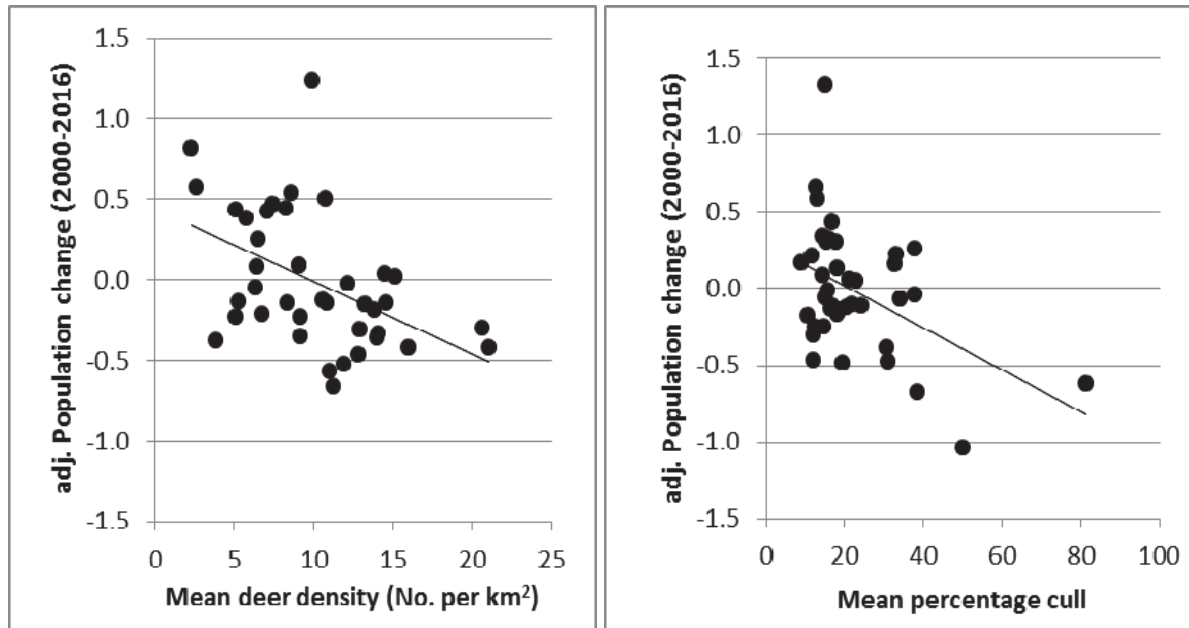| Parameter	estimate	s.e.	t(37)	t pr	lower 95%	upper 95%
Constant	0.746	0.207	3.60	<.001	0.3257	1.1670
Mean density	-0.045	0.014	-3.14	0.003	-0.0738	-0.0159
Mean %Cull	-0.014	0.005	-2.94	0.006	-0.0231	-0.0042

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Figure 9. The change in population density between 2000 and 2016, adjusted for the mean percentage cull, plotted against the mean population density (left-hand panel) and population change, adjusted for density, plotted against the mean percentage cull (right-hand panel).

3.3 Variation in sheep stocks

3.3.1 Overall trends in sheep densities

Sheep stocks have declined across much of Scotland, in particular in the North and West Highlands (SAC 2008, Thomson 2011). Across the Highland & Island region numbers have declined 40%, from around 65 ewes per km^2 in the early 1990s to around 40 ewes per km^2, recently (Figure 10). Because, there is no distinction between sheep on the open-hill and in the in-bye fields, changes on hill-ground may be even greater. However, we could find no evidence that these gross changes had any influence on the overall trend in red deer density, and recently deer have ceased increasing despite the substantial decline in competition from sheep.
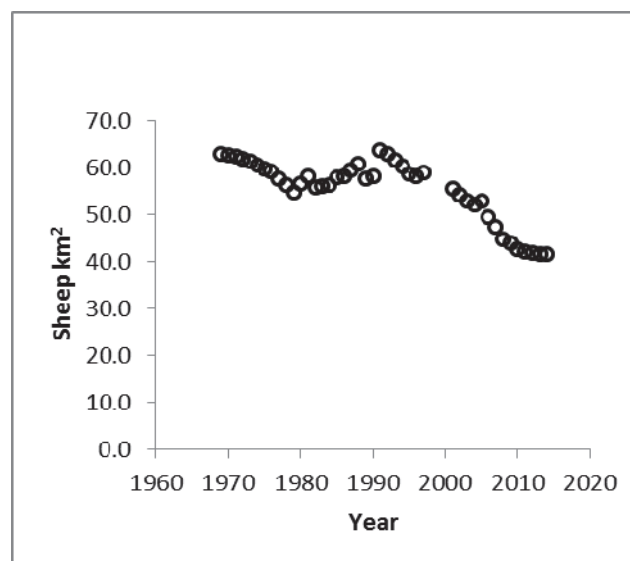

Figure 10. Trend in sheep per km^2 across the Highlands and Islands (1969–2014).

3.3.2 Regional variation in sheep density and impact on deer densities across Scotland

Using data for the DMAs we could find no evidence for a relationship between either deer density or change in density (2000-2016) and either sheep density (mean 2000-2016) or relative change in sheep stocks. Nor was there any evidence for relationship between deer density and sheep stock dynamics after accounting for the level of culling and density dependence described in Table 1, Figure 9 above. The apparent lack of impact of differences in sheep stocks at the scale of DMA may be partly because of a negative spatial correlation between the %cull and mean sheep density (r = -0.370, P < 0.05), and partly because the real variation in sheep density is at the smaller spatial scale of differences between Deer Management Units within DMAs (see below).

3.4 Influence of culling and sheep stocks on deer density within and between DMAs

To explore the effect of variation in sheep stocks more closely we followed the approach of Clutton-Brock and Albon (1989) and analysed variation in red deer density with the count data re-aggregated at the spatially smaller scale of parishes. The model used densities of deer and sheep since 1981 and incorporated both year and parish as random effects. The results showed statistical evidence both for a decline in total deer density with increasing percentage culled (Figure 11: left-hand panel), but also for a decline in deer density with increasing sheep density (Figure 11: right-hand panel).

There was also evidence for an interaction between the percentage cull and sheep density suggesting that the effect of high sheep stocks weakens at high culling rates and *vice-versa,* that the effects of high culling rates are weaker at high sheep densities (see ANNEX 2).
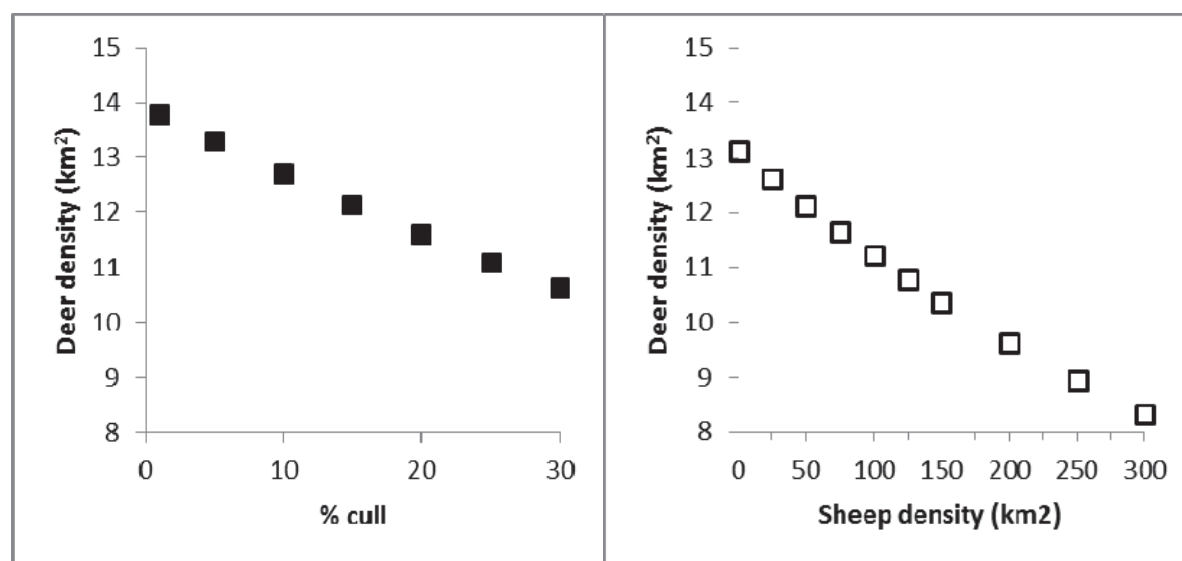

Figure 11. Model predictions for the relationships between deer density on open-hill ground and increasing cull percentage for a situation when sheep are stocked at 50 sheep per km^2 (left-hand panel) and increasing sheep densities for a situation where deer are culled at 15% (right-hand panel). Here all the data were collated at the parish level.

4.   IMPACTS OF HERBIVORES ON THE NATURAL HERITAGE

4.1   Approach

Using the Site Condition Monitoring network of SSSI and Natura sites (see Box 4, page 16 for details) within the Deer Management Areas in the Highlands & Islands, we investigated the probability of these protected sites being in favourable condition in relation to the local densities of deer and sheep, estimated from the models described earlier.

4.2   Variation in condition between feature categories

There was significant variation in the probability of favourable condition across feature categories (Figure 12). In general Wetland, Coastal and Bird features were most likely to be in favourable condition (all probability >0.7 – standardised to Cycle 2) compared with woodlands and vascular plants, which both had less than 0.5 probability of being in favourable condition.
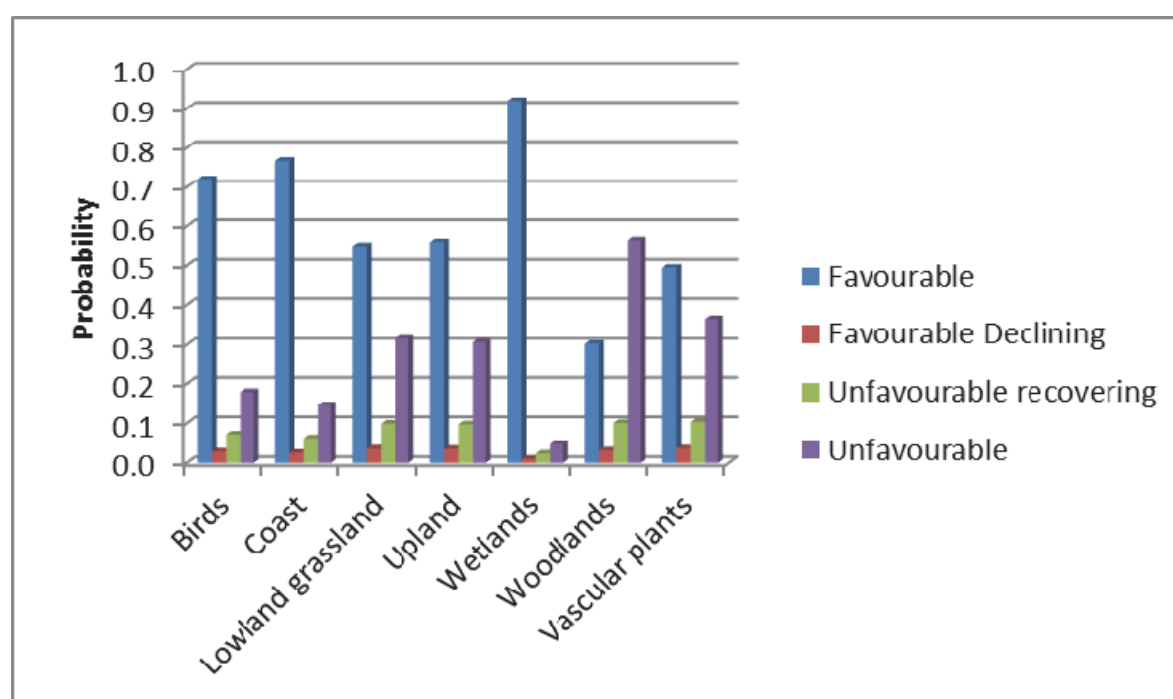
Figure 12. The modelled probability of condition of feature categories in Deer Management Areas in the Highlands & Islands. The estimates are standardised for Cycle 2 and averaged across pressure types.

4.3   Herbivore pressure: deer and sheep density effects

As expected the probability of 'favourable' condition was significantly lower where herbivore pressure was identified by the surveyor than in sites where features were subject to other pressures or no pressures. Nonetheless the model was improved when our estimates of both local deer and sheep densities were included (log ratio test = 5.66, P < 0.05) with increasing densities of both having negative effects on site condition. When modelled individually however, sheep density had only a weak effect (P = 0.055), and deer density was clearly non-significant (P = 0.16). Given there is some partial confounding between the pressure types, with both deer and sheep density higher where herbivore pressure was attributed to a feature, we also explored a model without including the pressure categories. In this case the influence of both deer and sheep density were supported by weak statistical evidence (P=0.041 and P=0.022, respectively; Figure 13).

BOX 4: Site Condition Monitoring

SNH monitors a variety of statutory nature conservation designations, from national-level statutory protection such as Sites of Special Scientific Interest (SSSIs) to European Natura 2000 designations – Special Protection Areas (SPAs) and Special Areas of Conservation (SACs) under the Birds and Habitats Directives. These protected sites may have several designated features, including specific habitats, species or geological features.

Feature categories in protected areas within the DMA of the Highlands and Islands, and considered at risk of impact by herbivores, included birds, coast, lowland grassland, lowland heath, upland, wetlands, woodland and vascular plants. However, in practice there were only seven lowland heath features, and therefore this category was excluded. Since 1999 the condition of individual features has been monitored in a rolling six-year programme, so some sites and their features have now been assessed three times. The condition of a feature can be assigned to one of the following categories:

- Favourable – maintained;
- Favourable – recovering;
- Favourable – declining;
- Unfavourable – recovering;
- *Unfavourable – no change;
- *Unfavourable – declining;
- Partially destroyed.

For the purpose of the analysis here, the condition scores above were collapsed into four groups by combining Favourable - maintained with Favourable - recovering into 'Favourable', and Unfavourable – no change with Unfavourable declining into 'Unfavourable'. Partially destroyed occurred rarely and was excluded. Surveyors also assessed the extent that particular pressures were impacting on a feature and these were also collapsed into four groups: none, other (invasive plants, climate change), herbivores alone and herbivores plus at least one other pressure.

The model – a form of regression model called a Cumulative Link Mixed Model was fitted, treating these condition scores as an ordinal scale, to analyse the changes in condition of features between successive cycles of monitoring. The basic model included variables for: Cycle; Feature category; a Cycle by Feature category interaction (to account for modifications in the assessment criteria between cycles); and Pressure. We compared this basic model with one which included the estimated local densities of both sheep and deer from the predictions of our previous models on trends. Since these direct estimates of herbivore density are likely to be at least partially confounded with the pressure categories we also considered a model which dropped the pressure categories but retained the estimated deer and sheep density.

The results presented here are for SSSI designated sites because this maximised the sample size. The smaller Natura data set gave qualitatively similar results to those for the SSSI sub-group.
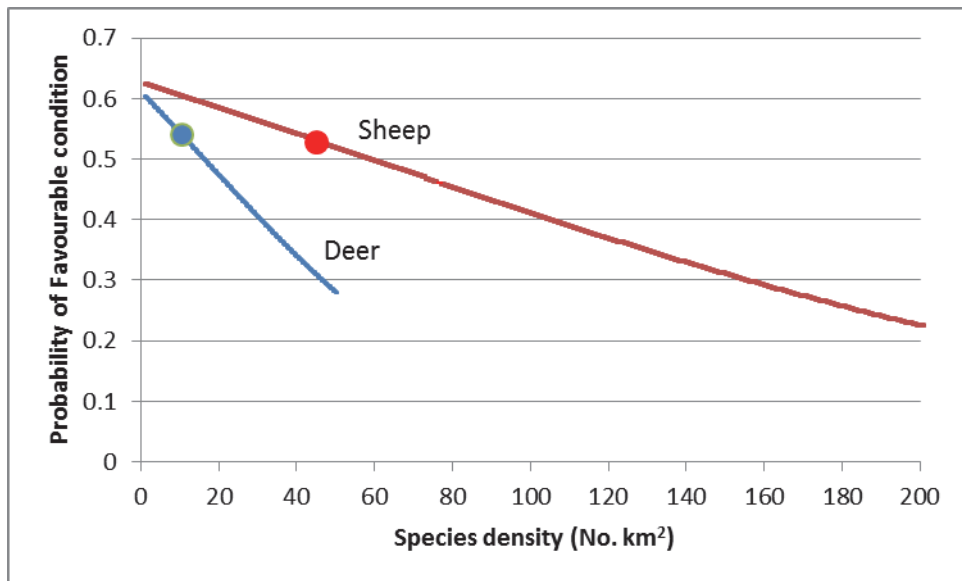
Figure 13. The modelled probability of 'favourable' condition in Cycle 2 for 'Upland' features in Deer Management Areas in the Highlands & Islands of Scotland in relation to the density of deer (blue line) and sheep (red line). The density dependent relationship for each herbivore is calculated assuming the other species occurs at the median density (shown by the filled circle).

4.4   Discussion

Herbivore impacts were clearly identified by surveyors and depressed the probability of a site being in 'favourable' condition. There was also some evidence that increasing deer and sheep densities did negatively impact on the natural heritage, though this only received statistical support when excluding the pressure type categorisation (Figure 13). Overall there was weak evidence that sheep had the bigger impact, as has been suggested in previous studies (Albon et al 2007).

Understanding better the impacts of herbivores and distinguishing between different species requires more specific data, such as that gathered for (rapid) habitat impact assessment. This type of data has been collected in Section 7 management agreements. Although targeted culling has been aimed specifically at reducing impact, to date only rudimentary analysis has been conducted. However, more might be done with the Site Condition Monitoring if the specific features were georeferenced rather than simply attributed to the centroid of the designated area. Since many of the upland sites are very large and may straddle many DMUs, and in some cases two DMAs, the heterogeneity in local density may be quite large but is currently masked.

5. REFERENCES

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ANNEX 1: THE DEER MANAGEMENT AREA TRENDS IN DEER DENISTY, DEER CULL DENSITY AND SHEEP DENSITY FOR EACH DMG INCLUDED IN THE ANALYSIS

Each row represents one Deer Management Area (DMA). Left hand column: The blue line represents the estimated trend in deer density (deer per km^2) from the statistical model. Points indicate recorded densities for the DMG (derived as an area-weighted average of densities for the individual DMUs). Black squares use actual counts only. In cases where only some DMUs within a DMA were counted in a particular year, densities for the DMUs that had no count available were filled in with the fitted values from the model and the weighted average formed (red triangles). Central column: cull density (no. deer culled per km^2). Right hand column: sheep density (no. sheep per km^2).

Blackmount

Breadalbane

Cabrach/Glenbuchat

Cairngorm/Speyside

East Grampian Birse Parish and othe

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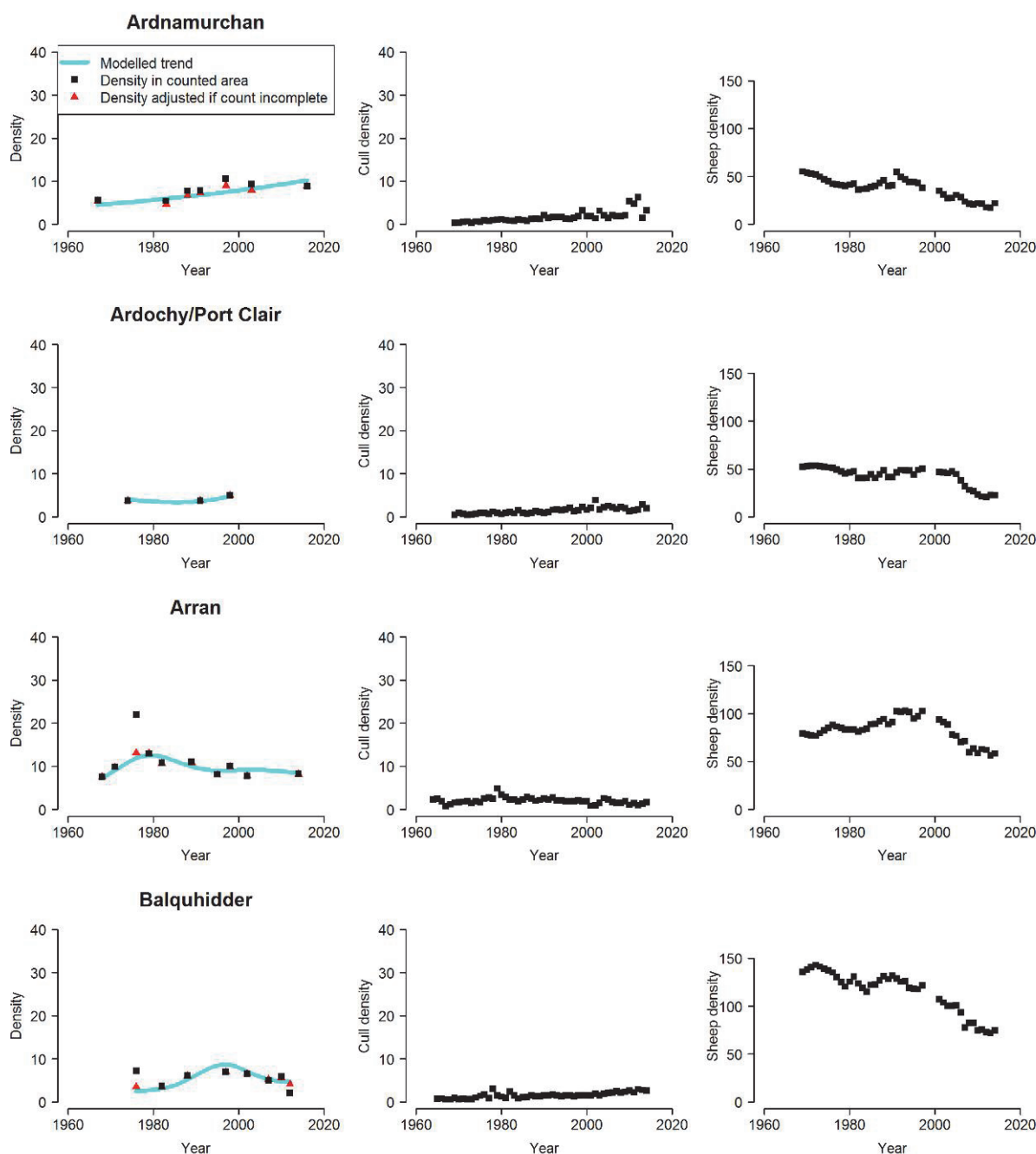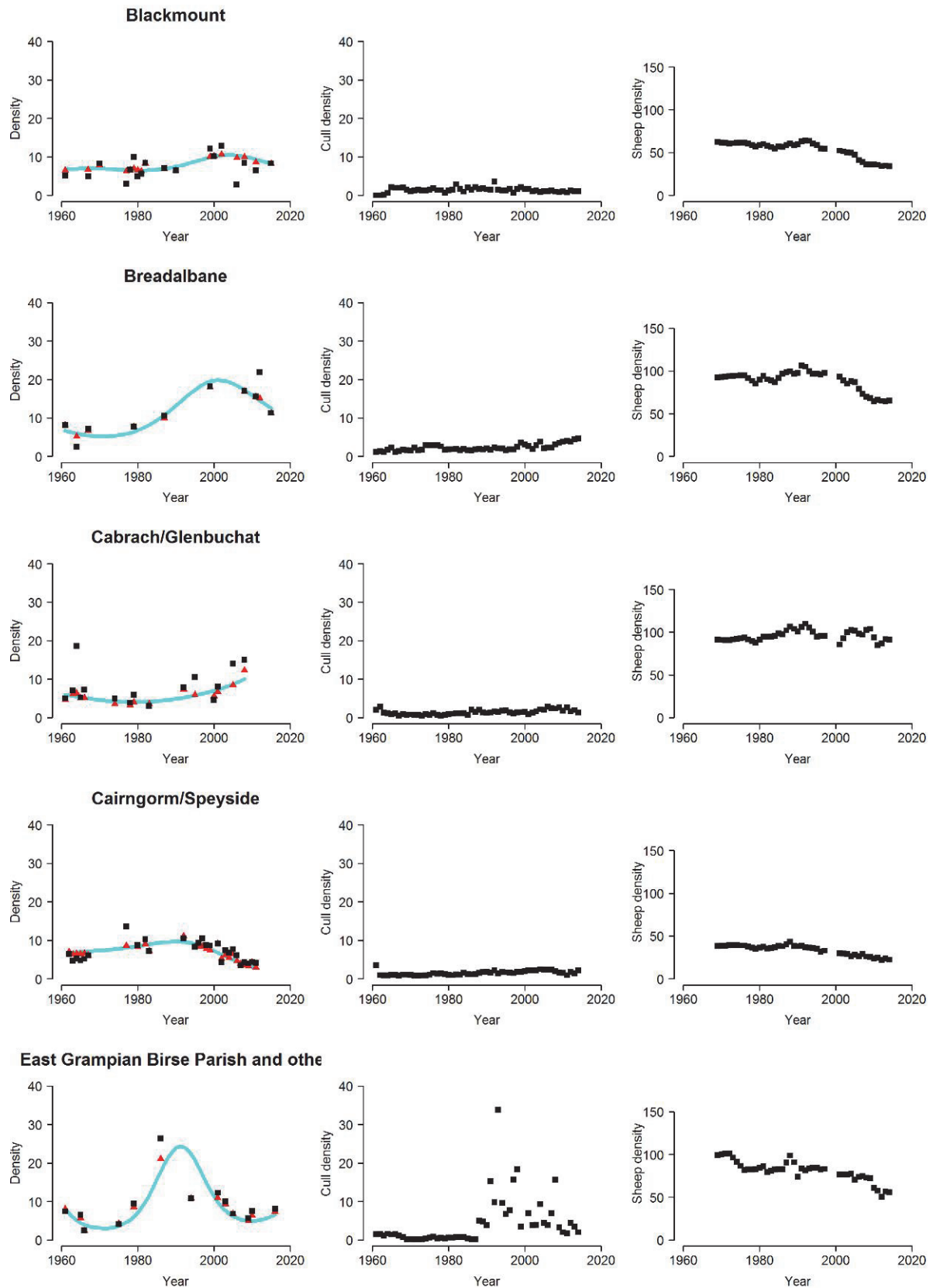
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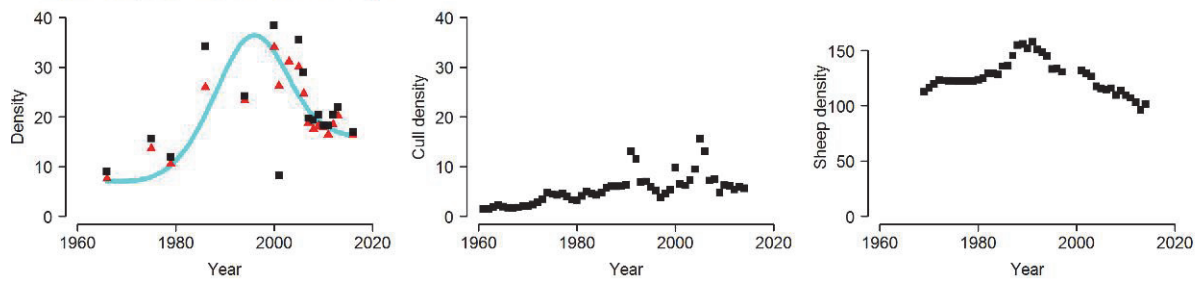
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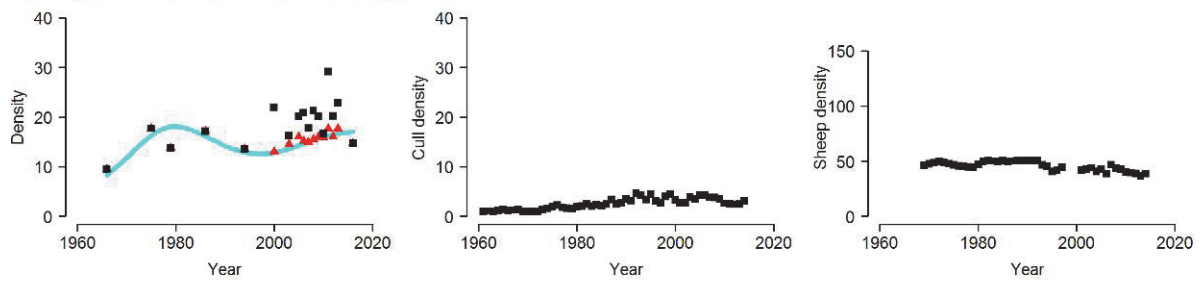
East Grampian Upper Deeside

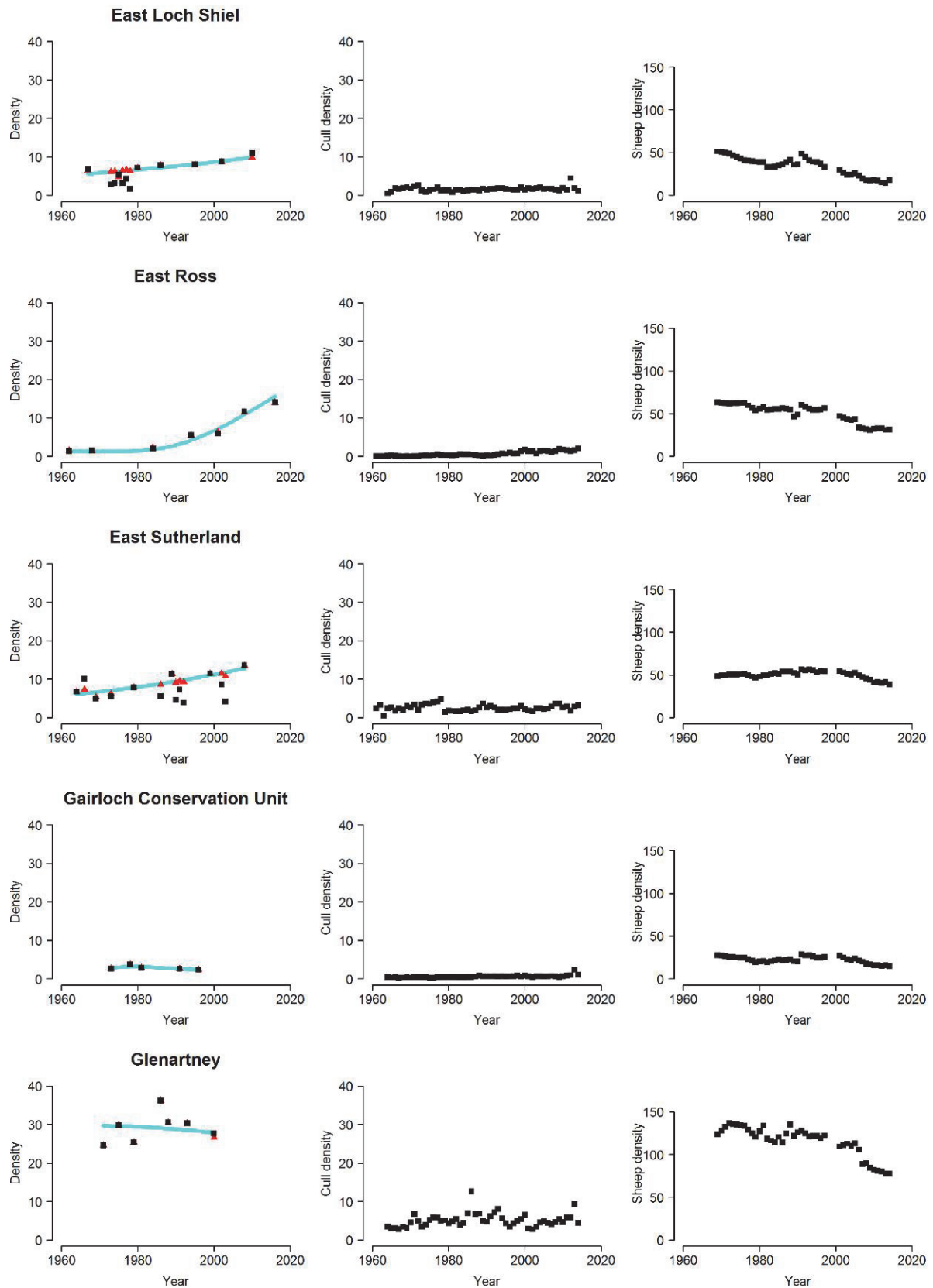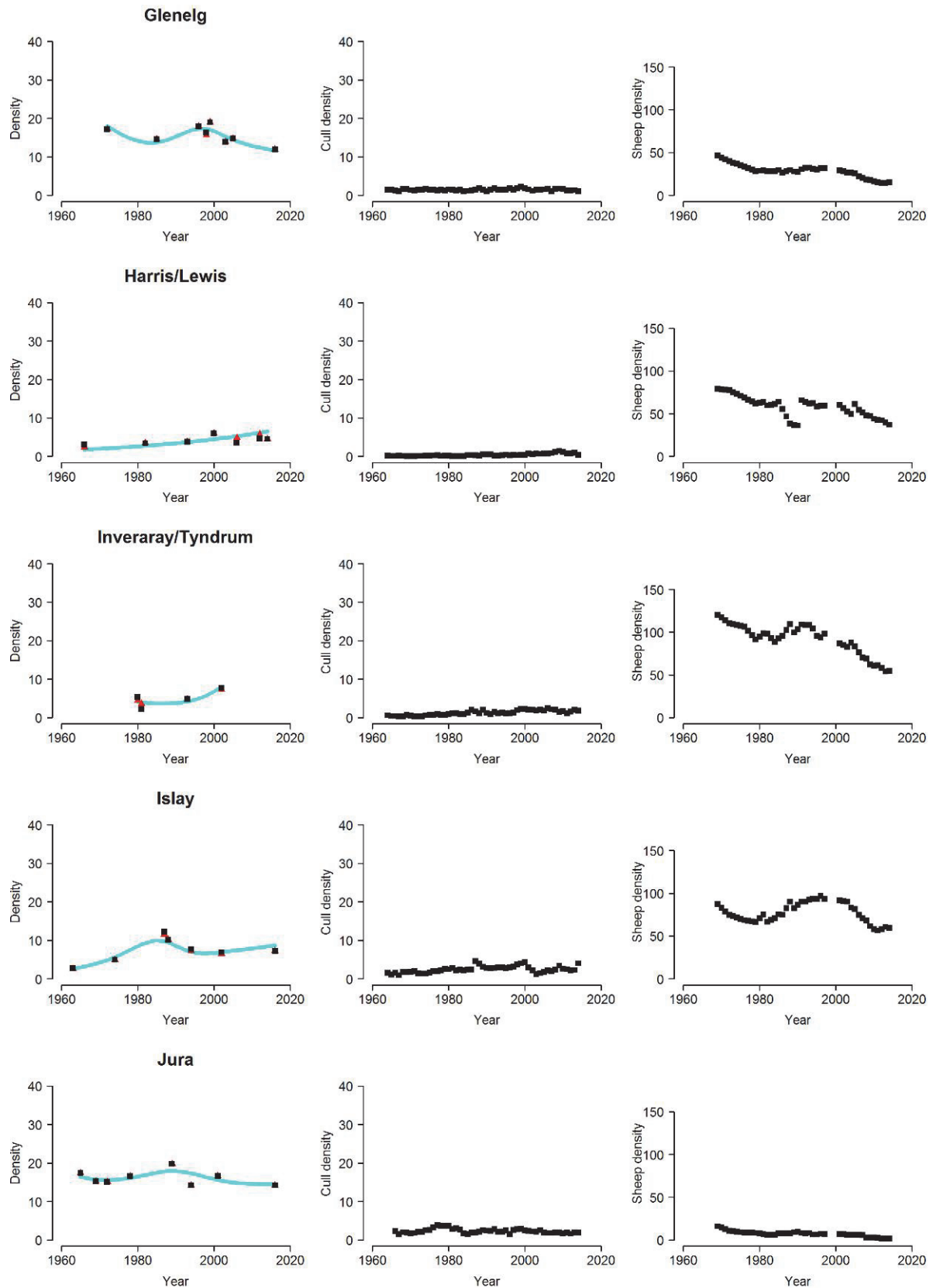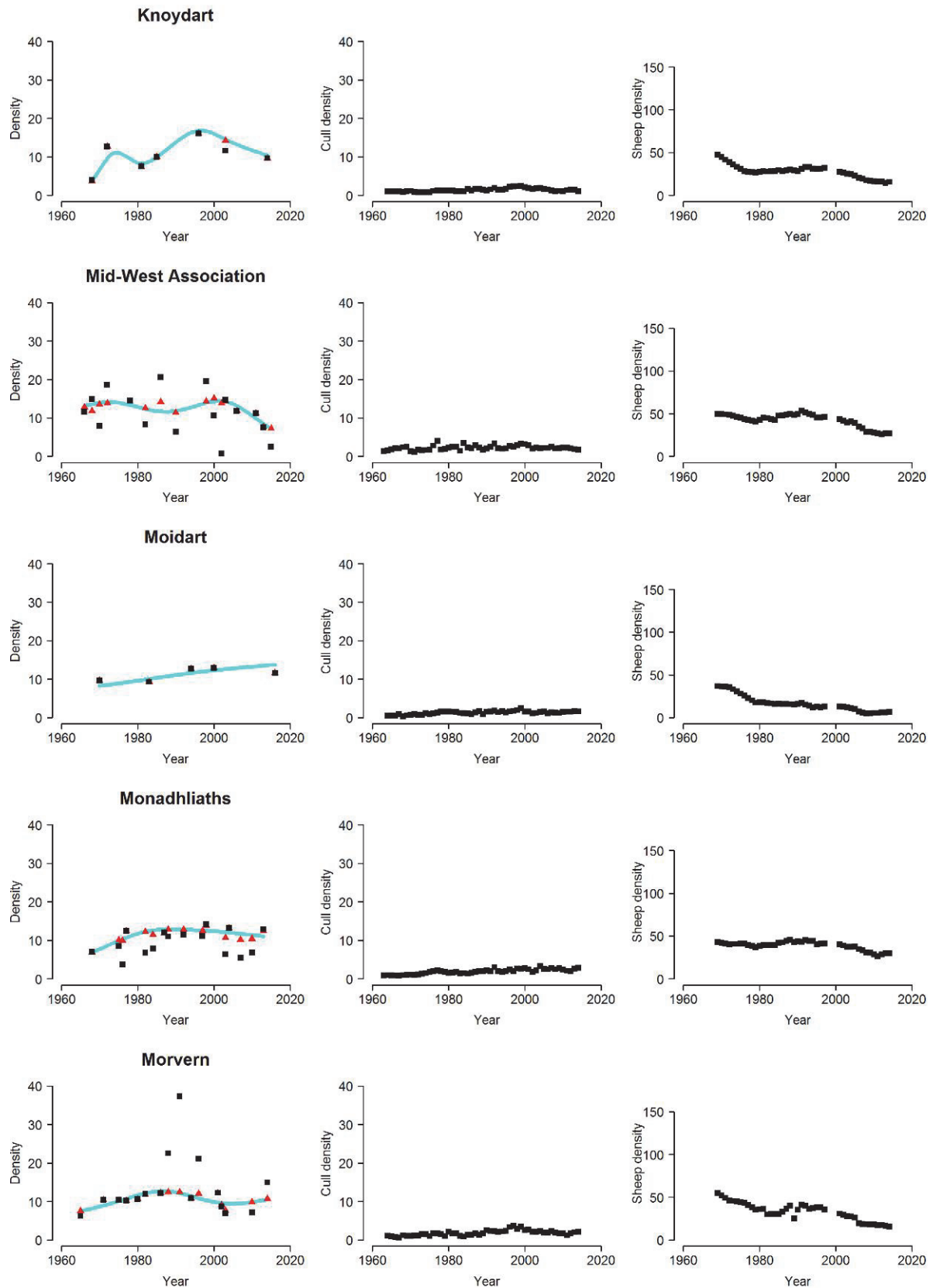**East Loch Ericht**

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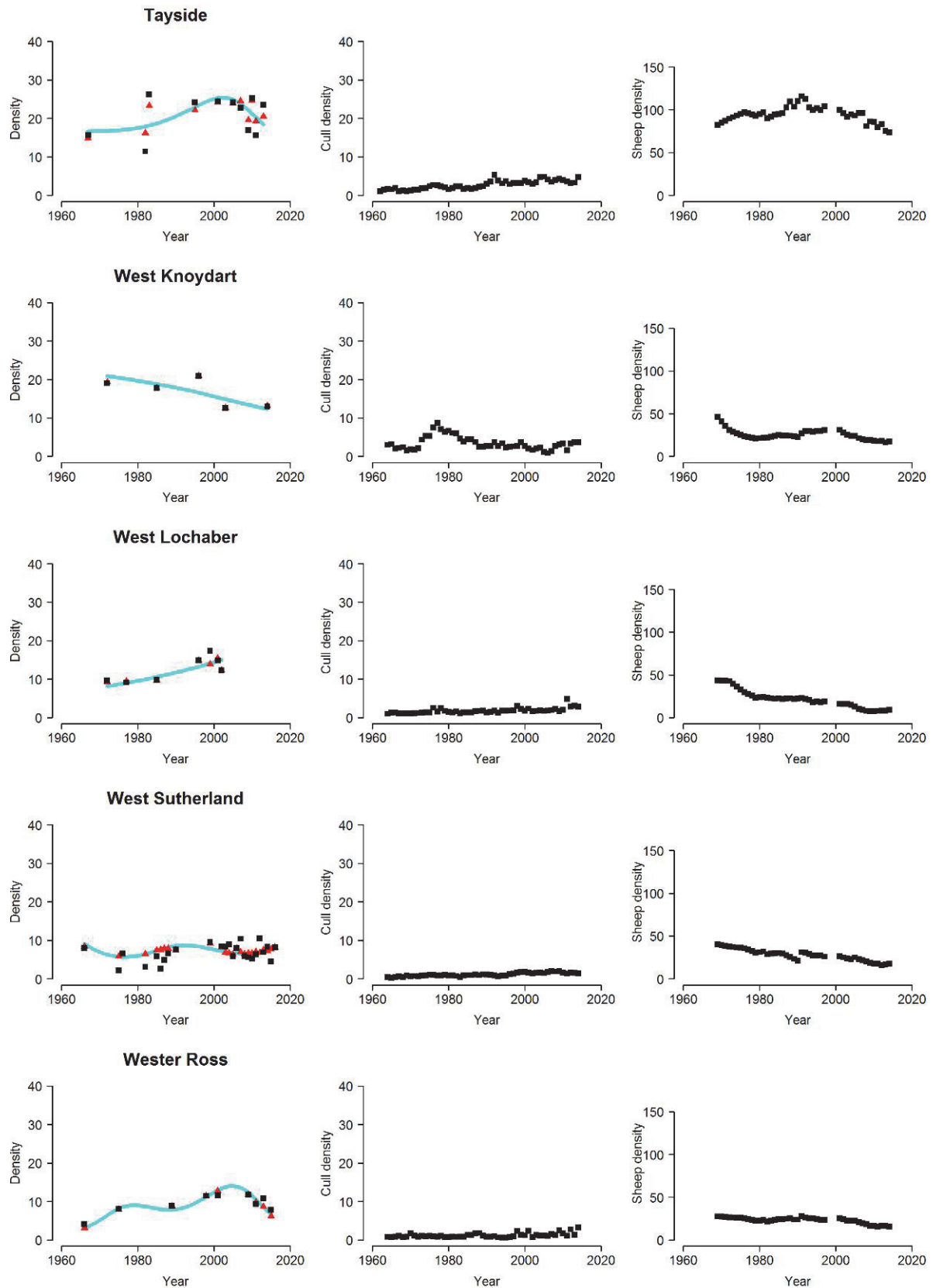**South Perthshire**

South Ross Affric-Kintail
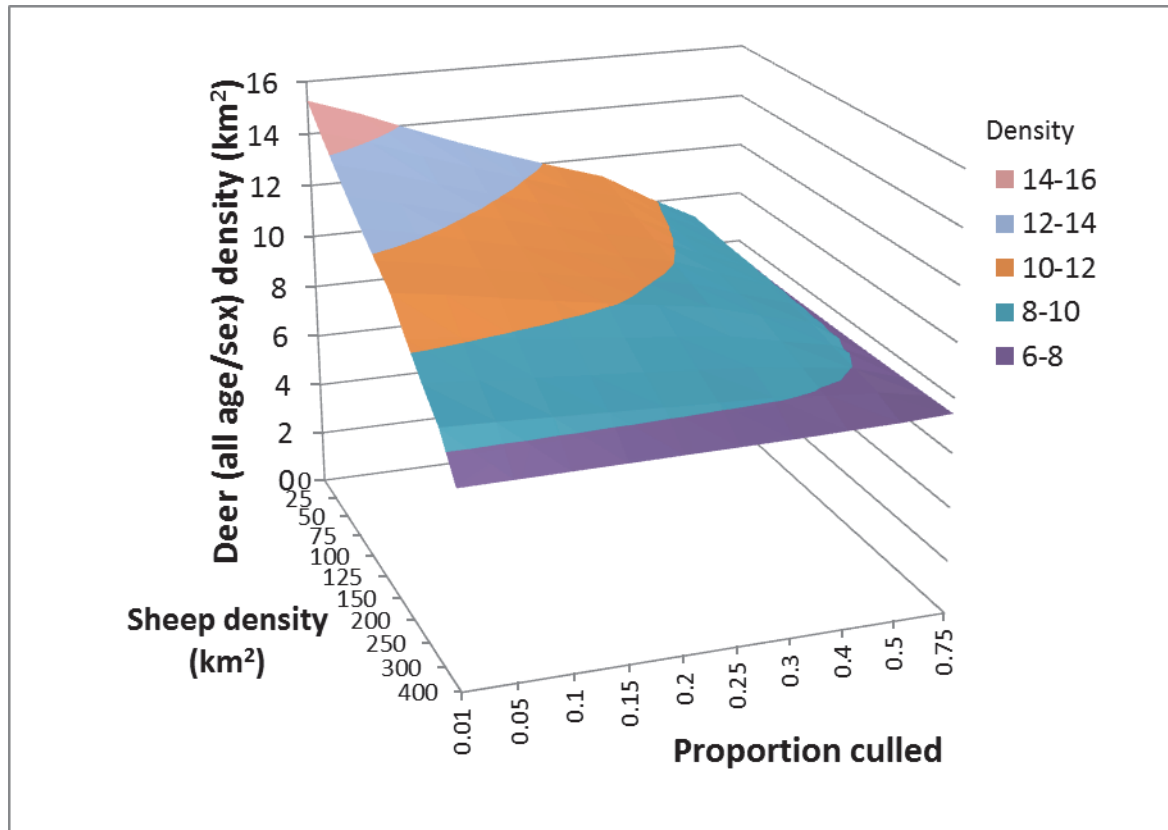
South Ross Glenmoriston
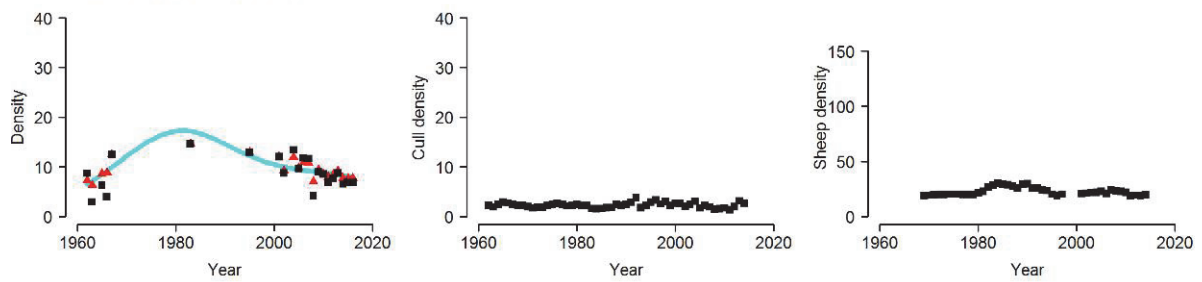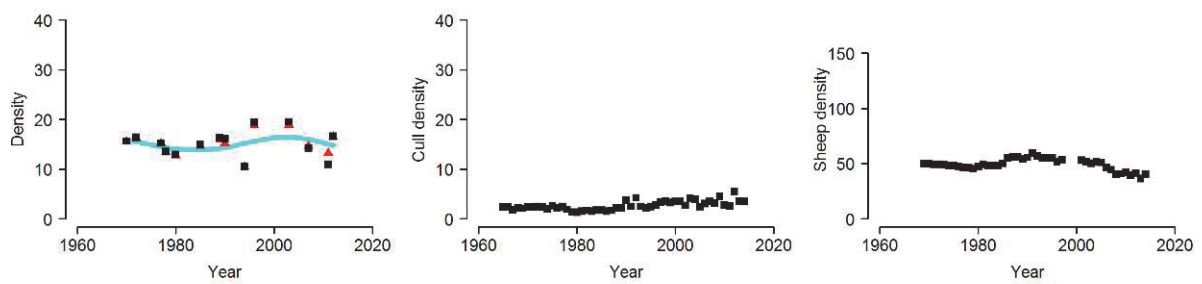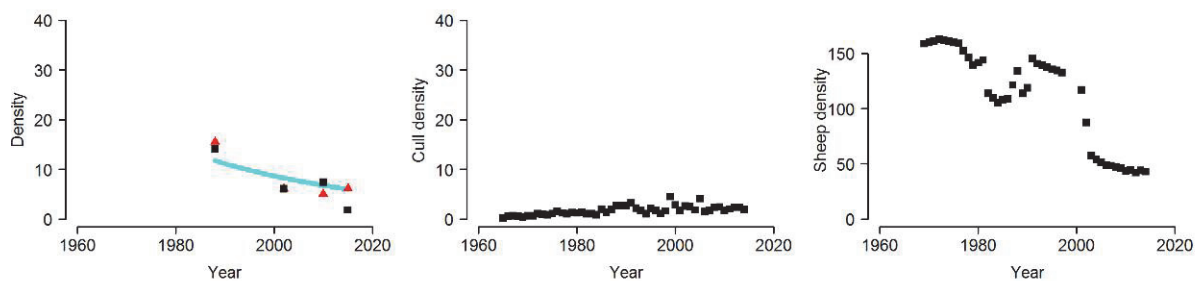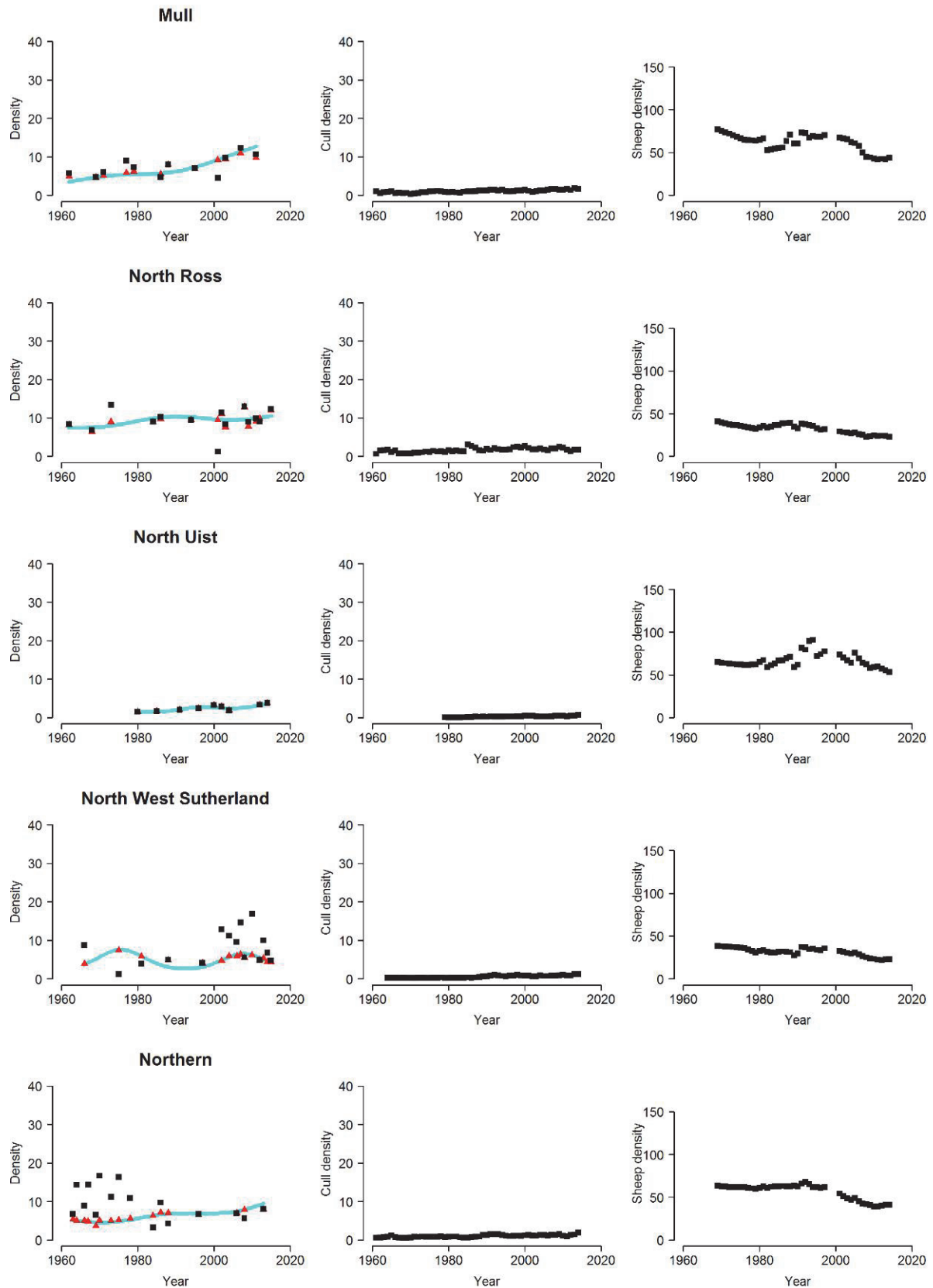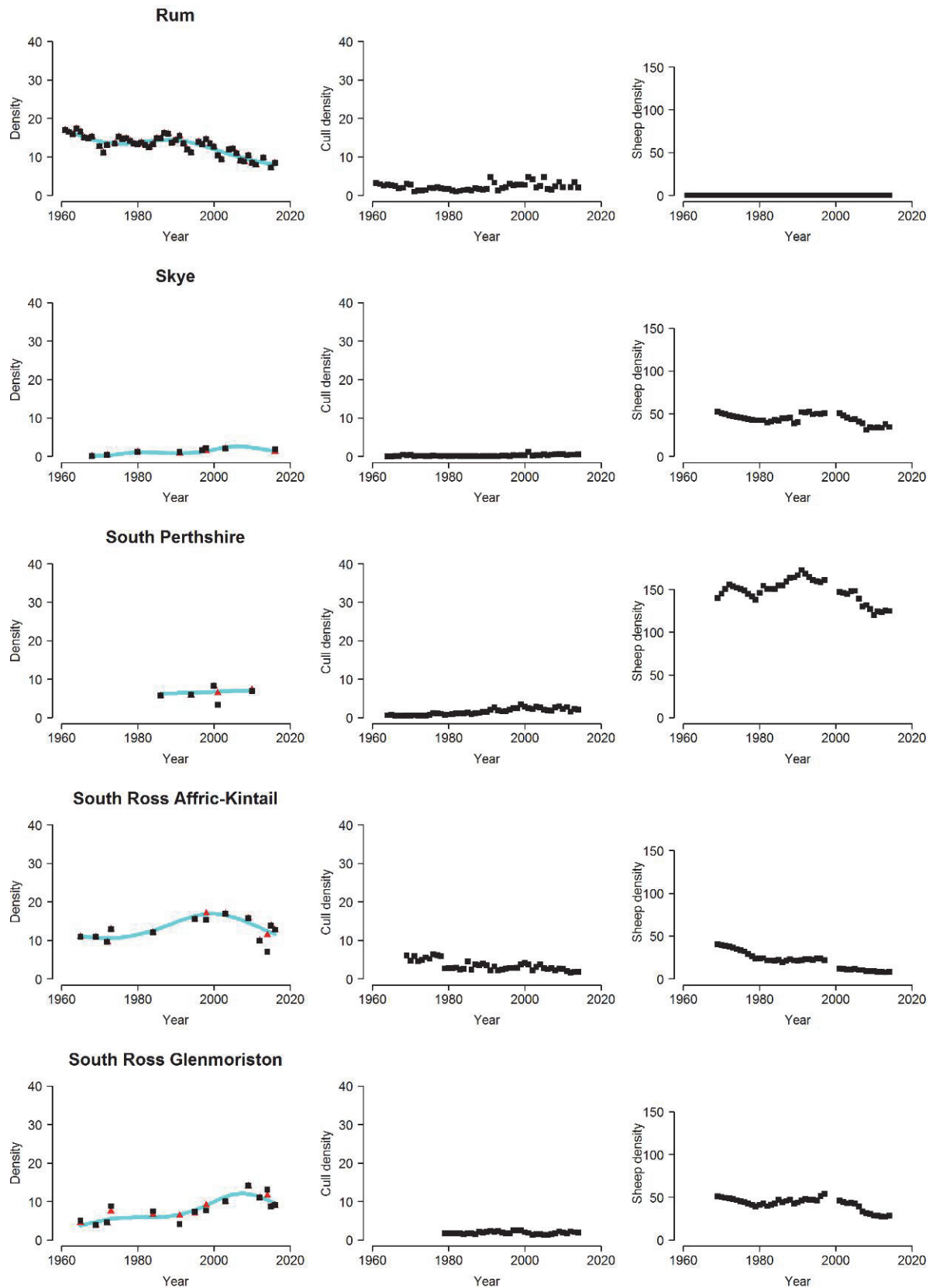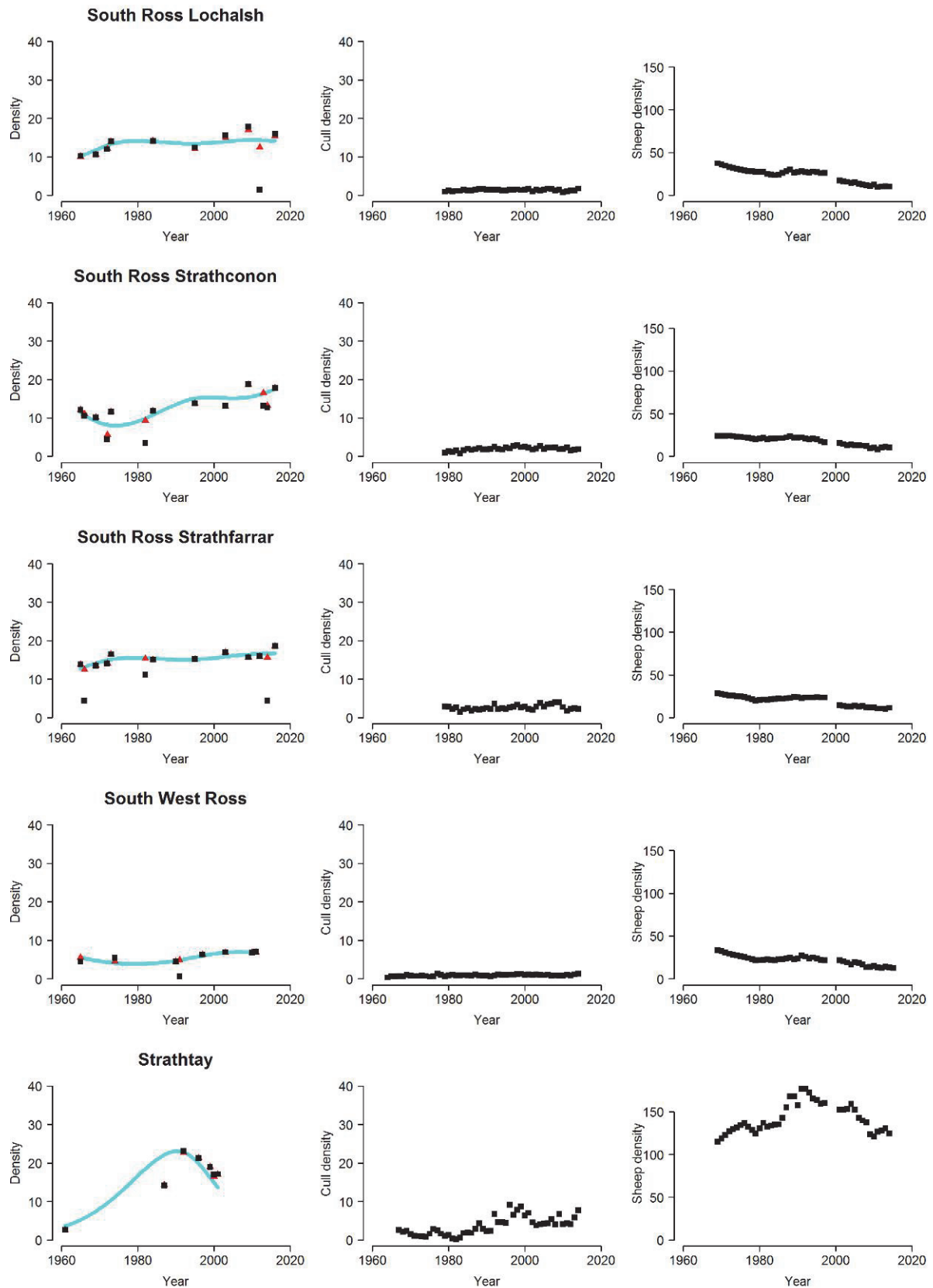
ANNEX 2: DEER DENSITY ACROSS PARISHES IN RELATION TO BOTH SHEEP DENSITY AND THE PROPORTION CULLED

The 3-D surface shows the interaction between the two explanatory variables (see text for details).

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