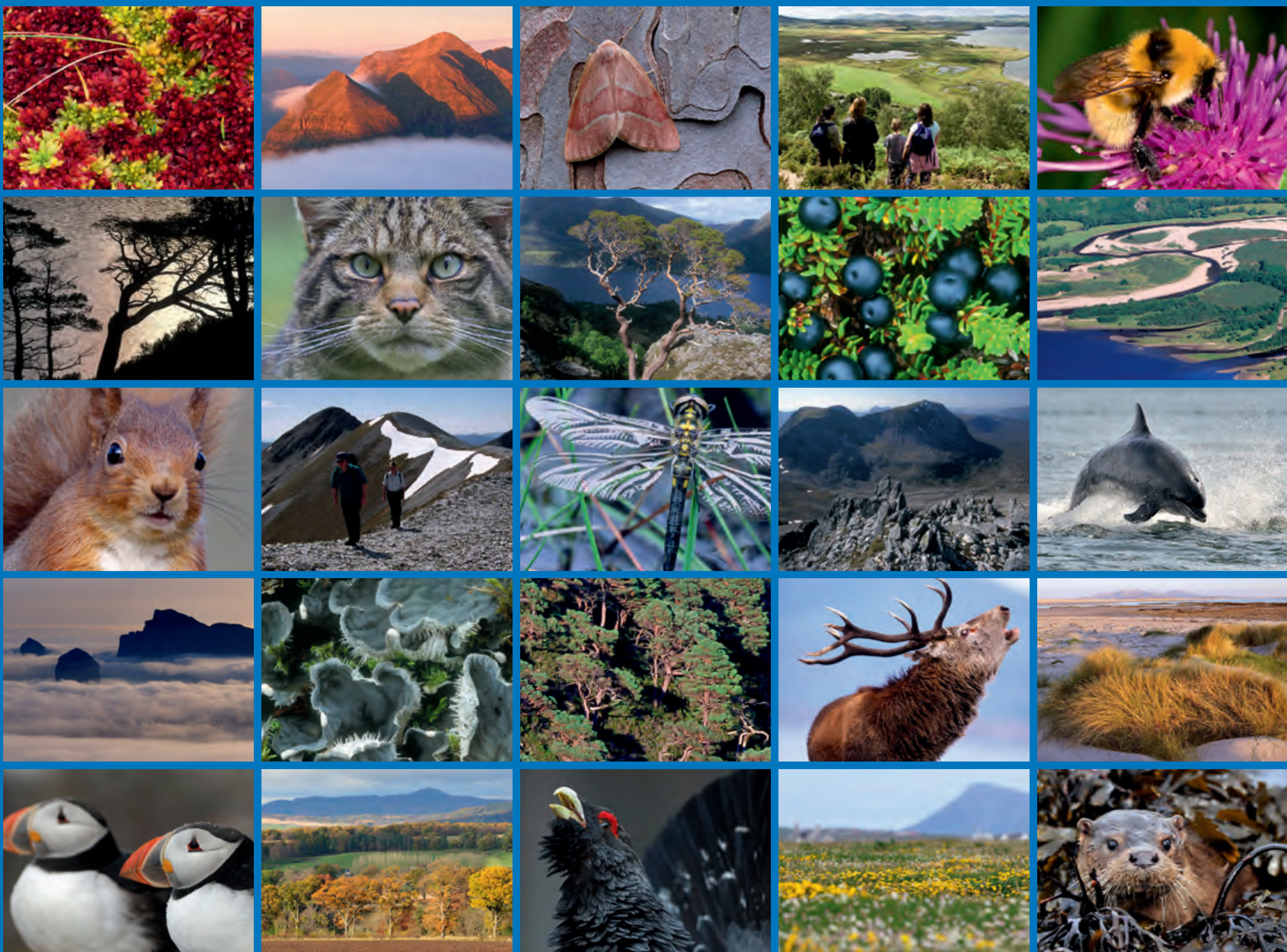
Scottish Natural Heritage
Commissioned Report No. 626

Golden eagles in the south of Scotland: an overview



COMMISSIONED REPORT

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COMMISSIONED REPORT

Summary

Golden eagles in the south of Scotland: an overview

Commissioned Report No. 626
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Keywords

Golden eagle; South Scotland; conservation framework; raptor; NHZ assessment; moorland.

Background

The SNH Golden Eagle Conservation Framework Report indicated that a number of factors may be restricting the golden eagle population in the south of Scotland. Currently, this is a small fragmentary population with one or two pairs breeding in Galloway and one to three pairs breeding or attempting to breed in the Scottish Borders. Several factors may account for so few ranges being occupied, including, in no particular order, historic conifer plantings, poor food supplies, poor productivity of pairs in currently and recently occupied ranges, a lack of potential nest sites, recreational disturbance, persecution, and a shortage of potential recruits from other parts of Scotland.

We collated a variety of data sets and developed a model that identified habitat that could potentially support breeding golden eagles. The analyses split the study area into 10 regions or hill groups and an assessment was made of the possible number of pairs that each region could support.

Main findings

How many pairs could be supported?

Southern Scotland could support 14-16 pairs although a more conservative estimate, excluding the Moorfoot and Lammermuir Hills and the Renfrewshire Heights, is 11-13 pairs. This would be a significant contribution to the Scottish population, with potentially positive implications for the species in the north of England.

Broad predictors of the golden eagle's range

Only the region's potential to support territorial pairs was considered. It is impossible to determine the likely productivity of any future pairs without additional work. Nonetheless, a relatively small number of areas were highlighted as a focus for more targeted work.

The most important predictor of potential golden eagle breeding habitat was the **extent of moors and heathland.** Analyses of **rainfall and growing degree days** changes since the early 1980s suggest that it will have become increasingly difficult for golden eagles to capture prey across the hill ranges. Two measures of **potential recreational pressure** were investigated but the type of information needed for a robust investigation is unavailable.

All of recently occupied golden eagle ranges have experienced significant reductions in potential ranging habitat because of forest expansion. However, some **woodland** would have been present while the ranges were occupied. If annual forest cover data were available for the periods while these ranges were occupied it would be possible to examine thresholds at which ranging losses were associated with range abandonment.

The amount of potential ranging habitat lost to golden eagles as a result of **wind farm developments**, assuming that golden eagles are displaced, varied between hill groups. The relationship between breeding productivity and **land management** is discussed in detail. **Nest sites** for the known ranges are a mixture of trees and crags. Given the undulating terrain it seems likely that crags will be unavailable over large areas. If **persecution** is a serious problem in any region it does not alter that region's potential as suitable habitat or reduce the *potential* golden eagle population in southern Scotland. It could, however, act as a serious constraint to the occupation of suitable habitat in the immediate vicinity of incidents and, more generally, it could reduce the pool of birds available for other suitable regions.

Regional assessments

Detailed assessments are provided for nine principal regions in south Scotland. For each of these the report considers how many golden eagle pairs might be supported.

Further work

Three lines of further work are discussed. First, the currently occupied ranges need to be monitored, and the potential ranges identified in the report need to be surveyed for non-breeding as well as nesting birds. Second, any work that can be carried out to reduce the constraints on golden eagles should be significant; this is especially important given the wetter spring and summer climate, and impending losses of ridge habitats to wind farms, Third, we need to develop our understanding of potential and actual recruits – where they come from, and their contribution to population viability; satellite tagging young golden eagles in areas specified in the report above would be especially instructive.

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Acknowledgements

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1. INTRODUCTION

The SNH Golden Eagle Conservation Framework Report (Whitfield *et al.* 2006a) indicates that a number of factors may constrain the golden eagle population in the south of Scotland. Currently, this is a small fragmentary population. It was estimated that southern Scotland has the potential to support 17 home ranges based on the extent of suitable habitat available (Whitfield *et al.* 2006a,b). Only three home ranges were occupied in southern Scotland in 2011. One occupied home range currently occurs in Northern England.

Several factors may account for so few ranges being occupied, including historic conifer plantings, poor food supplies, poor productivity of pairs in currently and recently occupied ranges, a lack of potential nest sites, recreational disturbance, persecution, and a shortage of potential recruits from other parts of Scotland.

Since the publication of the golden eagle conservation framework (Whitfield *et al.,* 2006a), there has been further work involving tracking of young/sub-adult eagles (using satellite technology e.g. http://www.raptortrack.org/golden-eagle/). One young bird (Roxy) fledged in Galloway in 2010 is being tracked and is still in S. Scotland. Some other birds from outwith the area have been tracked here, but these are rare sightings possibly because the Central Belt provides a partial barrier to movement of birds south from the Highlands. In addition, DNA analysis (using moulted eagle feathers collected at nest sites) is being used to monitor the history of individual birds and estimate breeding turnover and adult survival.

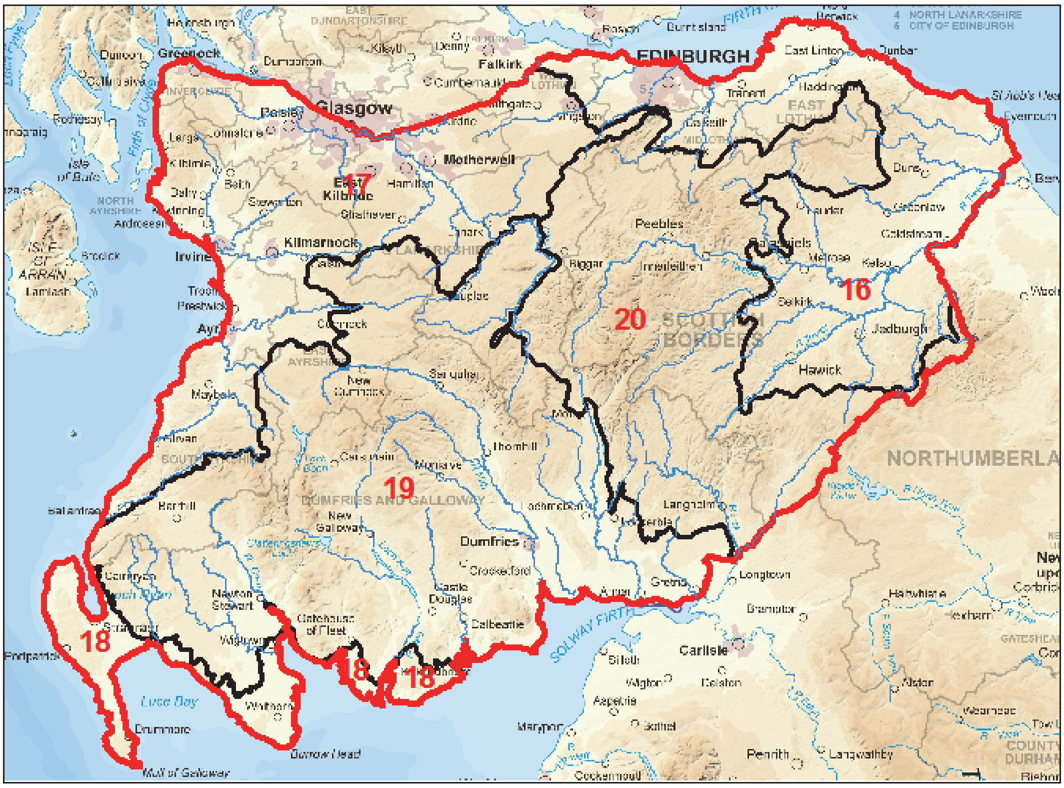


Figure 1.Southern Scotland Study Extent (red boundary) and Natural Heritage Zones (black line: Eastern Lowlands (16); West Central Belt (17); Wigtown Machairs and Outer Solway Coast (18); Western Southern Uplands and Inner Solway (19); Border Hills (20)). Contains Ordnance Survey data © Crown copyright and database right 2010.

Despite the apparent lack of breeding golden eagle activity in southern Scotland local Raptor Study Group (RSG) workers feel that wandering eagles are fairly regular (C. Rollie *pers.*

comm.) and are certainly seen each year away from breeding areas. The local RSG also notes that five pairs breed on Arran and there is known movement of birds between there and the Strathclyde mainland (K.D. Shaw *pers. comm*).

The primary aim of this study was to provide a robust estimate of the potential number of golden eagle ranges, given sufficient recruits, that could be occupied in southern Scotland. It is impossible for a scoping study such as this to estimate the potential productivity of any new pairs. Instead this study should be viewed as the base of a hierarchy of possible studies. Identifying areas that appear similar to areas with occupied ranges in the rest of Scotland will provide an estimated potential population size, irrespective of prey data. There are significant regions of Scotland where there are high densities of golden eagle ranges but very few young are produced, for example the land south of Loch Sealg on the Isle of Lewis and Morven on the mainland above Mull. Poor productivity in such regions (e.g. one young fledged from 10 or more pairs) is almost certainly related to food supply (Watson, 2010) and this could be an issue in southern Scotland. Detailed information on prey is relevant to studies that are further up the hierarchy. Possible future studies, which identify and suggest management options for constraints and prey resources that could maximise the productivity of the region's golden eagles, need more detailed data but which are not dependent on achieving the same national or even regional spatial extents used in this study. A practical consequence, which has constrained our approach, is the availability of data at appropriate spatial and temporal scales. Landscape level data that allow us to estimate the region's potential by comparing southern Scotland with the rest of Scotland are unsuitable for more detailed range-specific analyses, particularly those focused on productivity. Nonetheless, localised data can still be used to provide qualitative and informal assessments of particular locations and possible ranges.

2. METHODS

2.1 Geographical boundary

For the purposes of this study southern Scotland, referred to as the study area, is all mainland between the Scottish border and a line drawn between the Clyde and the Firth of Forth (Fig. 1): including South Lanarkshire, South Ayrshire, Dumfries and Galloway and the Scottish Borders. Within the study region there will be locations that are suitable for breeding golden eagles and others that are not. However, some of the unsuitable locations may be suitable for non-breeding golden eagles, such as sub-adult birds. The majority of the potential golden eagle habitat is restricted to two Natural Heritage Zones: Western Southern Uplands and Inner Solway and Border Hills (Fig. 1).

2.2 Information and data sources

2.2.1 Golden eagle distribution

Historic information of golden eagle distribution in southern Scotland came from three sources: Marquiss *et al.* (1985), Ratcliffe (2007) and Evans *et al.* (2012). Ratcliffe (2007, pp 238-244) has a detailed history of golden eagles in southern Scotland which builds on Marquiss *et al.* (1985). Evans *et al.* (2012) used place name evidence to assess the historical (500 AD onwards) distribution of eagles in the UK and Ireland. These data provide one means of testing any model predictions.

Current and recent information was obtained from golden eagle framework data files, SRSG data and local experts.

2.2.2 Topography

Topographical data were derived from the Ordnance Survey Digital Terrain Model (DTM), version 04/2010 supplied under the Ordnance Survey OpenData Licence.

2.2.3 Geology

Geological maps (1:625,000 scale) were downloaded from the British Geological Survey and are reproduced with the permission of the British Geological Survey ©NERC(All rights Reserved). Four datasets: bedrock, surface, dykes and faultlines were used and clipped to the study extent for some analyses.

2.2.4 Woodland extent

Woodland extent was extracted from the OS VectorMap District version supplied under the OS OpenData Licence. Data are supplied as 100 km x 100 km tiles and the shapefiles merged to create a single data set. The supplied data are simplified such that "*Areas of trees are represented as polygons. Small areas of woodland are omitted and small clearings in woodland are filled.*" The final data set was clipped to the study extent for some analyses.

2.2.5 Streams and lochs

Stream and loch information was extracted from the OS VectorMap District version supplied under the OS OpenData Licence. Data are supplied as 100 km x 100 km tiles and the SurfaceWater_Line and Surfacewater_Area shapefiles were merged to create single data sets. The supplied data are simplified such that "*Rivers and streams narrower than 5 m are represented as a single line. Lakes, ponds and rivers or streams wider than 5 m are represented as polygons with their perimeters held as lines. Water features are broken under bridges or other detail.*" The final data set was clipped to the study extent.

2.2.6 Crags

Information about crags was extracted from the OS VectorMap District version supplied under the OS OpenData Licence. Data are supplied as 100 km x 100 km tiles and the Ornament shapefiles were merged to create a single data set. The Ornament data are described as "*features are facsimiles of ornament artwork, represented as a polygon, that were previously drawn on paper maps to depict coastal rocks, outcropping rocks, screes and so on. They were drawn from aerial photography and give a good and accurate definition of rock strata.*" The final data set was clipped to the study extent. Because each crag is represented as a polygon the data set is very large. Consequently it was necessary to simplify. We use a count of the number of polygons per 1 km square as a surrogate for the potential availability of nest sites. Richard Evans also provided a spreadsheet of crags listed in the climbers' guidebooks held in the Central Library in Edinburgh.

2.2.7 Windfarms

The Scottish Windfarm Proposals (SNHi data) September 2012 data set was downloaded from the SNHi website. These data were clipped to the study extent.

2.2.8 Land use

LCS88 vector data were supplied by SNH, and Corine Land Cover 2000 raster data (version 13 (02/2010) CLC 2000 V13 - 100m) were downloaded. Both data sets were clipped to the study extent. Two Landsat images were downloaded from the Earth Science Data Interface (ESDI) at the Global Land Cover Facility with the aim of identifying recent changes in forest cover. The first image was a 1975 Landsat MSS image (57 m pixel, image acquired 10/06/1975) and the second was a 2001 Landsat TM image (28.5 m pixel, image acquired

10/02/2001). Three band false composite colour images were created from the near infrared, mid infrared and far infrared bands.

2.2.9 Weather

Spatial data on rainfall, mean temperature and the number of degree growing days for the period 1981 to 2006 were extracted from Meteorological Office 5 x 5 km gridded data sets. Data from this source are available for a range of weather variables on a monthly or annual basis. In addition monthly weather means for the period 1914-2012 were downloaded from the Met Office historic station data website for the Eskdalemuir weather station (32^{o}34'E 60^{o}26'N, 242m amsl).

2.2.10 NDVI

NDVI (Normalized Difference Vegetation Index) is directly related to the photosynthetic capacity of the ground vegetation and, therefore, indirectly to the land's ability to support grazing animals. NDVI is calculated from remotely sensed data, in this case from the MODIS satellite, as NDVI = (Near IR - Visible Red)/(Near IR + Visible Red). Healthy vegetation absorbs most of the visible red light that hits it and reflects a large portion of the near-infrared light. Conversely, when there is little healthy vegetation more of the visible red light is reflected while less of the near-infrared light is absorbed. A consequence of this is that healthier or more extensive green vegetation produces a larger NDVI value. Although the range of NVDI values is between -1 to +1 they have been rescaled in our analyses to lie between 0 and 255, with larger values representing healthier vegetation.

Differences between NDVI values for different years can tell us something about relative productivity. For example, lower NDVI values may reflect cold temperatures that have delayed or reduced the growing season. It might be expected that reduced vegetation productivity would be correlated with less live prey. In addition to annual variation there is variation within the landscape which is partly a consequence of altitude, soils and aspect.

Data (MOD13Q1.5) are available as 16 day averages with a 250 m resolution. Considerable pre-processing is needed to calculate a region specific value. For this reason analyses are restricted to the period April 23rd to May 8th (April 22nd to May 7th in a leap year and May 8th to the 23rd in 2000 when cloud cover in the previous 16 days was excessive). Datasets were restricted to those acquired during daytime, when there was less than 20% cloud, and where the data had passed quality tests. These data are distributed by the Land Processes Distributed Active Archive Center (LP DAAC, U.S. Geological Survey Earth Resources Observation and Science Center (lpdaac.usgs.gov).

Downloaded hdf files contain 12 layers of 16 day means: NDVI; EVI; red reflectance; NIR reflectance; blue reflectance, MIR reflectance; view zenith angle; sun zenith angle; relative azimuth angle; composite day of the year; pixel reliability. We only made use of the first layer in our analyses. The hdf files were initially processed using Multispec and the NDVI layer saved a GEOTIFF file. Subsequently, these files were converted into georeferenced Imagine files so that the mean and standard deviation for each hill group could be calculated. These data were clipped to the study extent.

2.3 Derived data

2.3.1 Ridges

Ridges appear to be very important to eagle flight in Scotland (McLeod *et al.*, 2002). Therefore it would be helpful if they could be mapped throughout the study region. This was achieved using a script for the open source R statistical software (see Annex 1 for the script). Briefly, the algorithm uses a 50m DTM (Digital Terrain Model) and examines the relative height of a central pixel with opposing test pixels 200 m apart. If the combined difference in altitude between the central pixel and the test pixels is greater than a user-supplied threshold the central pixel is a ridge. Four comparisons, horizontal, vertical and both diagonals are made and the central pixel only needs to pass one threshold test to achieve ridge status. A key element of the PAT (Predicting *Aquila* Territories) model (McLeod *et al.,* 2002) is the weighted distance to a ridge (Fig. 4 in McLeod *et al.,* 2002). The weighting is needed because the model assumes a non-linear decay in ridge use out to a maximum of 1,200 m from a ridge. Beyond 1,200 m the weighted distance is 0, i.e. effectively unused. The applied weights are given in Annex 1. A weighted distance-to-ridge map was created for Scotland and northern England. This was clipped to the study area for some analyses (Fig. 2).

2.3.2 Upland habitats

Fielding *et al.* (2006) assumed that non-breeding eagles (principally sub-adult birds) use open upland habitats which are not commercial conifer forest or standing open water bodies. It is reasonable to assume that these, plus other, constraints also apply to breeding adults. Previously, Whitfield *et al.* (2003) identified upland habitat in Scotland using the summary classes of the Land Cover of Scotland 1988 (LCS88: MLURI, 1993). Upland habitat included the following LCS88 classes: bog; bracken; strip muirburn; dry heather moorland; wet heather moorland; undifferentiated heather moorland; coarse grassland; montane and bare rock. ‘Cliff and bare rock’ was added by Fielding *et al.* (2006). The result was a series of patches that were subjected to several ‘cleaning’ operations which removed connections between patches that were less than 100 m wide and removed patches less than 1 km^2. After excluding woodland and standing water all other habitat is lowland. Fig. 3 shows the extent of lowland and forested habitats in southern Scotland. Upland habitats are the remaining patches. This map of upland–lowland habitats was clipped to the study region.

2.4 PAT modelling

All PAT modelling was carried out using a script written for the open source R statistical software (Annex 2). Unlike the original PAT model the starting point is the weighted distance-to-ridge map created in 2.3.1. Subsequent analysis steps follow the algorithm described in McLeod *et al.* (2002). It is therefore based only on the algorithm and not the detailed code for the original PAT model.

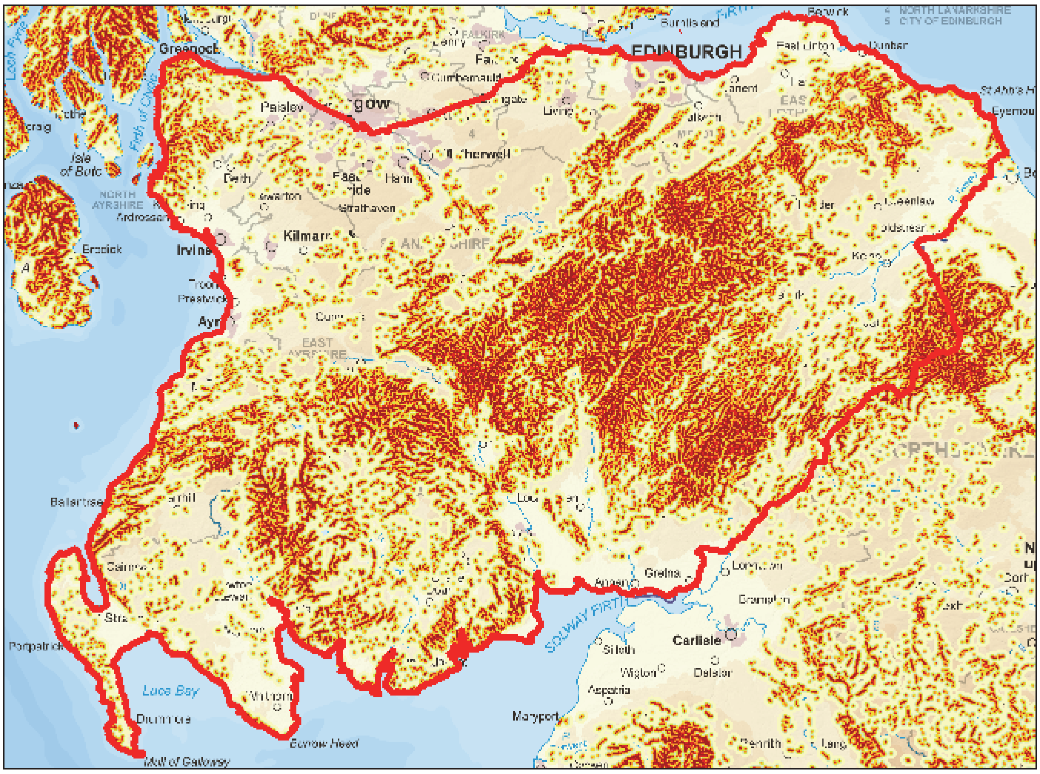


Figure 2. Weighted distance-to-ridges in Southern Scotland. Contains Ordnance Survey data © Crown copyright and database right 2010.

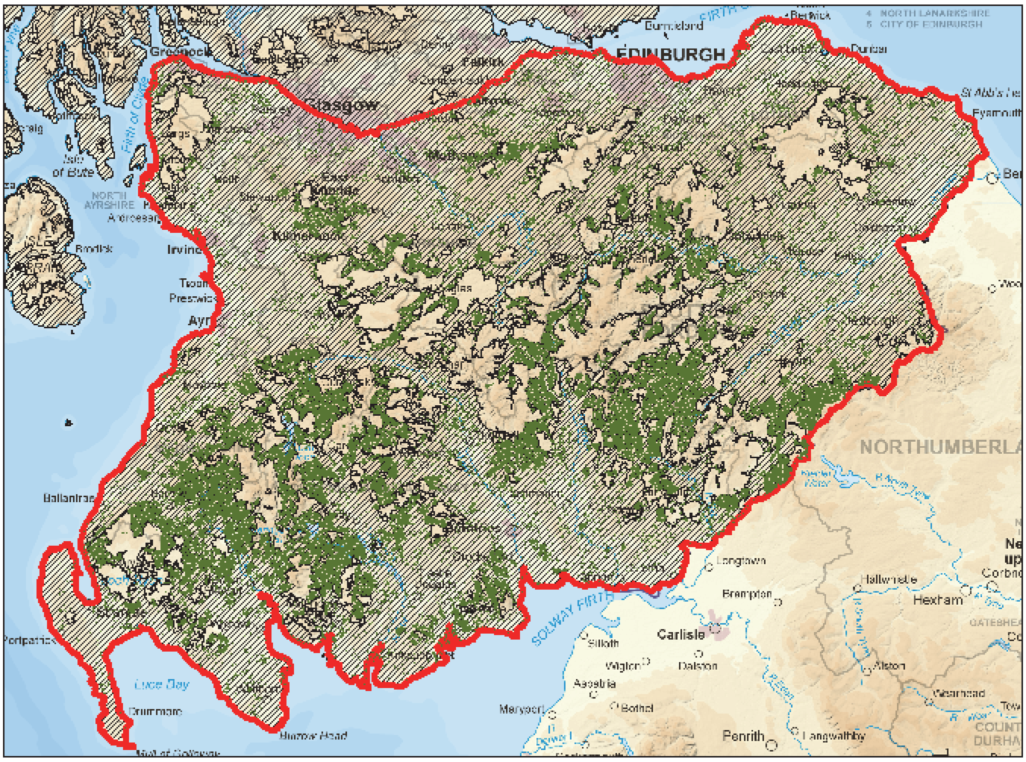


Figure 3. Lowland (hatched) and forested (green) habitats in Southern Scotland. Contains Ordnance Survey data © Crown copyright and database right 2010.

2.5 Species Distribution Models (SDMs)

2.5.1 SDM

A SDM is needed to predict the possible distribution of a future golden eagle population in southern Scotland. SDMs attempt to relate the distribution, and possibly abundance, of a species to one or more predictor variables. Predictors could be climate, habitat, other species or combinations. The probability of a species being present in a particular location is some function of the predictors. In other words, when the values of the predictor variables at that location are combined, perhaps by summing their weighted values, a single value is produced that is converted into a probability of presence.

In our models we use data from the whole of Scotland to identify places in southern Scotland similar to places occupied by golden eagles elsewhere in Scotland. The aim is to produce a map of the entire study region which highlights places that have the potential to support range holding birds. This analysis assumes that golden eagles in southern Scotland would show the same habitat preferences as those elsewhere in Scotland, which seems reasonable since their habitat preference relates to the cost of their soaring flight and the presence of appropriate open ground where suitable prey are present.

Annex 1 is a background to some of the important issues related to SDM. In this work we use Random Forests (2.3.3) as the most desirable SDM to fulfil the project's aims. We made this decision because of its strengths and relative lack of weaknesses (Fielding, 2006).

2.5.2 Training and testing data

The most important aim for a SDM in this context is that it should make accurate predictions. However, it is surprisingly difficult to arrive at an adequate definition and measurement of accuracy (see Fielding and Bell, 1997; Fielding 1999, 2002). Ultimately the only real test is future performance, i.e. the SDM's ability to correctly classify novel cases. This is known as 'generalisation' and it is linked to both SDM design and testing. It is generally accepted that robust accuracy measures must make use of independent data, i.e. data not used to develop the SDM. The two data sets needed to develop and test predictions are known by a variety of synonyms. The terms 'training' and 'testing' data are used here.

In general, complex SDMs are fine tuned to re-classify the cases used in developmental testing, i.e. arriving at the final model. As such they are likely to incorporate too much 'noise' from the training cases, leading to a decline in accuracy when presented with novel data. It is sometimes necessary to accept reduced training data accuracy if it leads to increased accuracy with novel cases. Focusing on the generalisation of an SDM differs from traditional statistical approaches which usually judge performance by the coefficient *p*-values or some overall goodness of fit (e.g. R^2). The statistical focus relates to the goodness of fit of the data to a pre-defined model and does not explicitly test performance on future data, generally because of assumptions made about parameters estimated by the statistics.

2.5.3 Random Forest Background

Decision trees, such as fault finding charts, use binary (Y/N) decisions to partition data and make predictions. The structure of the tree provides information about the nature of the differences between the predicted classes. Unfortunately, decision tree structures can be unstable (Breiman, 1996) such that small changes to the training data produce significant changes to the tree, either in the identity of the split variables or the value for the split. Despite these structural changes the accuracy may be less affected. Breiman and Cutler (2004a) noted that if you "*change the data a little you get a different picture. So the interpretation of what goes on is built on shifting sands*". Breiman (2001a, b) developed the RandomForests (a trademark of Salford Systems) algorithm to overcome many of these shortcomings while retaining, and possibly enhancing, interpretability. Breiman and Cutler (2004b) listed some of the important features of random forests which include:

- accuracy that equals or exceeds many current classifiers and they cannot overfit the data;
- efficiency (fast) on large data bases and can handle thousands of predictors without selection routines;
- estimate the importance of each predictor without selection routines.

Importantly, there are no underlying statistical assumptions such as the probability distribution of the model residuals. They are immune to the effects of data transformations, i.e. a logarithmic transformation offers no advantages over the raw data. Finally, there are no problems if a predictor is over-dispersed, e.g. a large number of zero values.

The algorithm generates many decision trees, the forest, and each tree in the forest differs because of the random nature of the technique (Liaw and Wiener 2006). First, each tree analyses a bootstrapped sample (each case can be included more than once), with n equal to the original sample size. Second, the number of predictors for each node in a tree (m) is set to be much less than the total available and a new, random, set of m predictors is drawn for each node in the tree. This means that the set of predictors considered for partitioning the data is unlikely to be same for any node in the tree. Therefore, each tree uses a different sample of data and different combinations of predictors. Once the predictors have been randomly selected for a node a computationally intensive routine examines every possible split point for its effectiveness at correctly partitioning the data into homogeneous classes. For example, if mean altitude was used, all possible values in the training data would be tested to examine how well the resulting split separated the classes (such as suitable/unsuitable for eagles). The decision trees are grown to their maximum extent which helps to keep the bias low.

Each tree is built using a bootstrapped sample that typically contains about 66% of the cases. The remaining 33%, the so-called ‘out-of-bag sample’, is run through the finished tree and predictions are made and compared with the actual values. Some trees predict these cases correctly, others do not. The proportion of times that a case is misclassified, averaged over all trees, is the out-of-bag error rate. A good model will have a low error rate.

Random forests can also be used to estimate the importance of each variable. This is achieved by testing what happens to the accuracy of the predictions if a predictor is excluded. If a predictor is important the accuracy would show a marked decline. The results from these tests can then be used to rank the predictors, with the most important predictors having the largest scores.

2.5.4 Random Forest analysis

Because of the way that a random forest works it is not essential to have separate test data. Predictions are only made on those cases that are withheld in the out-of-bag sample. Nonetheless, a better test of the performance would use truly independent data, i.e. cases unused to develop the predictions.

Two training data sets were considered that consisted of data extracted from 1 km radius circles drawn around active, vacant and 'empty' golden eagle range centres. A 1 km radius was used to capture the key habitat features around the core of the range. Active and vacant circles were drawn around actual range centres while the central point of an empty location was constrained to be outside of range boundary (vacant or active range) and had to be a minimum of 1 km from the coast. The separation from the coast was to prevent sample locations that were largely sea. The first data set covered the whole of Scotland, including all known ranges in southern Scotland (439 active ranges, 254 vacant range and 701 non-breeding locations). The second was identical to the first except that it excluded all recent eagle ranges in southern Scotland (434, 251 and 701 respectively).

A single test data set was created for the study region consisting of a regular grid of data points separated by 500 m but not within 1 km of the coast. The same predictors, as for the training data, were extracted for 1 km radius circles centred on the test data points. This data set was very large (69,816 data points) and presented a considerable data processing challenge. A prediction was made for each point using the completed random forest tree.

2.5.5 Random Forest predictors

Predictors were restricted to those which had a national coverage and could be processed using a GIS. The final set covered aspects of topography and land use. Elevation and slope information were obtained from a 50 m DTM while distance-to-ridge information was obtained from the data set described in section 2.3.1. Habitat data were extracted from the Corine data set. Full details of the development of the Corine data set and its accuracy assessments are given in Büttner *et al.* (2012). Classes used in the modelling are listed in Table 4. Although the LCS88 data have more attribute classes and a finer resolution their age was considered to be a potential problem.

Although predictors related to prey abundance would obviously be helpful they are unavailable at this scale. Even data such as national sheep *Ovis aries* statistics are of limited value because publically available data are summarised at the parish scale. Parishes can be very large and there is no reason to suppose that sheep are evenly spread throughout a parish.

Each data point's golden eagle class was labelled A (active or occupied range breeding habitat), V (vacant or unoccupied range breeding habitat) or NB (non-breeding habitat) and predictor summaries were obtained for all of the training and testing 1 km radius circles. The summarised predictors were:

- elevation (minimum, maximum, mean, median and standard deviation) from a 50 m DTM;
- slope (maximum, median and standard deviation) of a grid with 5° increments derived from a 50 m DTM;
- weighted distance to a ridge (minimum, maximum, mean, median and standard deviation) derived from a 50 m DTM; and
- area covered by each Corine land cover class (100 m resolution).

The golden eagle class of each 1 km circle was predicted using a random forest analysis with 2,000 trees. Each case has a prediction based on the number of votes for each class (A,V or NB) when it was in the out-of-bag sample (approximately 730 times). Each case was assigned to its majority class. In addition, predictions were made for each the 69,816 data points in the study region test data case using the completed random forest object.
The R code for one of the random forest analyses is shown in Annex 1.

In addition to the text output from the analysis, the predictions for the probability of a golden eagle range were assigned, in a GIS, to the sample locations so that a map of predicted golden eagle breeding habitat could be produced. The map was then overlaid with actual range locations, historic golden eagle locations from Evans *et al.* (2012) and, where available, locations of young birds obtained from satellite tracking studies. Using this information it is possible to test the accuracy of the predictions and identify potential future range locations and exclude other predicted locations that are likely to be affected by factors not included in the model's development, such as wind farms.

3. RESULTS

3.1 Description of the study area

The SNH Natural Heritage Futures reports provide a reasonably comprehensive description of the study area by summarising each NHZ. There are seven ranges of hills running SW-NE across the study region: Galloway Hills, Carsphairn Hills, Lowther Hills, Tweedsmuir Hills and the adjacent Ettrick Hills, the Moorfoots and the Lammermuirs. In addition, the eastern side of this line of hill groups have the Pentlands to the north and the Cheviots to the south (Fig. 4). The northern boundary to the SW-NE ranges of hills is quite well defined by a straight line following the Southern Uplands Boundary Fault. There are also volcanic outliers such as the Eildon Hills and Tinto.

The character of these hill groups is defined by their geology and the relatively recent glaciations. The Cheviots, some of the Galloway Hills and Pentland Hills are the remnants of volcanoes and granite intrusions while the majority of the Southern Uplands, between the Scottish border and the Southern Uplands boundary fault are mainly a type of sandstone known as a wacke. The sedimentary and igneous rocks have different weathering characteristics that produce different types of topography. The Galloway Hills are characterised by the two large igneous intrusions dating to the late Silurian - early Devonian period. The northern intrusion, mainly the Dungeon Hills, is characterised by terrain more characteristic of the NW Highlands and is bounded east and west by long ridges such as Merrick and the Rhinns of Kells. The southern intrusion is approximately oval in shape and occupies land between the A762 and Cairnsmore of Fleet. There is another large igneous intrusion close to the Solway Firth coast south east of Dalbeattie and a smaller one in the Carsphairn Hills, particularly around the Cairnsmore of Carsphairn. Most other hill groups are composed almost entirely of wacke sediments. The exceptions are the Pentland Hills, a complex mixture of sandstone, conglomerates and extruded lava, and the Cheviot Hills which, on the Scottish side of the border, are mainly made up of lava flows that have produced a mid-altitude but highly dissected and rugged landscape. The sedimentary rocks erode to a more rounded landscape characterised by thin and nutritionally poor acid soils.

During the last century there were significant changes to farming and land use practices that altered the characteristics of the upland habitats. In particular, agricultural land was converted to commercial forest plantations and sheep numbers increased. The SNH Natural Heritage Futures report (2002) for the Western Southern Uplands NHZ describes large reductions in the areas of heather moorland (>50%), blanket mire (>50%) and rough grassland (28%) between the 1940s and the 1980s. Cowie (2007) used a range of classified Landsat images to examine changes in land cover and estimated that almost half of the 34% reduction in upland heather cover in the Borders, between 1977 and 2001, was due to replacement with forestry. There was also a 22% reduction in grassland cover, with almost 80% of this loss being attributed to forestry. However, there were also some gains in grassland (138 km^2) at the expense of a 10% reduction in heather cover. This suggests that the major losses in heather cover between 1977 and 2001 were related to forestry rather than changes to muirburn or grazing practices.

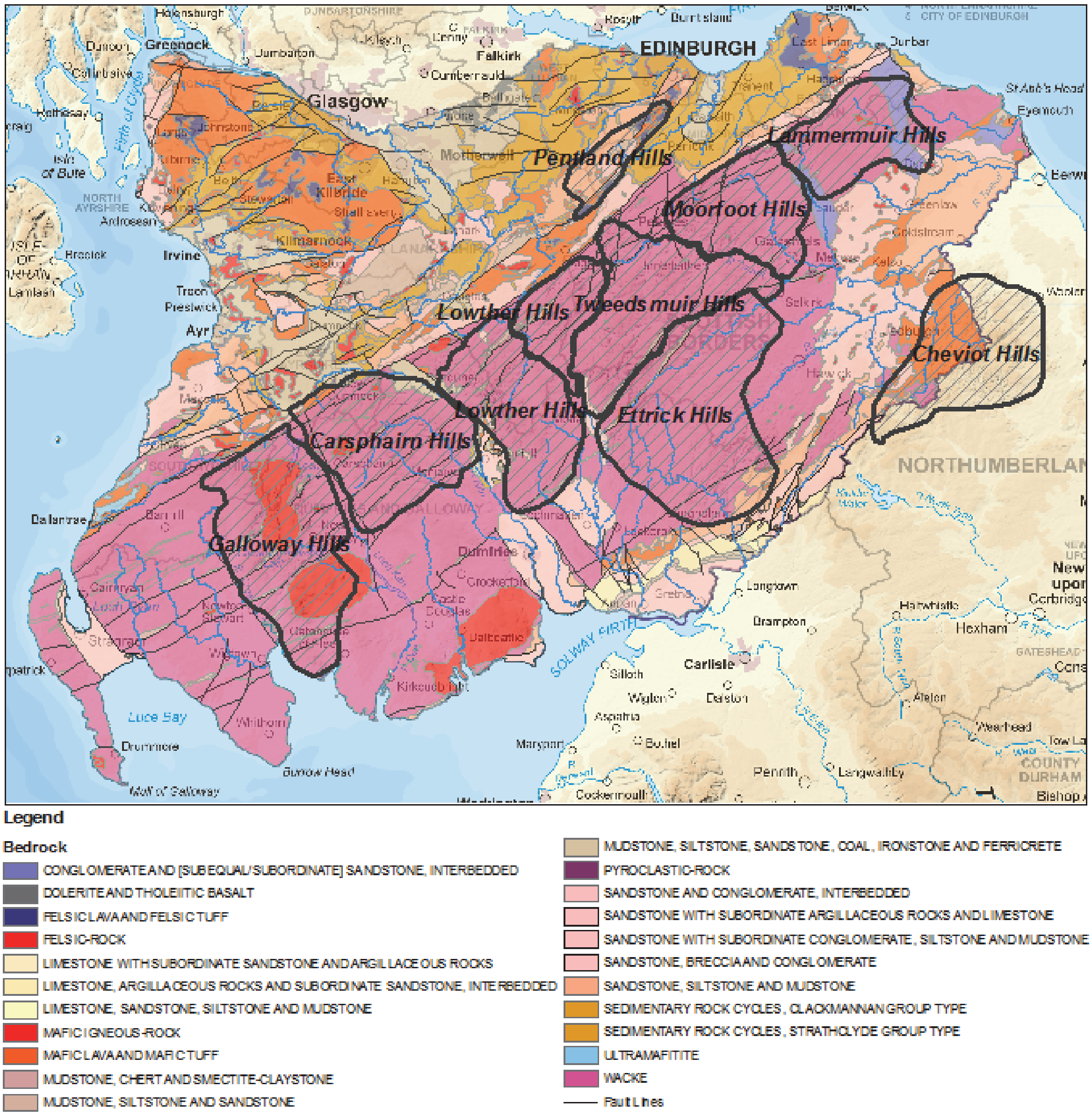


Figure 4. Southern Scotland Hill Groups and Bedrock Geology. Contains Ordnance Survey data © Crown copyright and database right 2010 and British Geological Survey ©NERC (All rights Reserved).

3.2 History of golden eagles in Southern Scotland

Evans *et al.* (2012) record 32 place names in the study region (and close to the border) that appear to be related to the historic presence of golden eagles. There are only two such names within the part of the study area north of the Southern Boundary Fault, one in the Pentland Hills and one in the Renfrewshire Heights. However, some of these locations are too close together to be evidence of separate ranges so a conservative estimate would be somewhere between 20 and 25 ranges. Fig. 2b in Evans *et al.* (2012) provides evidence of breeding attempts in ten 10 km squares in the 19th century, mainly the Galloway Hills plus two in the Ettrick Hills and one in the Cheviots. Fig. 3 in Evans *et al.* (2012) suggests that there were no breeding attempts in the study region in 1920 and Maxwell (1897,1919), cited in Evans *et al.* (2012), suggested that breeding may have ceased by the 1870s. This is supported by Ratcliffe's (2007) historical account of the golden eagle breeding history. He records that the last known nesting was in Glen Trool in 1876 (Table 1). Everett (1971) reported 18 breeding attempts in Galloway between 1964 and 1968 during which time three young were fledged at an overall rate of 0.17 per breeding attempt.

Baxter and Rintoul (1953, pp 296-300) present evidence from a number of sources to describe the history of golden eagles in southern Scotland. For example, there is a second hand quote that "*in 1834 .... there were six pairs of Eagles in Moffatt water*" but this appears to be contradicted by another source who said that golden eagles were breeding in the Moffatt Hills until 1833, with the last killed in April 1833. A local newspaper reported in 1850 that a young eagle had been taken from a nest on the Clints of Drummore, Gatehouse. Other sources note that golden eagles bred for "*some years after 1850 in Kirkcudbright*" whilst it was said it was still breeding in the Stewartry in 1869. Baxter and Rintoul (1953) say that the next record was in 1905 when a "*pair returned to Cairnsmore and built an eyrie but failed to hatch the three eggs they laid in it*". They also state that the keeper at Loch Trool told them that a pair nested above the Loch in 1935 whilst another source suggests that golden eagles nested successfully in Kirkcudbright after 1925. They quote Gray who said that golden eagles had ceased to breed in Ayrshire by 1865, but they also quote McWilliam who said that they had bred in South Ayrshire from 1911 to 1918, in 1920, 1921 and 1923, and in 1948 a brood was fledged. Finally they report that a pair returned and built a nest in 1921 when two infertile eggs were laid.

Rollie (*pers. comm.*) has provided more detail and some corrections on the early history of breeding in this region, some of which went uncorrected in Ratcliffe's book as a consequence of his untimely death. He notes that Evans *et al.* (2012) are mistaken in suggesting no breeding in 1920. Pair B laid two eggs which were robbed that year. However, breeding appears to have ceased in SW Scotland around 1876-1881, and there was then a 20 year gap with no reported breeding until 1905 (Site A), which failed – an adult was found shot some miles away in 1907, and another eagle was in the area in 1908. The next firm breeding attempt was in 1910 (Site B), which produced young. Breeding then took place at this site until 1923. At Site B, eagles were present in 1945-47, though first successful breeding was in 1948, as stated.

Ratcliffe's (2007) description of the history of golden eagles in southern Scotland (Tables 1 and 2) builds on the earlier description in Marquiss *et al.* (1985). Starting in the seventeenth century there is a report of eagles breeding in the Galloway Hills. During the nineteenth century there were reports of breeding in several places including six pairs nesting near Moffat Water. There is also evidence of conflict with sheep farmers. Unfortunately, as Marquiss *et al.* (1985) explain, this part of Scotland apparently had few people interested in birds in the late nineteenth and early twentieth centuries so records are, at best, patchy. Nonetheless, the centre of activity seems to have been in the area now known as the Galloway Forest Park but with other scattered records.

The second World War, as elsewhere in Scotland (Watson, 2013), appears to have allowed the golden eagle to recover from the apparent constraints of 'predator control'. Over a period of 17 years from 1945 four pairs established in the Galloway Hills, two re-occupying the old nesting sites used in 1905 and 1910-23. Four sites have been occupied elsewhere away from the Galloway Hills but in recent times the norm appears to be no more than four of the eight sites occupied. Since their reappearance in the study area golden eagles have experienced problems created by afforestation, pesticide contamination and persecution. It is also unclear how much immigration has taken place from birds fledged elsewhere.

The first known, recent, nesting attempt was in 1945 when a pair reared two young in the Galloway Hills. Marquiss *et al.* (1985) and Ratcliffe (2007) refer to this range as Area A. Their adjacent Area B range was occupied by a second pair in1948, again fledging two young. A third pair (Area C) became established in 1952 occupying a similar area to Area A. Area C was first successful in 1953 and Marquiss *et al.* (1985) report that it was regularly successful on the same cliff until 1975, after which they used alternative sites. The final, and fourth, pair (Area D) in the Galloway Hills laid eggs in 1965 but the range seems to have been occupied by a single bird in 1962. Marquiss *et al.* (1985) report that the Area D pair moved to an adjoining nesting area in 1969, where they remained. The nesting and breeding history of the four Galloway pairs is summarised in Table 2.

Table 1 - Summary of the golden eagle history of southern Scotland based on descriptions in Ratcliffe (2007, pp. 238-244)

Location	Notes
Minigaff Hills	Symson (1684) observed that ptarmigan sought refuge from the 'insults of the eagles'.
Gameshope	In McPherson (1892), eagles bred in 1833 on the farm of Gameshope.
Moffat Water	83 year old shepherd interviewed in 1834 said that six pairs used to nest.
Loch Dungeon	Early 1800s farmer used a lighted tar barrel in front of eyrie to drive away the eagles.
Minigaff Hills	Young bird taken in 1850.
Glen Trool	Last known nesting in 1876.
Carrick Hills	Also known to breed there in early 1800s.
Minigaff Hills	1905, three eggs laid but nest failed.
Carrick Hills	Bred 1910-23 but probably robbed most years.
Merrick	Birds seen around here in 1930s.
Minigaff Hills	1945 two young reared, laid at four different cliffs until 1951. 1952 another pair took over their most distant eyrie (two pairs now).
Loch Doon Hills	1948 another pair returned here - nesting every year until 2003, except 1995 when they used a distant rock in the Stewartry.
Laggan of Dee (Bennan)	A 'mysterious' nest built in 1948, no proof that eggs were laid.
Laggan of Dee 'general area'	1964 a fourth pair started nesting on a crag but by 1968 they had moved to distant shelter belt where they continued to breed. (sometimes on small nearby rocks).
Craigencallie	Uncertain reports of nesting in 1966.
Merrick	Unconfirmed rumours of nesting.
Craignaw	Unconfirmed rumours of nesting.
Moffat Hills	1971 pair reported, eggs laid 1972, 1973 said to lay east of the head of Wamphray Water.
Bentpath	1974 above pair had moved to a small tree lined glen where young where reared but assumed to move into the Cheviots soon after, nesting on a small rock in England before moving back to a shelter wood in Scotland where they have remained.
Borders	Two more tree nesting pairs are now reported.

The Galloway pair A last reared young in 1973. After that they deserted a clutch (1974) and did not lay in 1975. Between 1976 and 1978 the range was occupied by a single bird. Although a new pair occupied the range in 1979 and laid a single egg in 1980, the new pair was lost in 1981 following the death of a male eagle after eating poisoned bait put down for other predators on a neighbouring estate. The range seems to have been vacant since then. Range B is still occupied and producing young despite being occupied by single birds and immature birds between 1977 and 1982. When eggs were laid in 1983 they were the first in over a decade and the nest was successful again after a gap of 15 years. It appears that the eggs were robbed at least three times during the 1980s. Range C is unusual in that eggs were laid every year, however very few young were fledged. It is known that the eggs were robbed at least three times in the 1980s. Site D, which is very close to the A712, is currently occupied by a non-breeding pair having been quite successful in the 1980s when six young were fledged. Rollie (*pers. comm.*) has provided information about the reasons for nest failure in these four ranges (Table 3). It is clear that, particularly up to the 1960s, nest robbery was quite significant and that, even quite recently, some failures appear to be related to work in the forests.

Information about the recovery of golden eagles in other parts of the study area is more sketchy, with only occasional sightings in the Moffat-Tweedsmuir Hills during the 1950s and 1960s. In 1971 a pair was reported in the Moffat Hills, "*east of the head of Wamphray Water*" and eggs were laid in 1972 and 1973. Ratcliffe (2007) suggests that this pair moved in 1974 to "*a small tree lined glen where young where reared but assumed to move into the Cheviots soon after, nesting on a small rock in England before moving back to a shelter wood in Scotland where they have remained*". Subsequently, two more pairs have nested successfully in the Borders bringing the number of post second World War ranges to eight, although some are now vacant due to afforestation and others have suffered through persecution (Fig. 5).

It is clear that land use of the uplands of southwest Scotland has undergone large changes since the second World War with a move from sheep farming to forestry in some areas. For example in Figures 6a and 6b it is clear that large areas of the Galloway Forest Park had been converted to conifer plantation before the 1975 image was acquired but that the planted area had increased considerably by 2001. All four of the Galloway eagle ranges experienced some afforestation but the abandoned ranges lost large areas of the most prey rich habitat to forests, leaving only the rather degraded open land at higher altitudes. This loss of the best areas may have been exacerbated by changes in the amount of rainfall (section 4.2). Evidence for the impact of reducing foraging opportunities is apparent from the pellet analyses described by Marquiss *et al.* (1985). They found that the proportion of large birds, such as red grouse, in the spring diet was related to breeding performance, pairs with more large birds in their diet having higher breeding success. There was little evidence that the eagles were taking prey from the conifer plantations. The loss of open ground for these ranges is assessed in section 4.4 using PAT modelling.

Table 2 - Breeding history of four golden eagle ranges in SW Scotland (based on Table 3, p 242, in Ratcliffe 2007 with additional post-2005 data from SRSG data up to 2009 and updated and corrected by Chris Rollie). Ranges A and C are now thought to be merged.

Territory	Year range	Records	Pair (single)	Eggs laid	Successful
A	1945-63	17	17	19	5+
	1964-73	10	10	10	3
	1974-83	10	6 (4)	2	0
	1984-93	10	0	0	0
	1994-2005	12	0	0	0
	2006-2012	7	0	0	0
B	1945-63	17	17	17	8
	1964-73	10	8 (2)	7	1
	1974-83	10	5 (5)	1	1
	1984-93	10	10	10	6

	1994-2005	12	11 (1)	10	6
	2006-2012	7	7	6	3
C	1945-63	15	13	12	7
	1964-73	10	10	9	4
	1974-83	10	10	10	3
	1984-93	10	6 (1)	5	2
	1994-2005	12	0 (1)	0	0
	2006-2012	7	0	0	0
D	1945-63	12	1	0	0
	1964-73	10	10	6+	5
	1974-83	10	10	10	8
	1984-93	10	10	9	6
	1994-2005	12	12	10	1
	2006-2012	7	6 (1)	0	0
All	1945-63	61	48	48	20+
	1964-73	40	38 (2)	32	13
	1974-83	40	31 (9)	23	12
	1984-93	40	26 (1)	24	14
	1994-2005	48	23 (2)	20	7
	2006-2012	28	13 (1)	6	3

Table 3 - Reasons for nest failures for four golden eagle ranges in SW Scotland (based on information provided by Chris Rollie). The number in parentheses is the frequency in the decade.

Reason for failure	Pair A	Pair B	Pair C	Pair D
Addled eggs	1950s (1), 1960s (1), 1970s (2)	1960s (1), 2000 on (1)	1970s (5) 1980s (4)	1980s (2) 1990s (3), 2000 on (2)
Adult poisoned	1980s (1)	1960s (1)		
Adult shot	1950s (1)	1940s (1)		
Chick(s) died in nest	1960s (1)	1950s (1), 1990s (1), 2000 on (3)	1980s (1)	1990s (2)
Deserted/failed to hatch	1950s (2), 1960s (1), 1980s (1)	1950s (1), 1960s (2), 1970s (1)	1960s (2)	
Disturbance and chilling of eggs	1950s (1), 1960s (2, once due to forest planting)	2000 on (1 forest contractors)	1970s (1 contractors)	1960s (1), 1990s (1 forest operations)
Eggs broken in eyrie	1960s (1)			
Nest blew down				1970s (1)
Robbed of eggs	1940s (1), 1950s (2), 1960s (2-3), 1970s (1)	1950s (5), 1960s (2), 1970s (1), 1980s (2), 1990s (2)	1940s (1), 1950s (1), 1960s (2), 1980s (2)	1960s (1), 2000 on (1)
Reasons unknown	None	1940s (2), 1990s (1), 2000 on (1)	1950s (2)	1990s (1), 2000 on (1)
Total nest failures	22	30	21	16

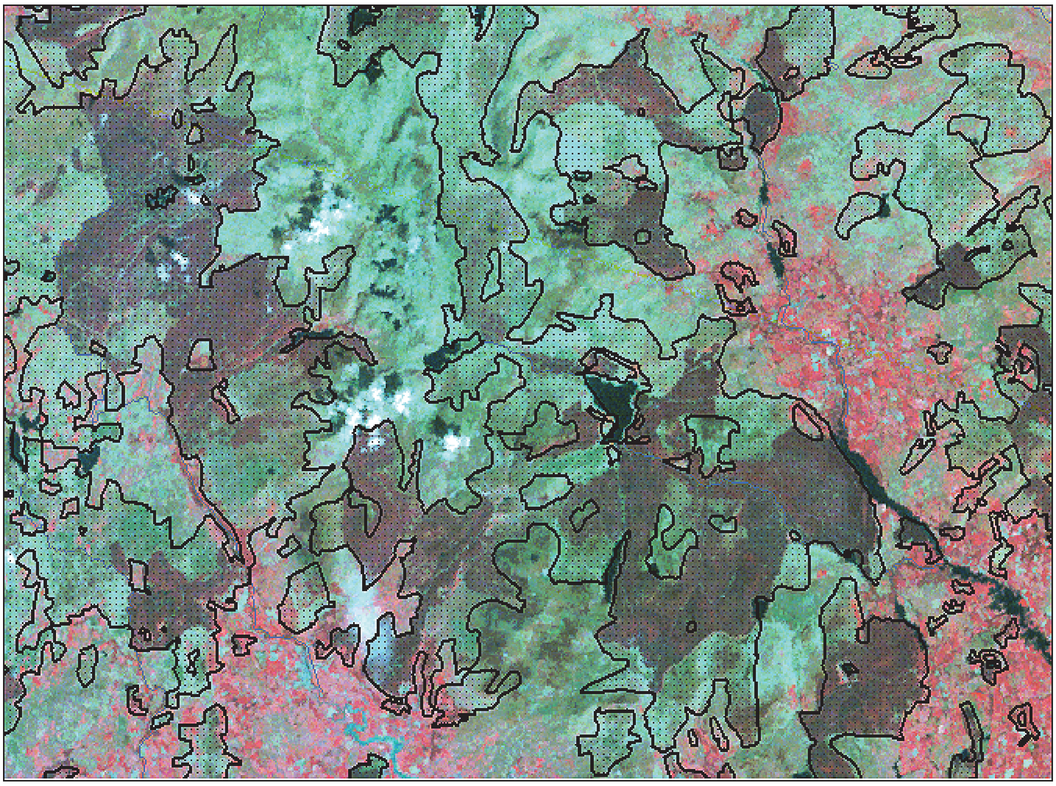


Figure 6a. Extract from a Landsat MSS image acquired on 10th June 1975 overlain with current woodland cover (stippled fill). Clatteringshaws Loch is right of centre on the images. Fields are red in this false colour image and forest cover is dark green.

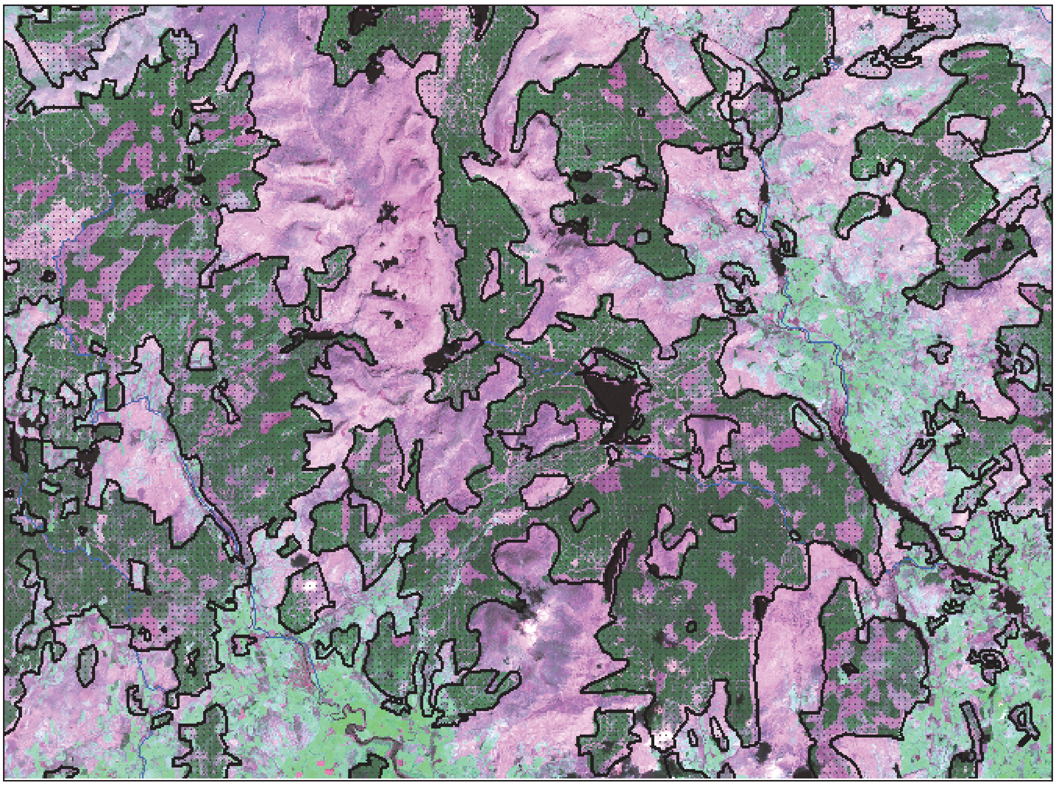


Figure 6b. Extract from a Landsat TM image acquired on 10th February 2001 overlain with current woodland cover (stippled fill). Forest cover is dark green in this false colour image. Contains Ordnance Survey data © Crown copyright and database right 2010.

3.3 Species distribution modelling

In these descriptions the training set that included golden eagle ranges in southern Scotland is referred to as the full training set and the one which excluded them is referred to as the reduced training set. Table 4 shows the class means for the predictors used in the random forest analyses.

The non-golden eagle breeding habitat tended to be on lower ground with smaller slopes. Vacant ranges tended to be at slightly higher altitudes than the active ones but with slightly reduced slopes.

The weighted distances-to-ridge values are not actual distances and, because the weights decrease in a non-linear fashion away from ridges, larger values indicate greater proximity to ridges. Consequently, samples from non-breeding locations were further from ridges and there was much less variability in the weighted distances. Vacant ranges tended to have slightly smaller weighted distances suggesting that there is slightly less ridge habitat in the vacant ranges.

All of the predictor means associated with human activity, including agriculture and pastures, were much greater in the non-breeding habitat samples. There was also more woodland of all types. Eagle breeding habitat, of both classes, was characterised by more natural grassland, moors and heathland, bare rocks and sparsely vegetated areas. Vacant ranges had more than double the mean area of pastures and coniferous woodland than in the active ranges but slightly less natural grasslands and moors and heathland. The vacant ranges had, on average, about 50% more sparsely vegetated areas.

However, it is important not to place too much emphasis on these mean differences. Golden eagle habitat varies considerably across Scotland. For example, many of vacant ranges in the east of Scotland are at higher altitudes than the active ranges in the west. Vacant ranges in the east are generally not vacant because of large forest plantations while, in the west, there are some vacant ranges at reduced altitude because of afforestation. Random forest analyses are an ideal tool to deal with this type of context dependency because the data are partitioned and each partition is treated separately. This allows for the situation in which, for example, ranges may be vacant for a variety of different and unconnected reasons.

Results from the two random forest analyses are almost identical (Tables 4 and 5). This means that excluding the south of Scotland ranges from the training data had no impact on the model's predictions. Although both sets of results are reported the final interpretation is based solely on the full model.

Table 5 shows how cases were misclassified by the models. Using the full data set as an example, about 20% of the active ranges were misclassified but most of these (13.7%) were misclassifications as vacant ranges, i.e. their characteristics share more in common with vacant ranges than they do with the other active ranges. The error rate for vacant ranges appears very high at almost 75%, however three quarters of these misclassifications were as active ranges. This is an important result since it indicates that many vacant ranges could support breeding golden eagles. It is certain that some vacant ranges are very suitable for occupancy but remain vacant because there are insufficient recruits or birds are prevented from settling there. Very few non-breeding sample cases (5.7% or 40 of 701) were misclassified as either active or vacant eagle ranges.

Table 4 - Summary of predictor variable means for the full training data set

Predictor	Active	Vacant	Non-breeding
n	439	254	701
Altitude (m)			
Minimum	143.9	237.0	132.4
Maximum	513.1	557.4	258.1
Mean	305.8	378.4	189.1
Median	301.9	371.9	187.4
Standard deviation	101.8	84.2	29.8
Slope (degrees)			
Maximum	42.7	37.8	19.5
Median	15.3	13.7	7.3
Standard deviation	8.4	7.3	3.1
Weighted distance-to-ridges (no units)			
Minimum	80.3	75.4	57.3
Maximum	997.7	985.8	655.8
Mean	498.0	450.2	182.5
Median	390.3	342.3	124.2
Standard deviation	343.0	330.6	152.6
Corine land cover classes (ha)			
Discontinuous urban fabric	0.0	0.3	20.7
Industrial/commercial units	0.0	0.0	2.3
Mineral extraction sites	0.0	0.0	2.5
Sport and leisure facilities	0.0	1.3	5.8
Non-irrigated arable land	0.0	0.0	192.7
Pastures	9.9	18.1	350.3
Complex cultivation patterns	0.0	0.0	40.6
Agriculture, with significant natural vegetation	0.9	2.3	32.5
Broad-leaved forest	1.9	6.2	19.3
Coniferous forest	31.4	71.3	150.0
Mixed forest	0.2	0.8	1.2
Natural grasslands	187.7	161.1	120.0
Moors and heathland	790.0	730.1	125.3
Transitional woodland-shrub	4.5	10.8	18.3
Bare rocks	24.2	20.4	0.4
Sparsely vegetated areas	98.9	142.2	1.7
Peat bogs	25.9	30.4	41.9
Water bodies	15.0	8.6	8.5
Sea and ocean	63.0	48.2	0.7

Table 5 - Confusion matrix for the training sets (left - full training set, right - training set excluding the south of Scotland ranges). Upper tables are frequencies, lower tables are percentages. For example, 60 (13.7%) of the active ranges for the full training set were predicted to be vacant and 28 (6.4%) were predicted to be non-breeding habitat (NB).

	A	V	NB	n		A	V	NB	n
A	351	60	28	439	A	349	59	26	434
V	140	65	49	254	V	140	64	47	251
NB	12	28	661	701	NB	13	28	660	701
A	80.0	13.7	6.4		A	80.4	13.6	6.0	
V	55.1	25.6	19.3		V	55.8	25.5	18.7	
NB	1.7	4.0	94.3		NB	1.9	4.0	94.2	

The importance of the predictors to the assignment of breeding class is measured by the mean decrease in the Gini index (Table 6). A Gini index is a measure of node homogeneity from 0 (homogeneous) to 1 (heterogeneous), i.e. whether or not a node is made up of cases from more than one class and in what ratio. Each time a predictor is used to split a node, the Gini coefficients for its child nodes are calculated and compared to that of the original node. Gini changes are summed for each predictor and normalized when all of the trees have been constructed. The normalised Gini index scores are used to assess the relative importance of the predictors because predictors that result in nodes with greater homogeneity (a better separation of the classes) will have a higher decrease in Gini coefficient.

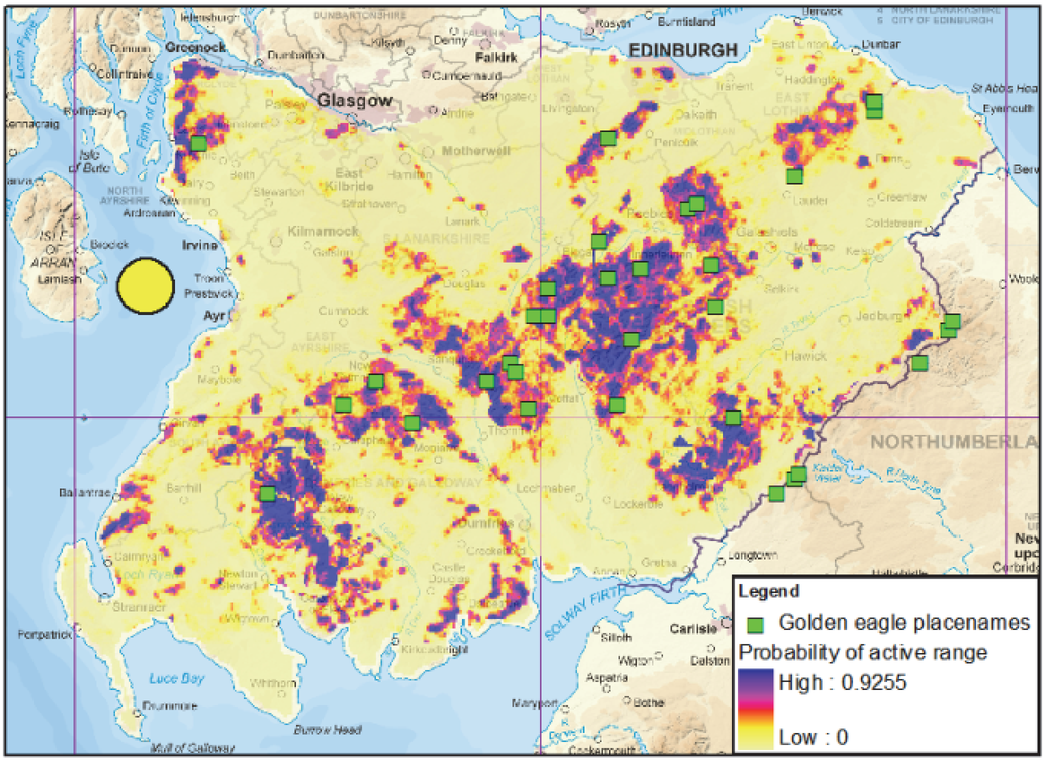
In Table 6, predictors are ranked according to the mean decrease in the Gini index. The most important predictor is the Corine moors and heathland habitat class. As shown in Table 4 the mean values for the area of this habitat are very similar for the active and vacant eagle ranges (790.0 and 730.1 ha respectively) compared with only 125.3 ha for non-breeding habitat. All of the altitude predictors have Gini decrease indices in the top 10. The most important of these was the altitude standard deviation (means of 101.8, 84.2 and 29.8 m respectively for active, vacant and non-breeding classes). Slope variability and the maximum slope were the second and third most important predictors with much larger values for the two range classes. Thus, golden eagle ranges are topographically more variable than the NB samples. They are also, on average, higher but there is some evidence for active ranges having a lower mean. The weighted distance-to-ridges, and its variability, are also important predictors.

The other Corine habitat variables are less important predictors. Given the very large differences in the mean area of pastures (9.9, 18.1 and 350.3 ha respectively for active, vacant and non-breeding classes) it is, perhaps, surprising that this isn't a more important predictor. The next two most important Corine habitat predictors both have gradients from active to non-breeding habitat but operating in different directions. Natural grasslands have a larger mean area for active ranges (187.7 ha) than vacant ranges (161.7) and non-breeding habitat (120.0 ha) while coniferous forest is most extensive (150.0 ha) in non-breeding habitat. Vacant ranges have more than twice as much conifer forest (71.3 ha) compared with active ranges (31.4 ha).

Each time that a tree is generated in the random forest a prediction (vote) of active, vacant or non-breeding is made for each case in the out-of-bag sample. At the end of the analysis each case will have a number of votes for each class and the case is assigned to its majority class. Because cases are included in the out-of-bag sample approximately, but not exactly, the same number of times the votes for each case are normalised to proportions that sum to one. Figure 7a is a map of southern Scotland showing the probability that each sample location is an active range, i.e. the proportion of times that each sample location was predicted to be 'active' when it was in an out-of-bag sample. The map is overlaid with the locations of golden eagle related place names (Evans *et al.,* 2012). Figure 7b is the same probability map overlaid by the approximate locations of the satellite-tracked sub-adult eagle Roxy in 2011 and 2012. Both Fig. 7a and 7b provide confidence in the random forest predictions, particularly the coincidence between Roxy's movements and the predicted habitat suitability. There is also a good fit between the locations of recently occupied ranges and the predicted habitat suitability (not shown to protect nest locations). However, there are other constraints that were not included in the modelling. For example, Arthur's Seat in Edinburgh has a high probability of being suitable habitat but it would be very surprising if any golden eagle could tolerate the level of human activity. Additional constraints are considered in the next chapter.

Table 6. Importance statistics for the two random forest analyses. Figures are the mean decrease in the Gini index.

Predictor	Full	Reduced
Moors and heathland	104.4	105.4
Slope sd	79.6	79.0
Slope maximum	77.2	74.0
Weighted distance-to-ridge mean	73.6	73.4
Altitude sd	71.2	66.8
Weighted distance-to-ridge sd	51.8	56.2
Altitude minimum	45.6	45.1
Altitude maximum	44.5	44.7
Altitude mean	40.6	40.4
Altitude median	38.9	38.8
Pastures	38.2	37.6
Weighted distance-to-ridge median	34.1	34.7
Natural grasslands	22.3	21.7
Coniferous forest	21.7	21.2
Slope median	21.2	19.1
Weighted distance-to-ridge minimum	15.0	15.0
Sparsely vegetated areas	14.7	14.6
Sea and ocean	9.3	9.8
Peat bogs	8.6	8.6
Water bodies	5.8	5.8
Bare rocks	5.6	5.5
Transitional woodland-shrub	5.5	5.3
Weighted distance-to-ridge maximum	4.6	4.6
Agriculture, with significant areas of natural vegetation	4.1	3.7
Non-irrigated arable land	3.1	3.7
Broad-leaved forest	2.0	2.2
Complex cultivation patterns	1.1	0.9
Discontinuous urban fabric	0.9	1.0
Mixed forest	0.7	0.8
Sport and leisure facilities	0.2	0.2
Industrial or commercial units	0.0	0.0
Mineral extraction sites	0.0	0.0



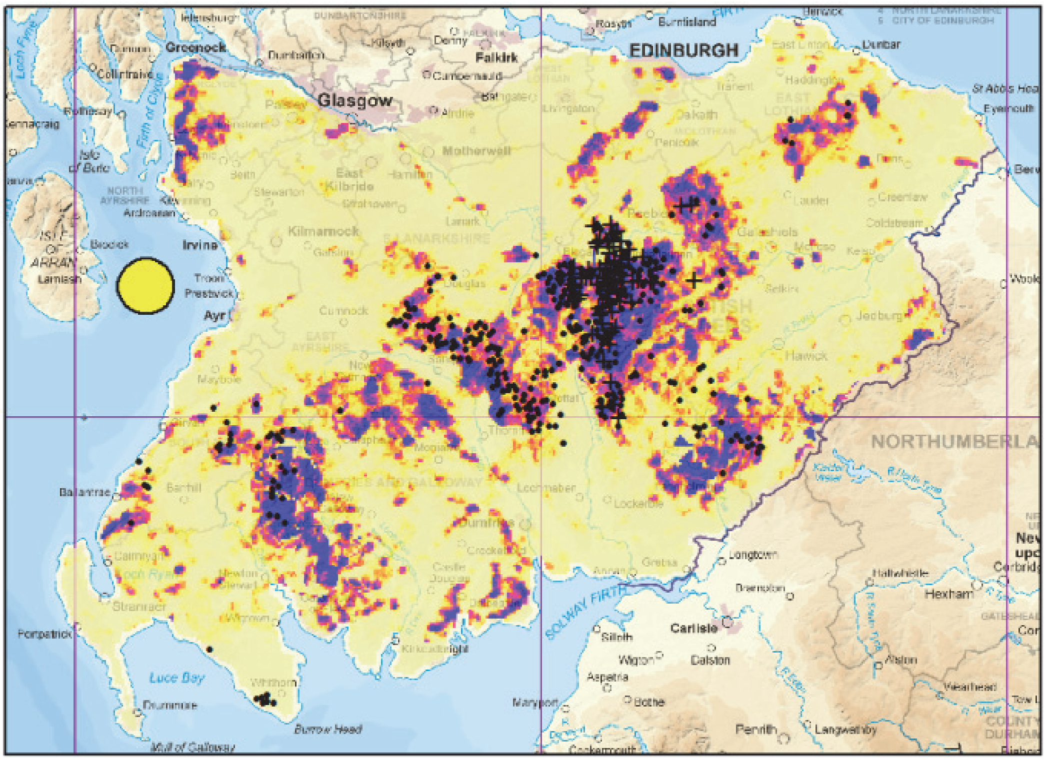


Figure 7a. Probability of active golden eagle breeding habitat from the random forest model with the full training data with golden eagle place names marked. The circle next to Arran has a 6 km radius (same as the notional maximum size in a PAT model).

Figure 7b is as Fig. 7a but with the approximate locations of Roxy during 2011 (dots) and 2012 (crosses).Contains Ordnance Survey data © Crown copyright and database right 2010.

4. ADDITIONAL CONSTRAINTS POTENTIALLY RESTRICTING GOLDEN EAGLE BREEDING

4.1 Introduction

The random forest model does not consider constraints that were not included as predictors. In this chapter we consider a range of factors that may either reduce the probability of breeding success or reduce the probability that apparently suitable habitat will be occupied.

4.2 Weather

There is little doubt that southern Scotland has experienced marked changes in its weather. In particular, it has become much wetter since the 1980s when the golden eagles were relatively successful (Table 2). For example, rainfall statistics from the Eskdalemuir weather station show that 2011 was the wettest year ever recorded, 66mm more than the previous wettest year in 1928. In addition, every month of 2011 saw above average rainfall levels. 2012 appears to be continuing this trend. It is not just rainfall totals that have changed. Fowler and Kilsby (2003) estimated that the magnitude of extreme rainfall has increased two-fold over parts of the UK since the 1960s such that rainfall intensities previously experienced every 25 years now occur at six year intervals with the largest changes being in autumn and spring. More recently, Schindler *et al.* (2012) suggested that there may be a trend to heavy rainfall events occurring earlier in the year in NW Scotland.

Weather is likely to have an influence on golden eagle breeding productivity. Various weather related parameters have been explored in conjunction with productivity data. Tjernberg (1981) suggested that in Sweden the good reproductive output in 1977 may be explained by favourable weather conditions that spring. Green (1996) suggested that the large reduction in productivity between the 1982 and 1992 national censuses, from 0.52 to 0.32 fledged per pair, was at least partly due to direct and indirect effects of the weather. It is worth pointing out that the order of magnitude in variation in productivity due to weather between 1982 and 1992 and between 2007 and 2008 appears to be as great as the productivity variation brought about by the variability in the differences in prey. Steenhof *et al.* (1997) found that rabbit *Oryctolagus cuniculus* abundance (the main prey) and the number of extremely hot days during brood-rearing were the variables most useful in predicting percentage of laying pairs that were successful. They also found that golden eagle reproduction was limited by rabbit abundance during approximately two-thirds of the years studied and that weather influenced how severely eagle reproduction declined in those years.

Whitfield *et al.* (2007) and Fielding (unpublished) suggested that climate change is most likely to affect Scottish eagles in the oceanic-influenced western Highlands and Islands. Haworth *et al.* (2009) expanded the earlier study by Watson *et al.* (2003) which identified relationships between productivity and weather that were inconsistent between regions. They also presented data which showed that, in some regions, low productivity is at least partially associated with an inability to convert eggs and young birds into fledged young. Almost certainly this is related to problems delivering prey to the nest or the incubating parent. These problems may result from a shortage of prey or increased difficulties catching prey. In this study we concentrate on how weather is likely to affect the delivery of prey to the nest at critical periods.

There are at least four periods in golden eagle reproductive phenology that could be influenced by the weather. First, there is the period before eggs are laid when females must accumulate sufficient resources to maintain body condition. The second begins once eggs have been laid. Watson (2010) suggests that two thirds of Scottish birds lay eggs between 16th March and April 4th. The laying date appears to have some plasticity and may be influenced by the February weather (Watson, 1997). Once eggs have been laid they must be protected from weather extremes and the male must usually obtain sufficient food for both parents (Collopy, 1984). Chicks seem to be particularly susceptible to weather events during the first 20 days (early to late May). For example, the female spends more time brooding young chicks when wind-chill is greater (Ellis, 1979). The potential effects of weather on the chicks should be expected to decline as the chicks grow, with fledging occurring from mid-July.

Therefore, given the potential importance of the weather in May, Haworth *et al.* (2009) investigated what relationship, if any, can be identified between productivity (number fledged per pair) and the May weather. They used eagle productivity data for a large area of Western Scotland (Skye, Mull, Lochaber and Argyll), which in combination represented about 25% of the national population. The majority of their analyses used mean estimates of productivity (number fledged per occupied range) and weather means derived from three Met Office weather stations (Paisley, Tiree and Stornoway). The analyses showed that productivity was significantly correlated across all four regions, suggesting that at least some of the factors influencing breeding success are large scale rather than range-specific. Weather is a good candidate for such a wide-acting factor.

Across all four regions mean golden eagle productivity was not significantly correlated with mean monthly temperatures for the early part of the year but was significantly, negatively correlated with the mean May rainfall total, although the strength of the correlation varied. The overall productivity of the combined regions was significantly correlated with the mean May rainfall total ($r = -0.528$). It is unlikely that May rainfall has an impact on prey abundance, instead its effects are probably related to a reduction in hunting success and possibly some direct effects on young birds in the nest.

On Skye, where there were good data, there was a clear negative relationship between the proportion of pairs fledging twins and the May rainfall total. This is additional evidence that May rainfall may be acting to reduce parental hunting efficiency and thereby affecting total productivity. There is some evidence for a similar mechanism in the American kestrel *Falco sparverius*. Dawson and Bortolotti (2000) showed that provisioning behaviour was not constrained by the abundance of food rather the availability of food since weather conditions appeared to significantly influence parental provisioning behaviour. In particular, during periods experiencing rain the parental prey delivery rates declined significantly as the duration of the period of rain increased.

Unless there are extremes, temperature is unlikely to have direct effects on golden eagles. However, there can be indirect effects related to changes in the number of growing degree days. Growing degree days is a measure of the accumulated heat above some base threshold and it is important because the development rate for many insects and plants depends upon the daily air temperature and its difference from a minimum threshold. It is possible, therefore, that a year with a larger number of growing degree days might have more prey because the food sources of potential prey (plants or insects) are more abundant.

Rainfall data were available on a 5 x 5 km grid from the Met Office for 1981-2006 and these data allow maps to be created that show how rainfall is unevenly distributed across the study region and how patterns have changed over time. Figure 8 has three maps for the spring period (April, May and June combined). The first map shows patterns of rainfall in 1981-1985, the second shows the pattern for 2001-2006 and the last one shows the mean over the period 1981-2006. The overall pattern is a west - east gradient but with higher rainfall totals over the hill regions, particularly the Galloway Hills. Because all three maps are drawn using the same colour scale it is also apparent that there have been enormous changes to the rainfall totals.

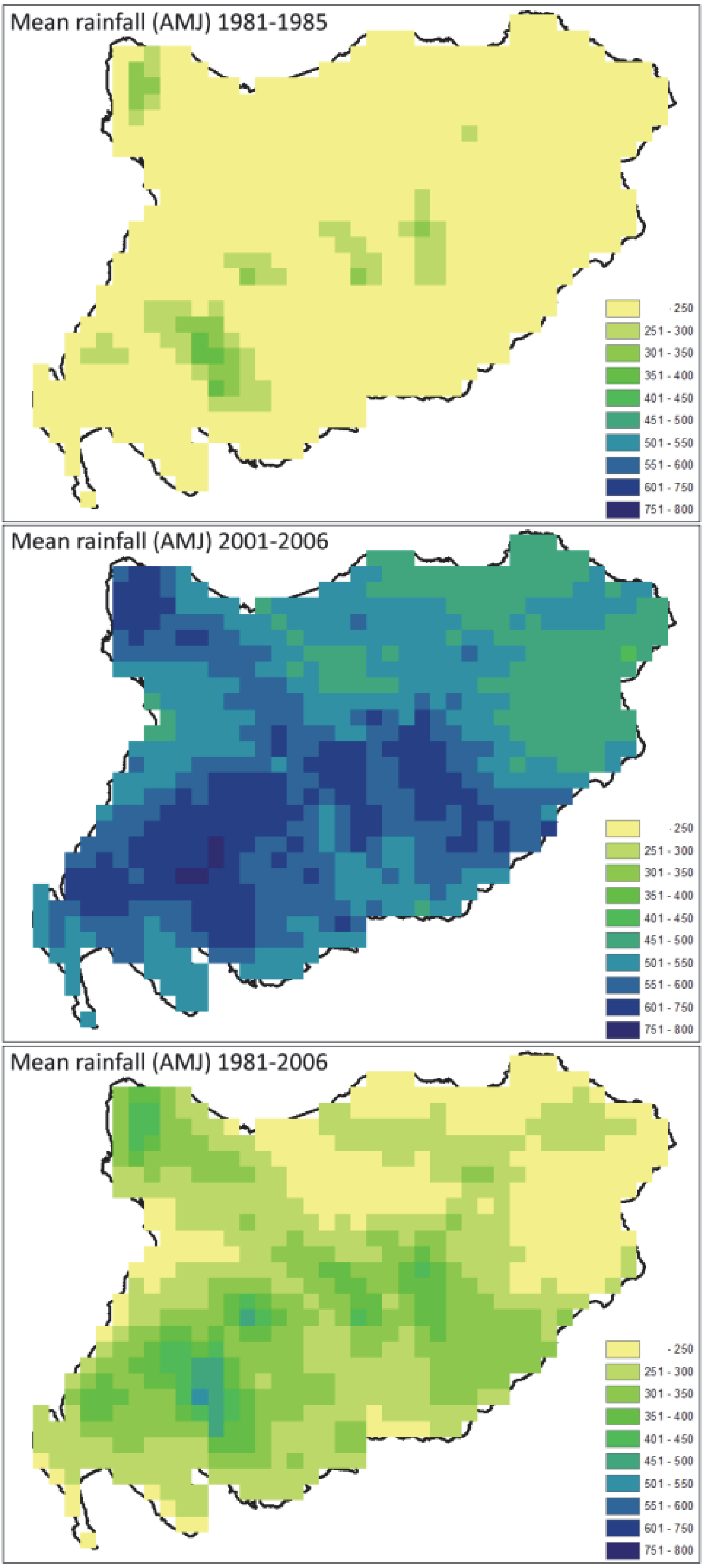


Figure 8. Mean rainfall (mm) for April, May, June for three time periods. Contains Ordnance Survey data © Crown copyright and database right 2010.

Rainfall totals between 1981-1985 and 2001-2006 have increased between 300 and 500 mm. The mean spring rainfall for 1981-1985 was 208 mm but this increased to 564 mm by 2001-2006. The third map in Fig. 8 and the change map in Fig. 9 show that most of the regions predicted to be suitable golden eagle breeding habitat have experienced disproportionately larger increases, particularly in the Galloway, Carsphairn and Lowther Hills. It is unlikely that such significant changes in rainfall, during an important stage of the golden eagle breeding season, would not have not affected the foraging ability of adults and, thereby, reducing the opportunities for successful breeding. Rollie (*pers. comm.*) notes that "*an underdeveloped 7-8 week old chick died in 2012 due to awful weather*." The effects of this additional rainfall would be exacerbated if prey were already at a low density.

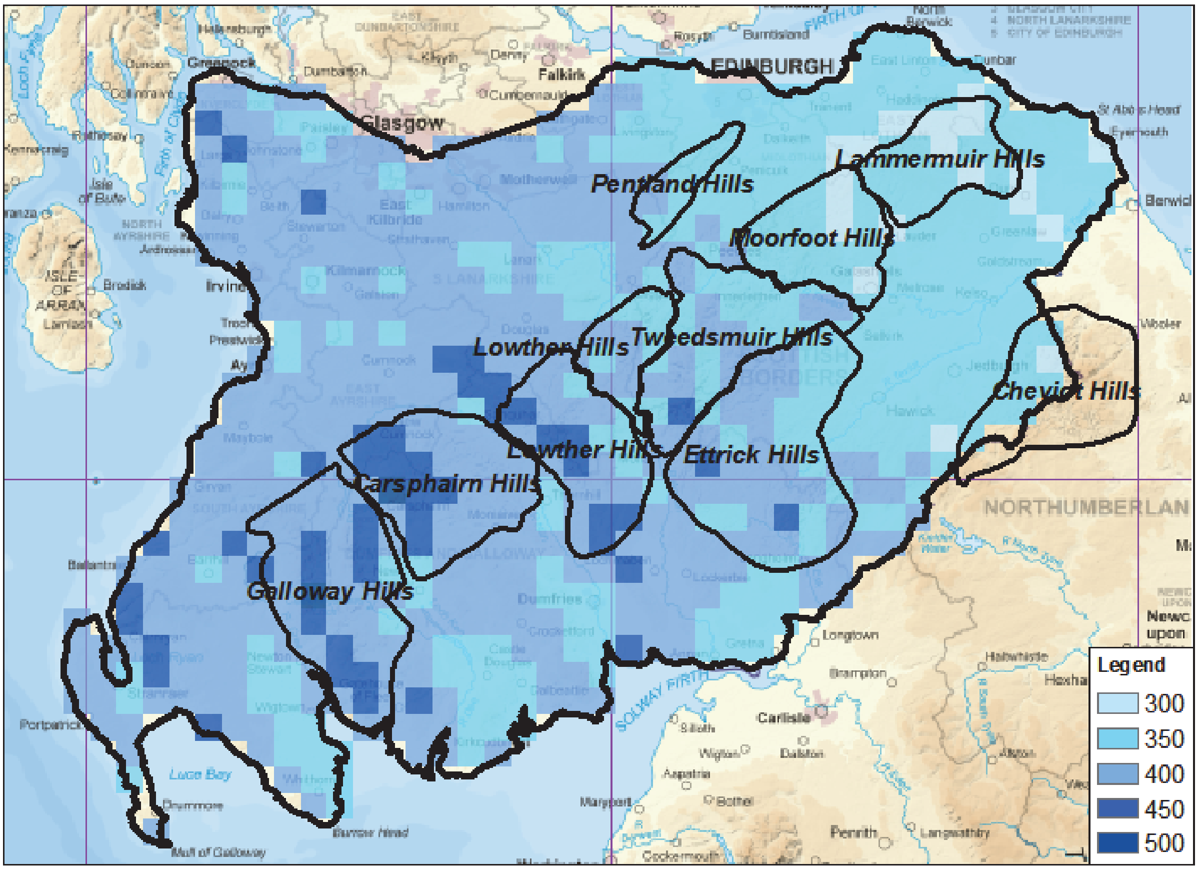


Figure 9. Increase in mean rainfall (mm) for April, May, June between 1981 and 2006. Contains Ordnance Survey data © Crown copyright and database right 2010.

Another source of evidence of changes in rainfall comes from the Eskdalemuir weather station. Fig. 10 appears to show that during the 1970s spring rainfall reduced but then went into a period of steady increase albeit with great variability. Indeed, 2010 was the fourth lowest since 1911 but 2011 and 2012 were in the 10 highest rainfall years. The evidence for annual changes (Fig. 11) is even starker. However, between year variability may now be exceedingly large. For example 2010 had a low rainfall total but 2009 and 2011 had the third highest and the highest rainfall totals for the period 1911-2011.

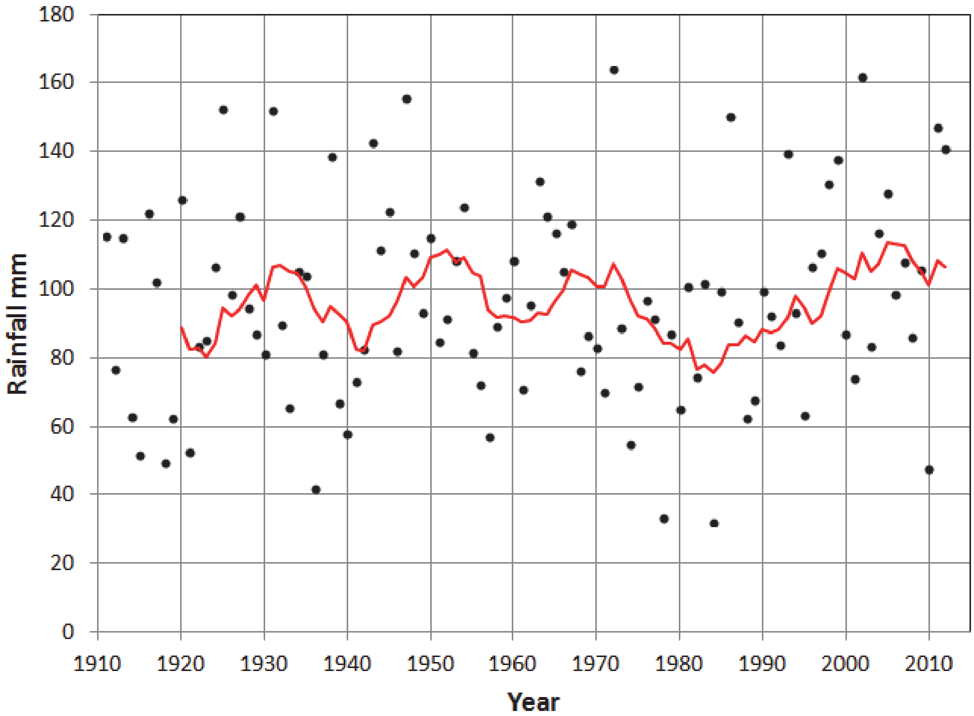


Figure 10. Eskdalemuir rainfall totals (mm) for April, May and June for 1911-2012 with a 10 year moving average.

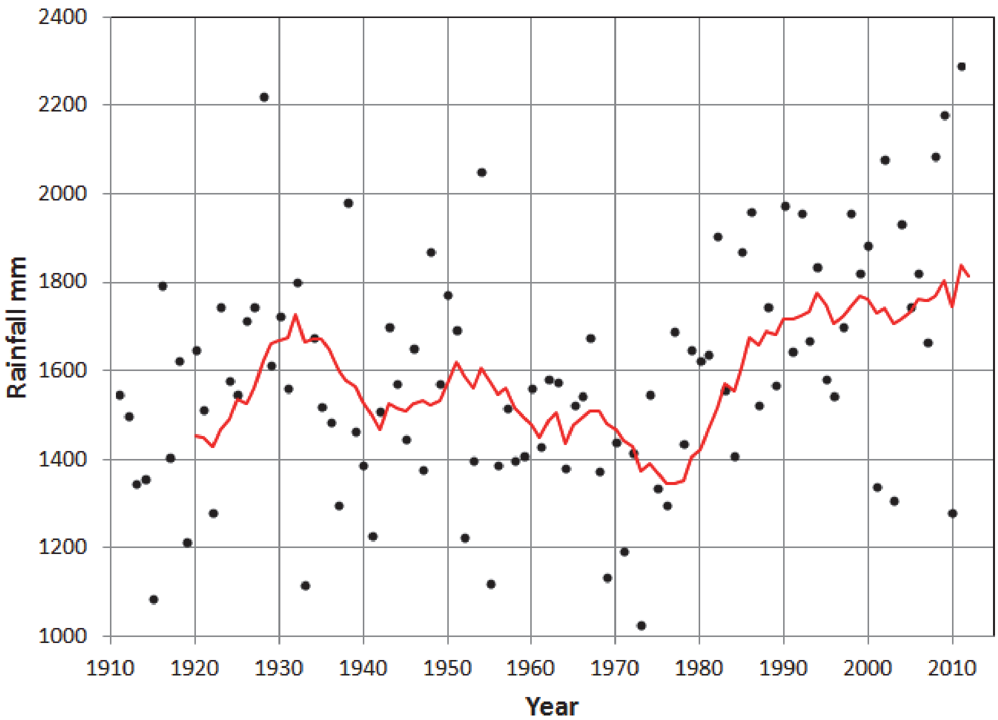


Figure 11. Eskdalemuir annual rainfall totals (mm) for 1911-2011 with a 10 year moving average.

Annual growing degree days, across the study region, have increased by an average of 184 growing degree days, or approximately 15% more between 1981-1985 (1,229 growing degree days) and 2001-2006 (1,413 growing degree days). However, the increase has not been universal (Fig. 12). All of the hill regions have had very small, or no, changes in the number of degree growing days while some lowland areas have had increases of over 300 growing degree days.

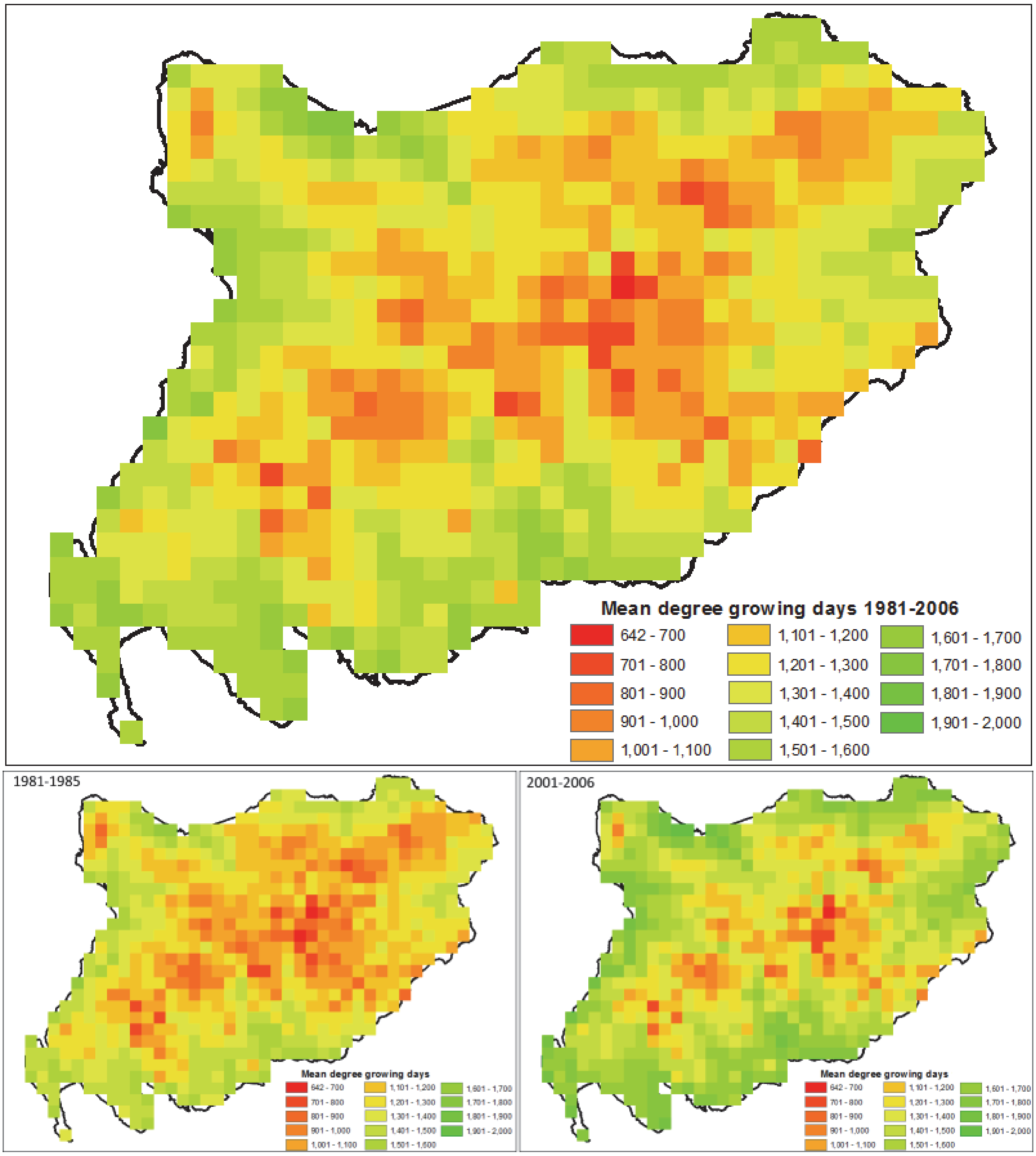


Figure 12. Mean number of annual degree growing days 1981-2006 (top) and two five year periods: 1981-1985 (lower left) and 2001-2006 (lower right).Contains Ordnance Survey data © Crown copyright and database right 2010.

Combining the rainfall and growing degree days changes suggests that it will have become increasingly difficult for golden eagles to capture prey across the hill ranges. This is a combination of no, or very little, increase in the number of growing degree days combined with spectacular increases in rainfall totals.

4.3 People, including recreation

Recreational impacts on golden eagles are very difficult to assess, not least because data on the timings and distribution of such activity is, at best, patchy even within a single range. Whitfield *et al.* (2006a,b), using the location of Munro mountains as a surrogate for recreational pressure, found no evidence, apart from the Northern Highlands, that range occupation was associated with either the proximity or the number of Munros in a range. It has been suggested that some ranges in the Cairngorm mountains, near to the Aviemore ski resort were abandoned after the ski lifts were installed but, conversely, golden eagles established a successful range near Haweswater in the English Lake District in a region that is renowned for the amount of recreational activity whilst, on Mull, one pair moved from a relatively secluded nest site to one that is very close (<200 m) to the main road across the island and is in full view from the road (and the many tourists who stop to observe it).

Other types of recreational activity, particularly hill climbing and hang gliding, possibly have greater potential to cause disturbance to golden eagles. A web search for climbing routes in southern Scotland did not identify many examples. The spreadsheet of crags listed in the climbers' guidebooks listed 35 crags, the majority of which (24 – seven winter and two all-year) were in the Galloway Hills. The Tweedsmuir Hills had eight listed, of which seven were winter climbs and are, therefore, less likely to disturb nesting eagles (though there is the possibility of disturbance from January onwards). There were only three other climbs, all summer climbs: one in the Lowther Hills and two in the Carsphairn Hills. If there were to be any conflict between climbing routes and nest sites these could be managed if a golden eagle reinforcement programme were operational.

In addition to the possible effects of recreational disturbance there is also the potential for disturbance arising from land management practices such as sheep gathering, muirburn and fox (*Vulpes vulpes*) control. The last would be an issue if, as in the Highlands, fox dens are below golden eagle crags. Sheep gathering will usually not cause harm as shepherds tend to pass through ranges quite quickly and a disturbed golden eagle is likely to return to its nest quite quickly. Muirburn and fox control could be more serious constraints on breeding than sheep gathering. However, both practices are now covered by the "reckless disturbance" provisions of the Wildlife and Natural Environment (Scotland) Act 2011. The recent addition of the golden eagle to the nest protection Schedule A1 of the 1981 Act also applies, making accidental disturbance less likely (or in the case of Schedule A1 nest protection, deliberate).

We have used two sources of information that may be useful as indices of *potential* recreational activity within each hill group. The first data source was footpath map data (Table 7). However, it must be realised that a full assessment of such data would incorporate information on the number of people using the footpaths, the times of day when they are used, presence of dogs and their visibility from, as yet, unknown nest sites. Second, we used three GIS layers from the SNH Wildness data sets: artefacts (the absence of the visibility of modern artefacts such as roads, rail and tracks; buildings and structures; pylons and wind farms); remoteness ("*the relative time taken to walk from the nearest public road or ferry landing... taking account of distance, relative slope, ground cover and barrier features such as open water and very steep ground*") and wildness ("*a scale of 1-256 indicating relative levels of wildness*"). Tables 7 and 8 summarise these data. Higher values, for all three measures, indicate land that is more remote, wilder and with fewer artefacts.

All but two of the hill groups had sections of long distance footpaths passing through them. The density of rights of way footpaths, which also includes large sections of the long distance paths, was below 0.3 (300 m per 1 km^2 of ground) in six hill groups and 0.4 in the Lowther and Lammermuir Hills. The Pentland Hills stand out as having a high density, a mean of 650 m of path per km^2. Bearing in mind the proximity of these hills to Edinburgh it seems likely that there may be considerable recreational activity.

Table 7. Length (km) and number (n) of rights of way paths per hill group. Density is the length of footpath (km) per km^2 of the hill group. LDFP is the length of long distance footpath (Southern Upland Way apart from the Cheviots which is the Pennine Way). Note that much of the LDFP network is already counted in the 'Claimed' category.

Hill group	Asserted	n	Claimed	n	Other	n	Total	n	Density	LDFP
Carsphairn			149.7	50	32.3	17	182.1	67	0.24	43.1
Cheviot			191.6	72	13.3	5	204.9	77	0.29	43.2
Ettrick			241.5	87	4.7	4	246.2	91	0.23	33.0
Galloway			279.1	178	46.1	14	325.3	192	0.36	34.7
Lammermuir	32.7	13	140.6	57	16.6	9	189.8	79	0.43	33.4
Lowther	0.9	1	298.3	99	51.4	15	350.5	115	0.40	51.5
Moorfoot			119.3	53	6.1	4	125.4	57	0.26	9.8
Pentland	10.3	8	83.3	39	14.3	11	107.9	58	0.65	
Renfrewshire	1.9	5	42.7	22	2.3	1	47.0	28	0.29	
Tweedsmuir			189.1	65	14.4	6	203.5	71	0.29	29.5

Table 8. Descriptive statistics for Artefacts, Remoteness and Wildness by Hill Group.

	Artefacts				Remoteness				Wildness			
Hill group	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD
Carsphairn	1	256	93.7	42.9	1	107	26.8	20.2	5	178	87.9	24.6
Cheviot	7	256	106.0	48.7	1	100	20.6	16.7	11	183	78.3	30.3
Ettrick	7	256	95.0	49.6	1	103	27.5	19.6	10	185	92.0	26.1
Galloway	6	256	96.0	43.1	1	135	35.2	29.1	11	191	99.6	23.8
Lammermuir	4	256	89.3	40.5	1	66	18.4	14.1	19	170	83.9	26.1
Lowther	4	256	104.8	53.4	1	97	26.7	18.1	8	179	96.2	28.3
Moorfoot	1	256	87.8	42.7	1	93	22.8	20.5	3	182	81.2	29.3
Pentland	7	256	108.1	40.9	1	70	25.9	15.6	19	170	97.1	28.0
Renfrewhire	6	256	87.6	52.5	1	105	18.0	19.1	2	185	78.4	33.0
Tweedsmuir	7	256	110.1	55.4	1	119	36.7	24.8	4	191	100.8	32.9

Table 9. Hill groups ranked by their combined 'wildness' indicators.

Hill group	Artefacts	Remoteness	Wildness	Combined
Tweedsmuir Hills	10	10	10	30
Galloway Hills	6	9	9	24
Pentland Hills	9	5	8	22
Lowther Hills	7	6	7	20
Ettrick Hills	5	8	6	19
Carsphairn Hills	4	7	5	16
Cheviot Hills	8	3	1	12
Lammermuir Hills	3	2	4	9
Moorfoot Hills	2	4	3	9
Renfrewshire	1	1	2	4

The Lammermuir, Moorfoot and Cheviot Hills, combined with the Renfrewshire Heights stand out as having much less wild land than the other hill groups (Tables 7 & 8). When the hill groups are ranked on the three measures the Tweedsmuir Hills consistently come out as the 'wildest'. When combined with the relatively low footpath density (Table 7), this suggests that this hill group is likely to experience the least recreational activity. However, it is also the location of the very well-used and publicised Glentress and Innerleithen mountain biking centre. Apart from artefacts, the Galloway Hills scores highly on the wildness indicators and is second ranked. The Pentland Hills have the third highest rank but score low on remoteness, perhaps reflecting the high density of footpaths and proximity to roads. The remaining three hill groups have mid-scores for all three measures, although both the Lowther and Carsphairn Hills have relatively low footpath densities.

4.4 Forestry

Golden eagles are large raptors that gather much of their prey in open habitats. Consequently, any activity or process that reduces the availability of open habitats may reduce their ability to forage successfully. Commercial afforestation is one such process and it has been associated with reduced breeding success and territory abandonment. Marquiss *et al.* (1985) working in the Galloway Hills, showed that large-scale conifer afforestation in the 1970s coincided with reduced breeding success of three of four pairs of eagles. Watson (2010) found that breeding success of golden eagles in Argyll was negatively related to the amount of commercial conifer plantations that were over 10 years old. However, Pedrini and Sergio (2001), working in the Italian Alps, found no relationship between forest cover and breeding success. In a detailed study that followed the spatial pattern and timing of afforestation on the island of Mull, Whitfield *et al.* (2001) found no overall relationship between productivity and afforestation. They suggested that, because productivity varied between territories in the absence of forestry, it was unlikely that a simple relationship between breeding success and forest cover would be identified.

In the Swedish mountain areas golden eagle density, above or close to the tree-line, was over twice as high as in areas of extensive forest (Tjernberg, 1985). Watson *et al.* (1987) estimated that six of seven eagle territories vacated during the 1960s and 1970s, in Argyll, contained over 40% plantation forest cover within 4 km of the range centre. In the same region, only three out of 15 occupied ranges had over 40% forest cover (Watson *et al.,*1987). Extrapolating from these observations, Watson *et al.* (1987) predicted that Argyll would lose a further five territories by 1997. There is little evidence that this has happened, indeed the Argyll golden eagle population is increasing (Haworth and Fielding, unpublished data) Whitfield *et al.* (2001) suggested that eagle responses to forest expansion was more complex, and advised against using simple criteria when predicting the continued occupancy of a range as forest cover expanded. Instead, using an approach based on the PAT model, they highlighted the importance of opportunities for a pair of eagles to compensate for the loss of a part of their territory. Such compensation would be difficult if a pair was constrained by surrounding neighbouring pairs but in the absence of neighbours, and with some favourable habitat, they may be able to adapt their range to compensate for the forest cover effects. In a subsequent piece of work, Whitfield *et al.* (2007) found that range abandonment was related to previous productivity. Ranges with a poorer breeding productivity history appeared to be more vulnerable to abandonment. Although productivity of individual territories showed no clear relationship with forest cover there was a relationship at the landscape scale with breeding productivity being negatively related to the extent of forest cover. Whitfield *et al.* (2007) also found that an increase in forest cover of less than 5% could be related to reduced productivity. However, some territories least constrained by neighbouring pairs of eagles showed an increase in productivity even when the forest cover of the original range increased. Territories experiencing the greatest increases in forest cover showed a greater use of spatially separated nest-sites by occupying pairs.

In this work we examine the potential effects of afforestation by again using the PAT model. We estimate the potential loss of ranging habitat as the sum of weighted range use covered by forest. Eight ranges recently used by golden eagles and 32 of the named ranges in Evans *et al.* (2012) are considered. For the actual ranges we used the range centre to model the range while we used the centre of the reported 1 km square for the 32 putative ranges. Unlike the earlier work by Whitfield *et al.* (2001, 2007) we have not examined dynamic changes in forest cover. Instead we built two PAT models for each range. The first assumes no forest cover and a PAT model is built using a 6 km radius circle, i.e. neighbouring ranges are not considered. The second uses the current extent of woodland cover as defined by the most recent Ordnance Survey Strategi Shape woodland region habitat. Woodland cover is used as an exclusion zone in the PAT model and a new ranging model is built. Subsequently, losses to the unconstrained range are found from the sum of weighted use for pixels covered by the forests. The full set of PAT maps is shown in Annex 3.

The percentage loss of eagle habitat and putative golden eagle ranges are shown in Table 10. All of the recent golden eagle ranges have experienced significant reductions in potential ranging habitat. However, some of this woodland would have been present while the ranges were occupied and productive. If annual forest cover data were available for the periods while these ranges were occupied it would be possible to examine the thresholds at which ranging losses were associated with the cessation of breeding or range abandonment.

Table 10. Percentage loss of ranging habitat due to woodland cover. The percentage loss is the sum of the weighted use pixels covered by woodland.

Name	Hillgroup	Range loss %
G/DG4	Galloway Hills	8.6
G/DG6	Tweedsmuir Hills	9.6
G/DG5	Ettrick Hills	11.8
G/DG3	Galloway Hills	16.9
G/LB2	Tweedsmuir Hills	23.8
G/DG2	Galloway Hills	41.5
G/DG1	Galloway Hills	44.8
G/EO4	Kielder	65.1
Henshaw Burn	Pentland Hills	0.1
Yearn Cleugh	Lowther Hills	0.2
Yearning Law	Cheviot Hills	2.2
Yearny Knowe	Tweedsmuir Hills	2.5
Yearn Stane	Renfrewshire Heights	2.8
Hen Hole	Cheviot Hills	4.4
Earn Craig	Lowther Hills	5.3
Yearn Cleugh	Lowther Hills	5.6
Yearning Cleugh	Cheviot Hills	5.8
Earn's Cleugh	Lammermuir Hills	7.2
Earn Cleugh	Tweedsmuir Hills	7.6
Earn Law	Lowther Hills	7.8
Earn Hope	Ettrick Hills	10.9
Ern Cleuch	Ettrick Hills	10.9
Benyellary	Galloway Hills	12.7
Earnhope Slack	Moorfoot Hills	15.2
Yearn Gill	Lammermuir Hills	16.8

Ern Cleugh	Carsphairn Hills	17.0
Yearn Gill	Lowther Hills	18.3
Earn Hope	Tweedsmuir Hills	18.6
Earn's Gill	Lowther Hills	19.6
Ewlairs hill	Lammermuir Hills	21.7
Earn Cleugh	Tweedsmuir Hills	23.0
Yearn Craig	Lowther Hills	29.7
Earn's Cleugh	Moorfoot Hills	45.6
Ewelairs Hill	Ettrick Hills	47.3
Yearn Craig	Carsphairn Hills	61.3
Earn Cleugh	Tweedsmuir Hills	63.2
Erne Sike	Kielder	69.5
Petillery Hill	Carsphairn Hills	81.2
Yearning Flow	Kielder	86.7
Yearning Sike	Kielder	88.9

The average loss of ranging habitat differed markedly between ranges in different hill groups (Table 11). In the Kielder and Carsphairn ranges the average loss was more than 50% while those in the Moorfoot Hills had an average loss of more than 30%.

Table 11. Average loss of ranging habitat due to woodland cover. N is the number of ranges modelled.

Hill Group	Average Loss	N
Kielder	77.6	4
Carsphairn Hills	53.2	3
Moorfoot Hills	30.4	2
Galloway Hills	24.9	5
Tweedsmuir Hills	21.2	7
Ettrick Hills	20.2	4
Lammermuir Hills	15.2	3
Lowther Hills	12.4	7
Cheviot Hills	4.1	3
Renfrewshire Heights	2.8	1
Pentland Hills	0.1	1

Creating woodland cover on open land is not always detrimental to eagles and there are a small number of woodland schemes in the study area that have the potential to benefit eagles by improving the prey base largely as a result of reductions in sheep grazing and the subsequent vegetation growth. For example, the Carrifran woodland regeneration scheme, organised by the Border Forest Trust (BFT) has planted over half a million trees in an area of 300 ha around Carrifran valley, between Saddle Yoke and White Combe, with the aim of developing one of the very few extensive areas of treeline woodland and montane scrub in Britain. Since this is one of the zones with the highest probability of containing breeding golden eagle habitat the effects of this management on eagle prey could be very important, particularly as the head of the glen has apparently suitable breeding crags ("Raven Crag"). According to the project's ecological restoration information there are no rabbits and the evidence of only slight damage by brown hares (*Lepus europaeus*) and mountain hares (*L. timidus)* may mean that their populations are small; perhaps, they suggest, because of the prevalence of foxes. There are no red deer (*Cervus elaphus*), and roe deer (*Capreolus capreolus*) have been subjected to intensive culling since 2004. However, it appears that the associated reduction in sheep grazing has "*caused a significant increase in black grouse, and possibly red grouse too*" (C. Rollie, *pers. comm.).*

The BFT has also recently started another project at Corehead (Devil's Beeftub) where the BFT plans to "*restore native woodlands in appropriate areas, montane scrub on the high tops, and heather moorland and wetland wherever possible*". The plans to reduce grazing may help to encourage the establishment of more eagle prey. If these projects prove beneficial to golden eagles they could provide a template for more extensive, proactive, management elsewhere in southern Scotland.

The Scottish Borders Woodland Strategy Steering Group (2005) has produced the Scottish Borders Woodland Strategy (SBWS) with the aim of informing planning and policy guidance for future woodland planting and woodland restructuring within part of the study region. Although there is emphasis on biodiversity benefits the strategy makes no specific reference to golden eagles. Nonetheless, there is a recognition that woodland expansion needs to be regulated. For example, the report (p 35) notes that "*there is a 'de facto' justification for expansion....almost anywhere in the region*" but that this should not happen when there would be "*direct conflict with other land use priorities or sensitivities including important open-space habitats and those species that depend upon an absence of trees*". Indeed, most of the 'Sensitive' areas on the SBWS map of 'Opportunities for woodland expansion for upland/upland fringe forests' coincide with areas predicted to be suitable golden eagle habitat (Fig. 7a). There is, however, a potential for a reduction in eagle prey given the perceived need for herbivore management to assist woodland expansion (p. 44). All of the species listed as potential problems are suitable eagle prey.

4.5 Wind farms

Wind farms may have impacts on the Scottish golden eagle population via a combination of displacement/disturbance and additional mortality which may apply to both range holding birds and the more free-ranging non-breeding adults and sub-adults. Displacement effects can be equivalent to the type of habitat loss arising for plantation forests. In their SNH-commissioned review of the impacts of wind farms on golden eagles, Fielding and Haworth (2010) concluded that the major impact in Scotland was likely to be habitat loss resulting from displacement away from land around the turbines. The evidence from Skye, which relates to non-breeding golden eagles, is that displacement operates at a scale of approximately 500 m around turbines (Haworth and Fielding 2012).

The method used by Fielding *et al.* (2006) to assess the potential loss of non-breeding golden eagle habitat to wind farms has been refined. The original approach used spatial overlap between habitats defined as non-breeding habitats (essentially upland habitats but excluding plantation forests) and loss was estimated on a simple area basis, i.e. all parts of the non-breeding habitat were assumed to be equal. If ridge habitat, identified in section 2.3.1, is relatively more important to eagles the resultant area loss should be adjusted by its relative value. In the revised calculations a weighted-distance-to-ridge map is used to measure loss of habitat. This means that a wind farm positioned along a ridge would lead to a greater habitat loss than the same wind farm positioned away from a ridge. This revised approach is, therefore, similar to that used to assess the potential losses due to conifer plantations (section 4.5). Table 12 summarises the percentage of distance-weighted ridge habitat that would be lost in each hill group for four categories of wind farm (SNHi September 2012 database).

Only the G/DG6 range currently has any proposal within 6 km of the range centre. This is the Earlshaugh wind farm which is in the application phase. All other wind farms, and much of the Earlshaugh wind farm, are on land not considered to be part of a known golden eagle range and would therefore only contribute to a habitat loss/collision risk for non-breeding golden eagles.

If all of the wind farms in the September 2012 database were constructed the loss of ridge habitat would be approximately 6% of the regional total. This loss is mainly attributed to wind farms currently in application or scoping (2.4% and 1.4% respectively). Installed and approved wind farms are predicted to result in a 2% loss of ridge habitat. This is unlikely to result in a significant threat to any recovering population and there is little overlap between the wind farm locations and the recorded locations for the satellite tagged Roxy in 2011. Predicted losses are not evenly spread across hill groups. As a percentage of all ridge habitat in a hill group, the Lammermuir, Lowther and Carsphairn Hills are predicted to have a greater than 10% loss. In the case of the Lammermuir Hills a greater than 10% loss is predicted for wind farms that have been installed or approved.

Table 12. Loss of ridge habitat to wind farms (September 2012 database). Figures are percentage of the weighted ridge habitat in each hill group for four categories: A - Installed; B - Approved; C - Application; D - Scoping. The second column, % ridge habitat, shows the percentage of the region's ridge habitat in the hill group.

Hill group	% ridge habitat	A	B	A+B	C	D	All
Carsphairn Hills	6.9	0.84	1.74	2.6	2.87	5.63	11.1
Cheviot Hills	1.3	0.00	0.00	0.0	0.23	1.84	2.1
Ettrick Hills	13.7	0.00	0.14	0.1	1.86	0.00	2.0
Galloway Hills	13.8	0.00	0.00	0.0	0.00	0.05	0.0
Lammermuir Hills	3.8	7.67	3.05	10.7	6.19	1.09	18.0
Lowther Hills	11.5	0.04	7.52	7.6	7.11	0.17	14.8
Moorfoot Hills	4.5	1.07	0.00	1.1	0.13	0.95	2.1
Pentland Hills	2.1	0.00	0.00	0.0	1.97	0.47	2.4
Tweedsmuir Hills	14.1	0.00	0.00	0.0	1.95	0.00	2.0
None	28.5	0.81	1.07	1.9	2.14	3.00	7.0
All		0.63	1.42	2.1	2.44	1.38	5.9

Table 13. Percentage loss of ridge habitat (measured as the sum of ridge pixel weights) when wind farm and woodland losses are combined. A includes wind farms in all stages of the planning process (SNH September 2012 database) while B excludes those at the scoping and application phases.

Name	% Lost A	% Lost B
Carsphairn Hills	42.3	31.9
Galloway Hills	38.3	38.0
Ettrick Hills	36.5	35.7
Lowther Hills	30.9	23.3
Tweedsmuir Hills	27.0	23.1
Moorfoot Hills	18.9	16.2
Lammermuir Hills	17.8	12.8
Cheviot Hills	4.6	0.0
Pentland Hills	2.4	0.3

Six hill groups have predicted losses of less than 3% and these hold almost 50% of the total ridge habitat. These hill groups also have very few or no predicted losses to currently installed or approved wind farms.

If the amounts of ridge habitat lost both to wind farms and woodland cover are combined it is clear that, apart from the Pentland Hills, quite large proportions have been, or will be, lost (Table 13). Two calculations were used for the wind farms: A includes wind farms in all stages of planning (SNH September 2012 database) while B excludes those at the scoping and application phases. Differences between the two percentages reflect the possible losses due to wind farms that are in early stages of the planning process. The largest differences are in the Carsphairn and Lowther Hills. Not all of the new wind farm developments are additional losses because some are planned in existing woodland.

4.6 Prey

If golden eagles are to become established as a non-sink population in southern Scotland they will need, amongst other things, a sufficiently robust and abundant prey base. It is clear that both the abundance and identity of food resources influences the density and productivity of golden eagles. In several parts of Scotland, e.g. Morven, there is a relatively high density of eagles but productivity is consistently very low (e.g. one fledged young from 10 pairs) almost certainly as a consequence of a low prey base. Although an adequate supply of carrion may be sufficient to enable pairs to survive for long periods without producing any young, a suitable supply of live prey is necessary for successful reproduction. Therefore, a more detailed understanding of prey resources is essential to target the best areas from those identified in this report. However, it is important to understand that even if significant resources are targeted at understanding prey the information return is likely to be qualitative and comparative rather than robustly quantitative.

In the early 1990s there were several attempts to quantify the diet of the Galloway pairs in the face of declining productivity. Rollie *et al.* (1994) reported on prey found in the Dumfries and Galloway nests B and D between 1983 and 1993. Although they have some important caveats about the robustness of the data, they were able to identify some general trends. Firstly, lagomorphs appear to have been the most important prey item during the nestling period, forming 41% of all items, by number, recorded at pair `B', and 53% of those at pair `D' including a total of 39% of rabbits. Red grouse appeared to be more important for pair `B', forming 26% of recorded prey items, compared with 14% for pair `D'. Other non-passerine birds (including duck, gulls, waders, pigeon and pheasant) accounted for roughly similar proportions of recorded prey items at each site, namely 16% (pair `B') and 17% (pair `D'). There were few records from nest C but the three records were all birds: one greater black-backed gull, one unspecified gull and one black grouse. Shaw (1994) reported on an analysis of pellets from the three extant ranges (B, C & D) using information from pellets collected between August 1992 and October 1993. Lagomorphs were the most important component in the pellets for all three pairs at all times of year, contributing between 37%-65% of the recorded items. When they could be separated, rabbits were the majority for pairs B & D while, in range C, hares were the majority item. Other species identified included deer, goat *Capra aegagrus hircus*, sheep, 'other' mammal, grouse and 'other' birds. The RSPB assessed potential prey availability in the same three ranges (McGrady 1994). Prey was assessed while walking transects (38 km in pre-thicket forest, 32 km in ungrazed open ground and 142 km in sheep grazed open ground). Range B had more encounters with deer and grouse while C had more sheep and goats. Range D had more encounters with lagomorphs and corvids. The amounts of carrion were the same in each range. Despite the considerable surveying effort the data were deemed to be of insufficient quality to make any statements about actual prey numbers, largely because encounter rates were low and it was difficult to survey rare habitats with sufficient effort.

Haworth *et al.* (2009) and Whitfield *et al.* (2009) demonstrated that, contrary to common perceptions, golden eagle productivity was not linked to diet specialisation. Instead it appears that prey abundance is important and diet specialisation is an inevitable outcome when a small number of prey items are super-abundant. These two studies concentrated on pairs in the Inner and Outer Hebrides and found that failed breeding attempts occurred most frequently during incubation or with small young. There is relatively little information on the timing of nest failures. Payne and Watson (1983) recorded that, in 1982, 21 of 25 pairs (84%) in NE Scotland laid eggs, of these three nests failed to hatch young (85.7% of eggs hatched) and 15 nests fledged young (71.4% of eggs converted to fledged young). Lockie (1964) describes the death of two young eagles at six weeks which he ascribes to a shortage of food. Fernández (1993) examined the impact that rabbit viral haemorrhagic disease had on golden eagle productivity. The main impacts were on the proportion of pairs laying eggs, reduced from 84% to 67%, and also on the proportion of successful pairs, reduced from 59% to 31% largely because of an increase in failures during incubation.

Marquiss *et al.* (1985) recorded quite large proportions of lagomorphs in the diet of eagles in Galloway. If rabbit or lagomorph abundance has declined since that study it may have had some impact on their productivity. However, it has to be realised that neither grouse nor hares are a prerequisite for golden eagle range occupation or productivity. This is obvious because Skye has more than 30 pairs but the hare population is in a precarious state and red grouse are not abundant (Haworth and Fielding, unpublished data collected for SNH).

Corkhill's (1980) interpretation of the causes of breeding failure on Rum also raises the need for caution when interpreting data from the 1950s and 1970s. He shows that five of 28 breeding failures (18%), between 1957 and 1978, were because eggs were not laid. A further nine (32%) were due to broken eggs and twelve (41%) resulted from addled eggs. Only two (7%) were a result of chick death. Corkhill (1980) provides evidence to suggest that these failures were not the result of a shortage of food. Rather, they arose as a result of contamination by toxic residues derived from their seabird prey. Similarly, and more worryingly, Nygård and Gjershaug (2001) found relatively strong negative correlations between reproductive output and shell thickness and DDE concentration in eggs from ranges in western Norway (1973-1999). They suggest that their data indicate that the golden eagle may be a particularly sensitive species to DDE and that the higher organochlorine content found in the eggs of coastal birds was a result of a diet that includes marine birds. Both studies build on the pioneering work of Ratcliffe (1960) who had noted that eggs of golden eagles were sometimes broken in the nest by incubating females during the 1950s and Lockie and Ratcliffe (1964) who demonstrated that reduced reproductive success in golden eagles, in the Scottish Highlands in the 1960s, was due to organochlorine compounds arising from the use of dieldrin in sheep dip. Although dieldrin levels have been greatly reduced in seabirds, DDE levels can still be elevated in seabirds (Leat *et al.* 2011), especially those that winter off west Africa where DDT is still in use (Leat *et al.* 2013), and methyl-mercury levels remain high in many seabirds, and so it is possible that golden eagles feeding heavily on seabirds may accumulate toxic burdens of DDE or mercury.

Marquiss *et al.* (1985) examined the factors associated with a reduction in breeding in SW Scotland. Although they thought that afforestation was the principal cause they suggested that good breeding performance was associated with spring (pre-breeding) diet with the most productive pairs consuming more live prey and less carrion. Although based on a small sample, Pout (1998) suggested that adult golden eagles may have a diet that contains a significant proportion of carrion at the same time that they are feeding the young eaglet with live prey. However, he also thought that adult eagles favoured live prey over carrion during the pre-breeding period. Tjernberg (1981) suggested that, whether breeding occurs or not, is probably determined by prey abundance early in spring just before eggs are laid. Steenhof *et al.* (1997) also found that the percentage of pairs laying was related positively to jackrabbit abundance and inversely related to winter severity.

In the more northern regions, e.g. Alaska and Scandinavia, breeding success is closely linked with the availability of live prey, primarily because major prey species at higher latitudes often have marked abundance cycles that are much less clear in, or absent from, Scottish prey species. For example, Tjernberg (1981), working in northern Sweden (1975–1980) found that the proportion of golden eagle pairs with successful breeding (21%–85%) and the number of young produced per occupied territory (0.27–1.24) varied greatly between years. Productivity in the northern pairs was significantly correlated with the total hunting bag of small game species. However, this was not the case in more southerly pairs. The lack of a correlation was thought to be due to a good reproductive year (1977) when small game species were scarce. Tjernberg (1981) thought that this may be explained by favourable weather conditions that spring. Nystrom *et al.* (2006), also working in northern Sweden, examined the relationship between prey density fluctuations and golden eagle productivity. Even though the available prey diversity was low, pairs maintained a relatively broad food niche. Most main prey species (Microtine rodents, hare and ptarmigan *Lagopus muta*) had similar population fluctuations and golden eagle breeding success was correlated with the annual density index of the most important prey category, the ptarmigan.

Lockie (1964) thought that in the relatively poor regions of Wester Ross, that may equate with the southern Scotland prey base, there was variation in the amount of live prey and carrion and that in "*good years*" the combination of live prey and carrion would be sufficient to allow reproductive success for the golden eagle. Brown (1969) came to a similar conclusion in that he suggests that the supply of food *"appears rather scare in Sutherland compared with the Eastern Highlands*" but that the difference changed between years. He identified 1967 as a year in which there seemed to be very little live prey with a possible ten-fold reduction compared with the period 1958-1960. However, he thought that it was unlikely that there was less than 5,000 kg of carrion per territory, a figure that would allow birds to continue their occupation despite the scarcity of live prey.

Lockie writing in 1964 said that it was clear "*from the writings of sportsmen*" that wildlife, in NW Scotland, was much more abundant in the early 19th century. However, Lockie also noted that, despite the decrease in live prey, there were more foxes and golden eagles than previously. Lockie quoted Darling (1955) to suggest that the reduction in live prey arose as a consequence of increasing sheep density combined with excessive burning that has destroyed much of the cover needed by many prey species. Lockie (1964) thought that eagles would be more likely to take larger lambs, outside of their preferred prey size-range, when live prey and carrion were scare. Watson (1997, p 141) suggested that the tendency for golden eagles in the United States to lay larger clutches is due to the better food supply and that there is evidence that clutch sizes have declined in Scotland since the middle of the nineteenth century. Indeed, Ratcliffe (2007) described regular clutches of three eggs in one of the Galloway nests in the 1980s. A decline in clutch size is consistent with the types of habitat degradation described by Lockie (1964) and others.

There has been discussion and speculation previously as to how much prey is required for a productive eagle range. McGahan (1967) working in south-central Montana, recorded that one pair of eagles brought an estimated 490 g of edible food mass per eagle per day to a nest during a 39-day period. Each eagle took an estimated 40-49 prey individuals over a 100-day period, with lagomorphs being the most important species. Brown and Watson (1964) estimated that a pair of eagles needed 174 kg of live prey and carrion per year. Brown (1969) expanded on this by suggesting that another 54 kg was required if an average of 0.8 young per year were reared plus an additional 43 kg for sub-adult birds using the territory intermittently. Takeuchi *et al.* (2006) had a larger figure for the young bird. Using video recordings at nests they showed that there was temporal change in prey selection during nestling periods, but with similarities in later deliveries of snakes and in total prey weights (83.7–89.9 kg) delivered to successfully fledged broods. This is more similar to the figure that can be extrapolated from Collopy (1984) who gave a mean delivery of 1.42 kg per day (approximately 100 kg). However, these are delivery and not consumption figures so a lower figure is presumably adequate. Indeed, Collopy (1984) quoted a much lower figure of 0.885 kg per day given by Lockhart. Even after making allowances for the assumed 0.8

fledging, the adjusted figure for Brown and Watson (1964) remains lower at 67.5 kg. Similarly, Fevold and Craighead (1958) arrived at a larger figure for adult birds. They fed captive golden eagles mainly venison during autumn and winter. Extrapolating from their figures gives annual requirements of 112 kg (female) and 96 kg (male) or 208 kg for a pair. If the average range areas per pair quoted by Brown and Watson (1964) are used (4613 ha – 7273 ha) their food requirement estimates equate to only 0.06 and 0.04 kg prey ha^{-1} $year^{-1}$. Even if Brown and Watson had made a large underestimate it seems unlikely that such small quantities are not reached, even in degraded habitats. Indeed, using more conservative estimates the requirement is still less that 8 kg per km^2 per year. Brown and Watson (1964) recognized this and noted that the average food potential in all areas is greatly in excess of the requirements. However, they also recognized that live prey may be relatively scarce in some western areas and that this is offset by the amounts of carrion. The statement that "*large differences in food potential between areas do not correspond with differences in eagle density*" was later refined by Watson *et al.* (2010) who showed a correlation between eagle density and carrion abundance. It must also be remembered that eagles need to find the food, so that there will be some critical prey density that will be required in their home range that is greater by an unknown factor than the amount they actually consume.

There is limited evidence from Mull that, at least for some ranges, sheep removal has had little measurable negative impact on golden eagle productivity. At one range sheep and deer were removed in 1995 to facilitate large scale landscape regeneration. This pair has continued to breed successfully averaging more than one chick per year from 1997 onwards. More recently sheep have been reduced to very low numbers across three other ranges in central Mull and in 2008 these three produced five young. At another range in north Mull extensive afforestation by broadleaf native woodland of a large part of the range three years ago coincided with the pair laying eggs for only the second time in almost 30 years and then breeding successfully in both 2007 and 2008. However, it is essential that monitoring of such ranges continues over a much longer period to determine if such improvements are transient or more general.

The relationship between breeding productivity and land management is complex. In general, however, deer are most likely to exert an indirect influence on prey abundance and availability through grazing pressure either on their own or most frequently in combination with sheep and burning. Unfortunately neither sheep statistics nor deer counts correspond to golden eagle range boundaries making it difficult to assess accurately the impacts of varying levels of grazing upon breeding productivity. Differing levels of grazing intensity are likely to have different impacts on the various key groups of potential prey, particularly hares and rabbits, and this in itself will vary from region to region.

If it is assumed that vegetation productivity is an adequate surrogate for the potential abundance of prey, both live and carrion, the NDVI is one of the few measures that provides a reliable indicator at the landscape, rather than very local, scale.

Figure 13 shows the mean NDVI statistics for the study area over an 11 year period. Woodland cover is shown on the map because woodlands tend to have large amounts of chlorophyll, leading to a high NDVI, but relatively little eagle prey.

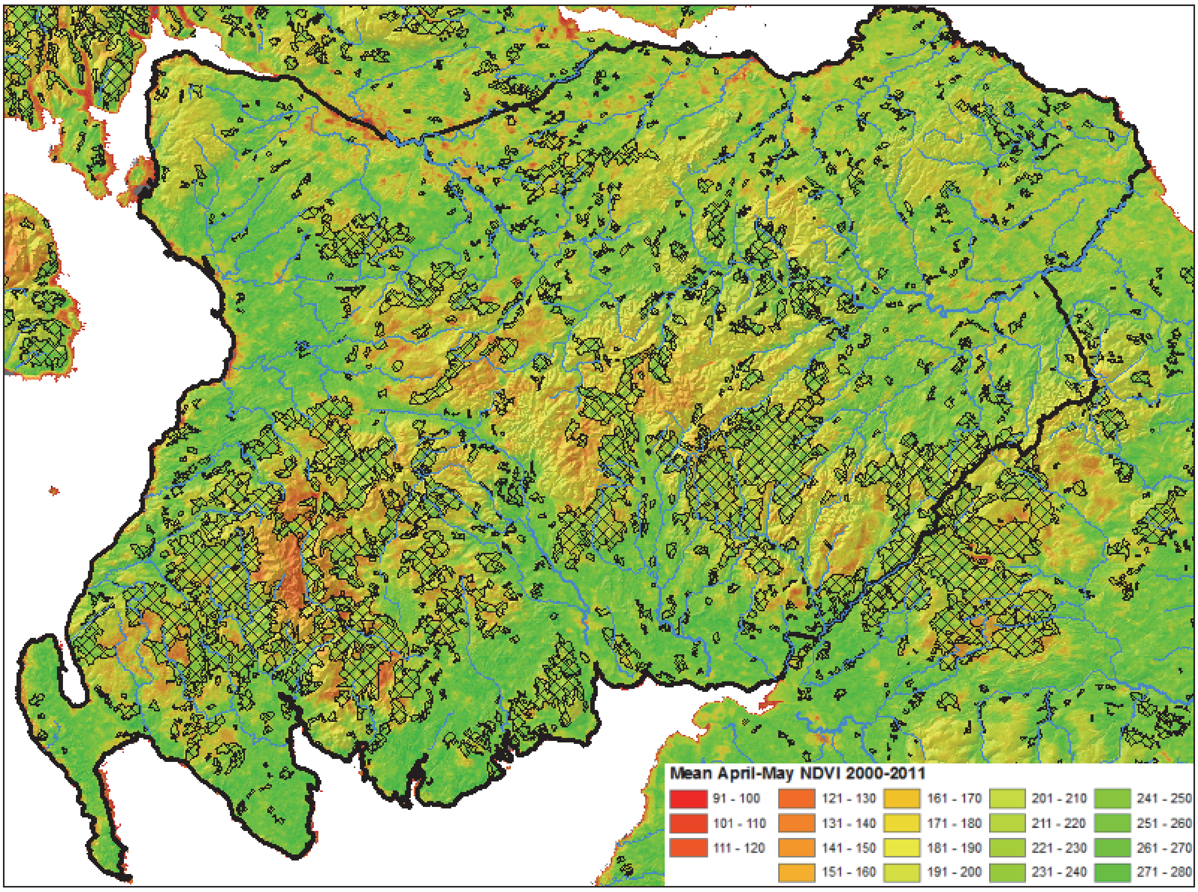


Figure 13. Mean NDVI (2000-2010) for the period April to May. Woodland cover is shown cross-hatched. Contains Ordnance Survey data © Crown copyright and database right 2010.

Table 14. NDVI statistics for hill groups in the study region. Mean_adj is the mean NDVI after removing woodland cover.

Name	Min	Max	Mean	Mean_adj	SD	Area (km^2)
Galloway Hills	92	265	188	171	32	907
Lowther Hills	118	263	194	187	25	620
Pentland Hills	165	256	198	198	16	167
Lowther Hills	143	255	199	194	21	262
Carsphairn Hills	132	267	202	196	25	751
Tweedsmuir Hills	127	258	202	197	25	699
Ettrick Hills	129	261	202	195	21	1091
Cheviot Hills	143	263	207	206	22	699
Lammermuir Hills	160	267	213	211	20	441
Moorfoot Hills	152	262	216	215	23	490

As expected, vegetation productivity, as measured by the NDVI, is highest in the large river glens and lowest at high altitude. There are also quite large differences between some hill groups (Table 14). The Galloway and Lowther Hills have quite low values which become even lower when woodland cover is removed. These figures suggest that there may be less live prey in some hill groups. This has to be treated with caution because the amount of vegetation biomass available to potential golden eagle prey also depends on the 'equity' remaining after accounting for that consumed by domestic livestock such as sheep. Also, whilst it is unlikely that the NDVI can ever provide a precise estimate of golden eagle prey, if only because it cannot be used to locate rabbit warrens, it is reasonable to assume that large differences in NDVI will be related to the potential prey in a region. If the vegetation is in poor condition it is unlikely that it will support much eagle prey whilst vegetation in good condition has the potential, which may not be achieved, to support more eagle prey.

The GWCT (Game & Wildlife Conservation Trust, 2014) data for the 'Intermediate uplands/islands' in Scotland suggest that there had been a 115% increase in mountain hare between 1961 and 2009 although rate of increase seems to have decreased (87% increase 1984-2009 and 59% increase 1995-2009). However, it is worth noting that the confidence limits are very wide. In Scotland as a whole there is evidence for a cyclic trend, as measured by an index of bag density, with 2008 and 2009 being recent poor years. Overall, the GWCT did not identify any significant long-term trends in the national gamebag census.

Relatively small areas of the study region were covered by the 2006/2007 SNH commissioned mountain hare survey (Fig. 2 in Kinrade *et al.*, 2008). Nonetheless, their Fig. 4 shows that mountain hare were reasonably widespread throughout most hill groups to the east of the Carsphairn Hills. Kinrade *et al.* (2008) said, of the south of Scotland "*mountain hares appeared to be locally common in some areas but the total area occupied within each 10x10-km square was considerably less than in the northeast*" (of Scotland). Very few areas, in southern Scotland, had sufficient survey coverage to examine changes in mountain hare distribution between 1995/96 and 2006/07 (Fig. 7 in Kinrade *et al.*, 2008). However, where there were data most 10 km squares suggested an increase.

Conversely, Battersby & Tracking Mammals Partnership (2005) present evidence from three independent monitoring schemes (NGC (National Gamebag Census), BBS (Breeding Bird Survey) and WBBS (Waterways Breeding Bird Survey)) to indicate that rabbits have been in decline since the mid-1990s, particularly in Scotland, following a long term increase since the 1960s. The GWCT (2014) data showed a significant increase in the bag index between 1961 and 1996, and particularly between 1990 and 1996 - a period when several golden eagle ranges seem to have been particularly productive (Haworth, unpublished data). This trend to 1996 was a period of recovery from the very low levels caused by myxomatosis. However, since 1996 there has been a steep decline possibly linked to the new rabbit viral haemorrhagic disease, for example the NGC rabbit index declined by 85% between 1995 and 2009. This large reduction in the rabbit population has been reflected in a decline in the productivity of some previously productive golden eagle ranges (Haworth, unpublished data).

Spatially explicit data, even at a coarse scale, do not appear to be available for red grouse in southern Scotland although it is clear that red grouse densities are higher where the land is actively managed for driven grouse shooting (mainly the Lowther, Tweedsmuir, Pentland, Moorfoot and Lammermuir Hills). Given that the shooting estates have large quantities of potential golden eagle prey but no breeding golden eagles, it is clear that an abundance of prey, by itself, is not a good indicator of golden eagle distribution.

4.7 Nest sites

Nest sites for known ranges in the study area are a mixture of trees and crags. Given the undulating terrain it seems likely that crags will be unavailable over large areas. The OS Ornament data provide some indication of the distribution of possible crag sites and there are large differences between hill groups (Table 15). Because the number of crags from the climbing locations database, provided by Richard Evans, is highly correlated with the OS Ornament density we have added confidence that it is a sufficient surrogate measure of relative cliff availability.

Table 15. Number and percentage of all Ornament polygons in each hill group. Also shown is the hill group area and the Ornament density (number per km^2).

Hill group	n	Percentage	Area (km^2)	Density
Carsphairn Hills	18525	7.8	751	24.7
Cheviot Hills	3469	1.5	699	5.0
Ettrick Hills	13558	5.7	1091	12.4
Galloway Hills	97875	41.1	907	107.9
Lammermuir Hills	513	0.2	441	1.2
Lowther Hills	9173	3.9	882	10.4
Moorfoot Hills	8267	3.5	490	16.9
Pentland Hills	2111	0.9	167	12.6
Tweedsmuir Hills	84381	35.5	699	120.7

Over three quarters of all of the OS ornament polygons are in the Galloway and Tweedsmuir Hills. Even if corrections are made for the different areas of the hill groups by calculating a density of Ornaments, the Galloway and Tweedsmuir Hills stand out as having much higher densities. The Lammermuir Hills have a very low density and the others have similar density values in the range 10-20 per km^2. If these ornaments reflect crag nesting availability there are many more cliff nesting opportunities in the Galloway and Tweedsmuir Hills. Although the density for the Cheviot Hills is low the analysis only considered the study region and much of the Cheviot Hill group is in England.

It is much more difficult to assess the availability of tree nest sites and it is known (Anderson *pers. comm.)* that some nests are in trees in shelter belts. Consequently, it is possible that local knowledge could be used to create artificial nests in suitable areas with the aim of encouraging nesting attempts in those regions lacking crags.

4.8 Persecution

If persecution is a serious problem in any region it does not alter the region's potential as suitable habitat or reduce the *potential* golden eagle population in southern Scotland. It could, however, act as a serious constraint to the occupation of any suitable habitat in the immediate vicinity of the incidents and, more generally, it could reduce the pool of birds available for other suitable regions.

Persecution data (up to 2011) were included. Poisoning offences relate only to abuse cases, i.e. they exclude “accidental” rodenticide or sheep-dip cases. Grid references varied from 2-figure to 8-figure and all incidents listed have a “confirmed” status, no 'probable' cases are included. A confirmed status follows RSPB standard classification criteria, i.e. incidents where definite illegal acts were disclosed, that is the substantive evidence included birds or baits confirmed by the Scottish Agricultural Science Agency (SASA) as containing illegal poisons; an offence seen/found by a witness and/or confirmed by post-mortem, illegally-set traps etc. All of the poisoning incidents included in the analysis are corroborated and accepted as incidents by SASA/PAWS with the RSPB providing the data; non-poisoning incidents for 2000-2011 were further verified by the National Wildlife Crime Unit and SNH.

Data were separated so that only cases in the hill groups are analysed. Although we analyse by hill group it is unwise to place too much emphasis on regional differences because there are no data on relative 'search efforts'. For example, if persecution incidents were spread equally but one hill group had ten times more search effort than others we might expect to find more incidents in the more intensively searched hill group even if there were the same number. We also separate the data into 'early' (pre-2000) and 'late' (2000-2011) cases.

There were 100 poisoning cases recorded in the hill groups, 84 of which were between 2000-2011. Only five cases had 4-figure coordinates, the remaining 96 had 6+ figure coordinates. There were 63 non-poisoning cases recorded in the hill groups, 36 of which were between 2000-2011. Only three cases had 4-figure coordinates, the remaining 60 had 6+ figure coordinates.

Poisoning records are summarised in Table 16 and, in more detail, in Annex 4. In Table 16 'None' refers to incidents in which poison bait was found but no victims were found. Clearly, birds of prey are the most frequently recorded victims, particularly buzzards. There was one recorded case of a poisoned golden eagle which occurred in the Tweedsmuir Hills in 2007. Half of the poisoning incidents were recorded in the Lowther Hills and a further quarter in the Moorfoot Hills. Very few incidents were recorded in other hill groups. Given the small number of records, it is unsafe to assume that, for example, poisoning occured twice as often in the Lowther Hills compared with the Moorfoot Hills. Although it was recorded twice as often it is possible (as an example to illustrate a problem with the data) that there were actually more poisoning incidents in the Moorfoot Hills but they went unrecorded. Nonetheless, 17 recorded poisoned buzzards in the Lowther Hills and 16 in the Moorfoot Hills during 2000-2011 is indicative of a serious and systematic problem that could have acted as a constraint on golden eagles.

The non-poisoning cases are summarised in Table 17 and, in more detail, in Annex 4. In Table 17 'None' refers to incidents such as an illegal trap but with no victims. As with the poisoning data the Lowther Hills had by far the most records, including almost half of those recorded during 2000-2011. The Lammermuir Hills had the next highest total of recorded incidents, although there was a large decrease during 2000-2011. Raptors were, again, the most frequently recorded group although peregrines replaced buzzards as the most common victim. Most of the types of non-poisoning persecution were either shooting or nest destruction.

Table 16. Poisoning incidents by hill group and species for two time periods (recorded in all years up to 2011, and 2000-2011). (species codes: BO Barn owl; BZ Buzzard; C. Carrion crow; EA Golden eagle; GI Goshawk; MG Magpie; RN Raven; KT Red kite; RO Rook; SH Sparrowhawk).

Hill group	Period	None	BO	BZ	C.	EA	GI	MG	RN	KT	RO	SH	Cat	Dog	Fox	All
Carsphairn	All															0
	2000-															0
Cheviot	All			1										1		2
	2000-			1												1
Ettrick	All			1												1
	2000-			1												1
Galloway	All									1				1	1	3
	2000-									1						1
Lammermuir	All	2		5					3							10
	2000-	1		5					3							9
Lowther	All	17	1	19	3			1	4	2	1	1	1			50
	2000-	17		17	3			1	4	2			1			45
Moorfoot	All	3		17					2	3						25
	2000-	2		16					2	2						22
Renfrewshire	All			3										1		4
	2000-			1												1
Tweedsmuir	All	1		2		1	1									5
	2000-	1		1		1	1									4
Total	All	23	1	48	3	1	1	1	9	6	1	1	1	3	1	100
	2000-	21	0	42	3	1	1	1	9	5	0	0	1	0	0	84

Table 17. Non-poisoning incidents by hill group and species for two time periods (all recorded up to 2011, and during 2000-2011).

Hill group	Period	None	ML	BZ	GI	HH	K.	PE	KT	SE	SH	TO	All
Carsphairn	All							2					2
	2000-												0
Cheviot	All	2		1				1				1	5
	2000-	2						1				1	4
Ettrick	All	1				1							2
	2000-	1											1
Lammermuir	All	5	1	1	1	1	1		1				11
	2000-	4			1				1				6
Lowther	All	2		5	1	3	1	4		3			19
	2000-	1		3		2	1	3		3			13
Moorfoot	All	3		1									4
	2000-	1		1									2
Pentland	All							4					4
	2000-							3					3
Renfrewshire	All					1		2			1		4
	2000-												0
Tweedsmuir	All	1		1	3			5					10
	2000-				1			2					3
Total	All	14	1	7	5	6	2	16	1	3	1	1	59
	2000-	9		4	2	2	1	9	1	3		1	32

5. ESTIMATING THE POTENTIAL FUTURE POPULATION

5.1 Introduction

This section collates information from the previous sections to arrive at an understanding of the constraints and resources that enable an estimate for the potential number of pairs in each region within southern Scotland. In order to simplify this task the region is split into the nine hill groups plus the Clyde Muirshiel Regional Park (mainly the Renfrewshire Heights SPA). Other habitat, outwith these zones, is not considered suitable or extensive enough to support any golden eagle ranges.

5.2 Galloway Hills

The Galloway Hills have been central to the south of Scotland golden eagle population. Since the end of the second World War there have been up to four separate ranges, although this is now reduced to two. The topography is similar to the more rugged highlands and there are many cliff nesting opportunities. Despite significant open ground losses to forestry (Figs 6a and 6b, Table 13), sufficient habitat and potential breeding sites remain to support at least two pairs. However, it seems unlikely that current prey resources are sufficient to support a level of productivity that would turn this group of ranges from a sink to a source population. There has been a very large increase in spring rainfall (400-500 mm, Fig. 9) and the region has the lowest mean NDVI (Table 14). However, it is one of the 'wildest' in southern Scotland (Table 9) and wind farms are unlikely to impinge on its eagle habitat. It also had very few recorded persecution incidents, with a single red kite found poisoned during 2000-2011 (Tables 16 & 17).

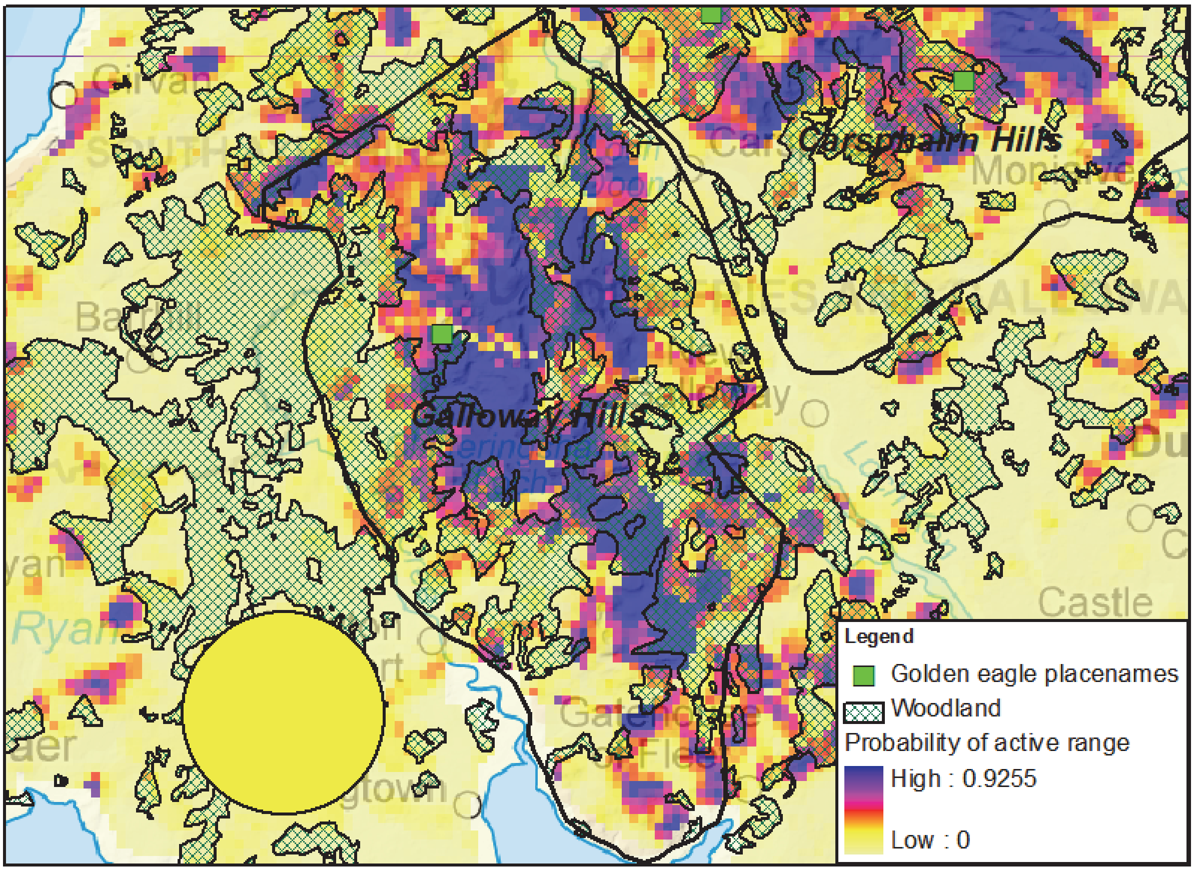


Figure 14. Galloway Hills region. Yellow circle is a 6 km radius indicating maximum range size. The background (legend shown in inset) is the probability of breeding habitat from the random forest analyses overlain with current woodland. Contains Ordnance Survey data © Crown copyright and database right 2010.

5.3 Carsphairn Hills

There are no historic golden eagle ranges in this region but place names suggest that parts were once occupied. A combination of forestry and wind farm developments suggests that there is now space for only one potential range in the hills south of Sanquhar. However, crag nesting locations may be limiting here. It may be significant that Roxy does not appear to have visited this region, possibly because the habitat and/or prey resources are unsuitable. Nonetheless, there does appear to be suitable habitat for between one and two pairs (Fig. 15). As with the Galloway Hills, it has experienced a very large increase in spring rainfall (400-500 mm, Fig. 9) although its mean NDVI is more than 10% higher than the Galloway Hills (Table 14). It is not a particularly 'wild' region, only scoring above average for remoteness (Table 9). Almost a third of its ridge habitat has been lost to a combination of woodland and wind farms and there is a possibility that additional wind farms could increase this to over 40% (Table 13). However, there were no recorded persecution incidents since during 2000-2011 (Tables 16 & 17). It is unlikely that this would be one of the first regions occupied by territorial birds should an enhancement scheme go ahead.

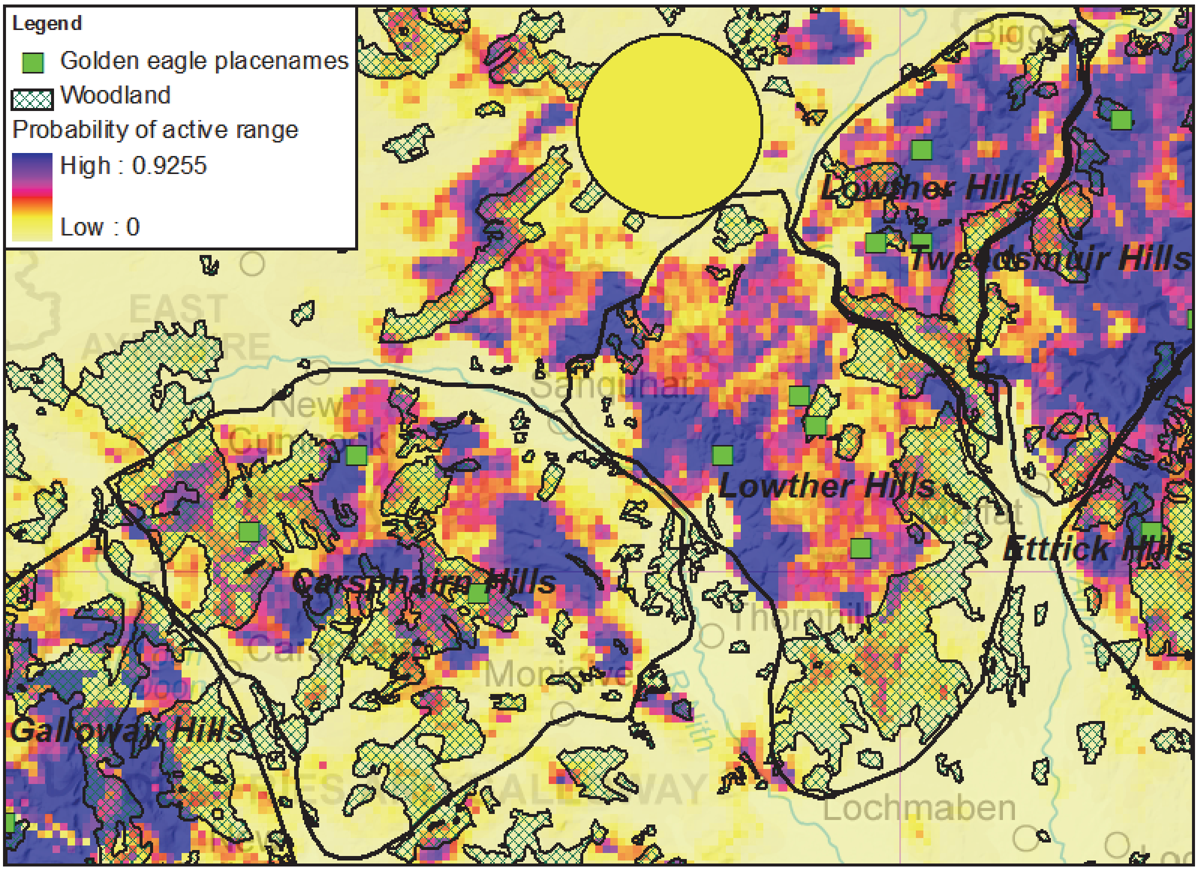


Figure 15. Carsphairn Hills and Lowther Hills region. Yellow circle is a 6 km radius indicating maximum range size. The background (legend shown in inset) is the probability of breeding habitat from the random forest analyses overlain with current woodland. Contains Ordnance Survey data © Crown copyright and database right 2010.

5.4 Lowther Hills

Potentially this looks like one of the most promising regions for new golden eagle ranges. There is historic evidence, from place names, that the region was used and, despite the extensive wind farm developments, there is sufficient space for at least three ranges: one on each side of the A74/M74 and one to the north of the Clyde wind farm (Fig. 15). This is also one of the regions that Roxy visited extensively. However, crag nesting sites may be limiting although Rollie (*pers. comm.*) notes that there are some good crags and there is some historical and recent use of some of these (e.g. Earn Craig).

As with the other hill groups to the west, it has experienced a large increase in spring rainfall (400-500 mm, Fig. 9) although there is evidence of a west-east gradient across these hills, and the mean NDVI (Table 14) is the second lowest of all of the hill groups, suggesting that prey availability may be an issue if any pairs become established. This region scores above average on all of the 'wildness' features and wind farms are unlikely to impinge on its eagle habitat. Unfortunately, it had by far the largest number of recorded persecution incidents, of either type (Tables 16 & 17). Persecution of birds of prey was certainly an issue in this region and, unless it is controlled, could affect eagle success.

Almost a quarter of the ridge habitat has been lost to woodland and wind farms (Table 13) which could rise to 30% depending on future wind farm developments.

5.5 Tweedsmuir Hills

Marquiss *et al.* (1985) noted that "*The history of the golden eagle in the Moffat-Tweedsmuir Hills is even vaguer, though there would be sufficient space and nesting habitat for 3-4 pairs. Breeding here had evidently ceased by 1850 (Gladstone, 1910*) ". Even with the additional forestry and wind farm proposals there is still sufficient space for two to three ranges, perhaps with a new range north of Meggets Reservoir (Fig. 16). Roxy visited this region extensively in 2011 and became increasingly attached to this hill group in 2012 (Fig. 7b). Unlike some other regions, there appears to be sufficient potential nesting habitat as both crags and mature trees.

Although it has experienced an increase in spring rainfall (300-400 mm, Fig. 9) this is much less severe than the hill groups to the west and the mean NDVI (Table 14) is about 15% larger than in the Galloway Hills. This region has the highest score on all of the 'wildness' features suggesting that it could be good eagle habitat. Unfortunately, it had many recorded persecution incidents, including the only golden eagle poisoning recorded in southern Scotland during 2000-2011 (Tables 16 & 17).

Almost a quarter of the ridge habitat has been lost to woodland and wind farms (Table 13) which could rise by an additional 4% depending on future wind farm developments.

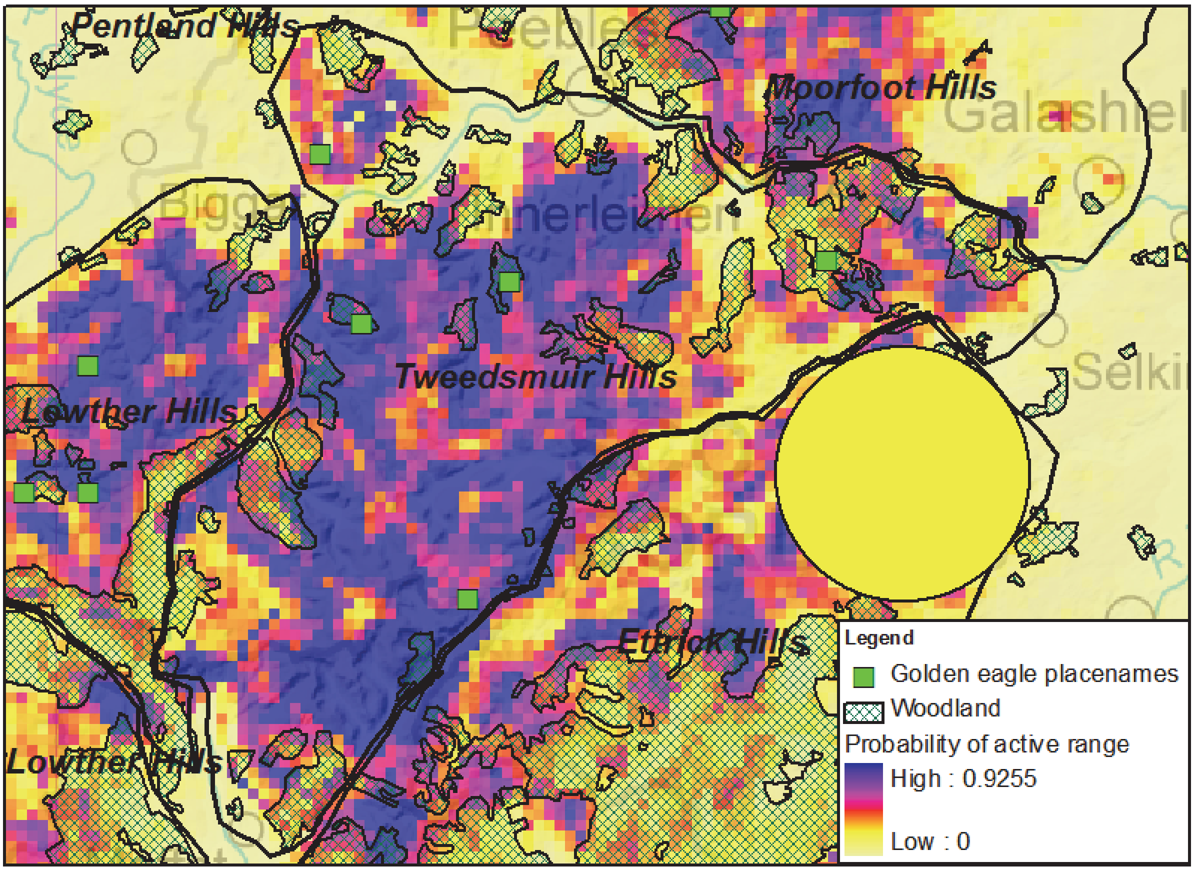


Figure 16. Tweedsmuir Hills region. Yellow circle is a 6 km radius indicating maximum range size. The background (legend shown in inset) is the probability of breeding habitat from the random forest analyses overlain with current woodland. Contains Ordnance Survey data © Crown copyright and database right 2010.

5.6 Ettrick Hills

There is probably space for only one range in the vicinity of the historic range north of Langholm in the southern part of this hill group (Fig. 17). Roxy visited some of this habitat east of the A7 (Fig. 7b).

Because this hill group is towards the east of the study area it has not experienced the same very large increases in spring rainfall as the hills in the west (300-400 mm, Fig. 9), and the mean NDVI (Table 14) is about 15% larger than in the Galloway Hills. Very little ridge habitat has been lost to wind farms and it is unlikely that there will be much in the future because of the location of the Eskdalemuir seismological recording station. However, over a third of the ridge habitat has been lost to woodland. It has an average score for its 'wildness', scoring highest for remoteness (third highest of all hill groups). There were two recorded persecution incidents during 2000-2011 (Tables 16 & 17).

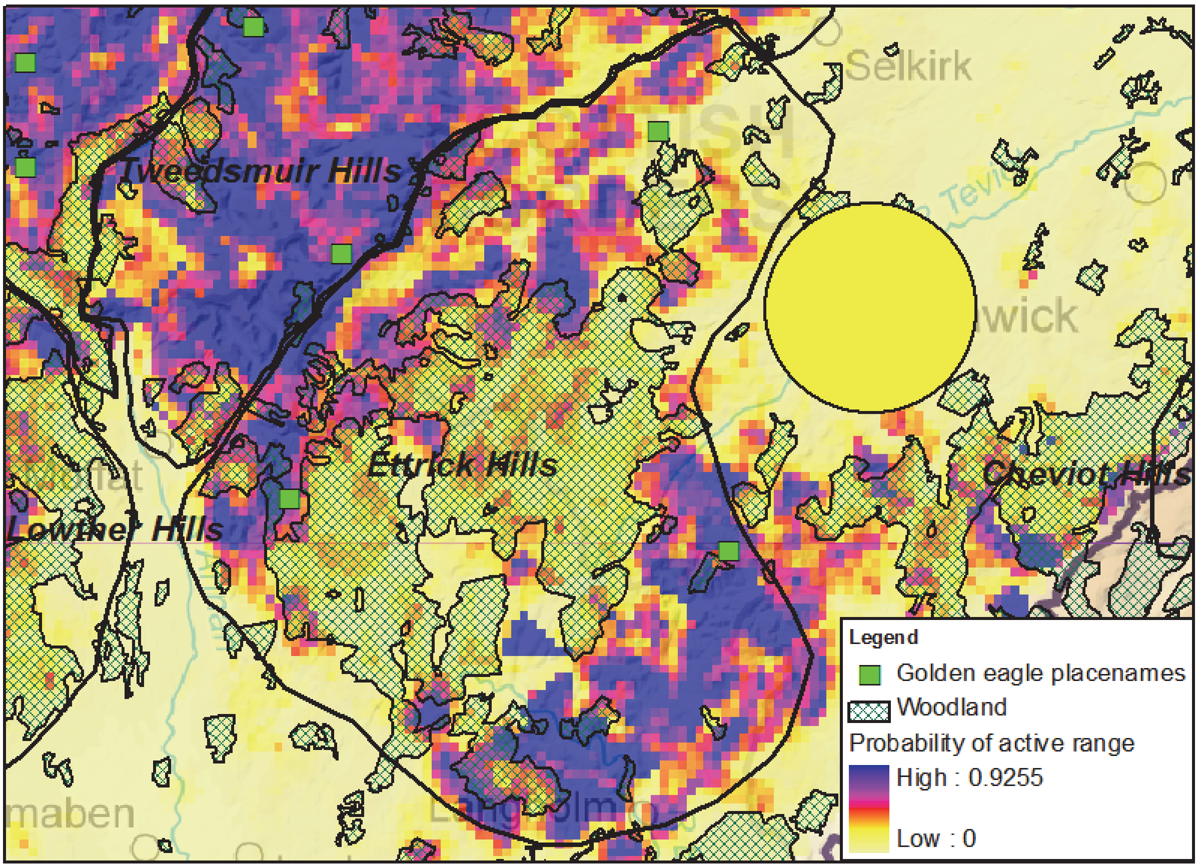


Figure 17. Ettrick Hills region. Yellow circle is a 6 km radius indicating maximum range size. The background (legend shown in inset) is the probability of breeding habitat from the random forest analyses overlain with current woodland. Contains Ordnance Survey data © Crown copyright and database right 2010.

5.7 Moorfoot Hills

There are two place names associated with eagles and there appears to be sufficient, contiguous space to support one pair of eagles (Fig. 18). Roxy visited some of this habitat in 2011 (Fig. 7b). These hills have low scores on all of the wildness indicators. Their position in the east of the region means that they have experienced relatively small increases in spring rainfall compared with the hills in the west (Fig. 9) and they have the highest mean NDVI (Table 14, Fig. 13) suggesting that prey may be more available than in the west. However, there are few nesting crags and this is likely to be a region where tree nesting is a more probable outcome. Sixteen percent of the ridge habitat has been lost to woodland, mainly, and wind farms with a potential for this to rise slightly if more wind farms are developed.

Unfortunately this group of hills had the second largest number of recorded persecution incidents, particularly those involving poisoning (Tables 16 & 17). Persecution of birds of prey has been an issue in this region and, unless it is controlled, it could affect eagle success.

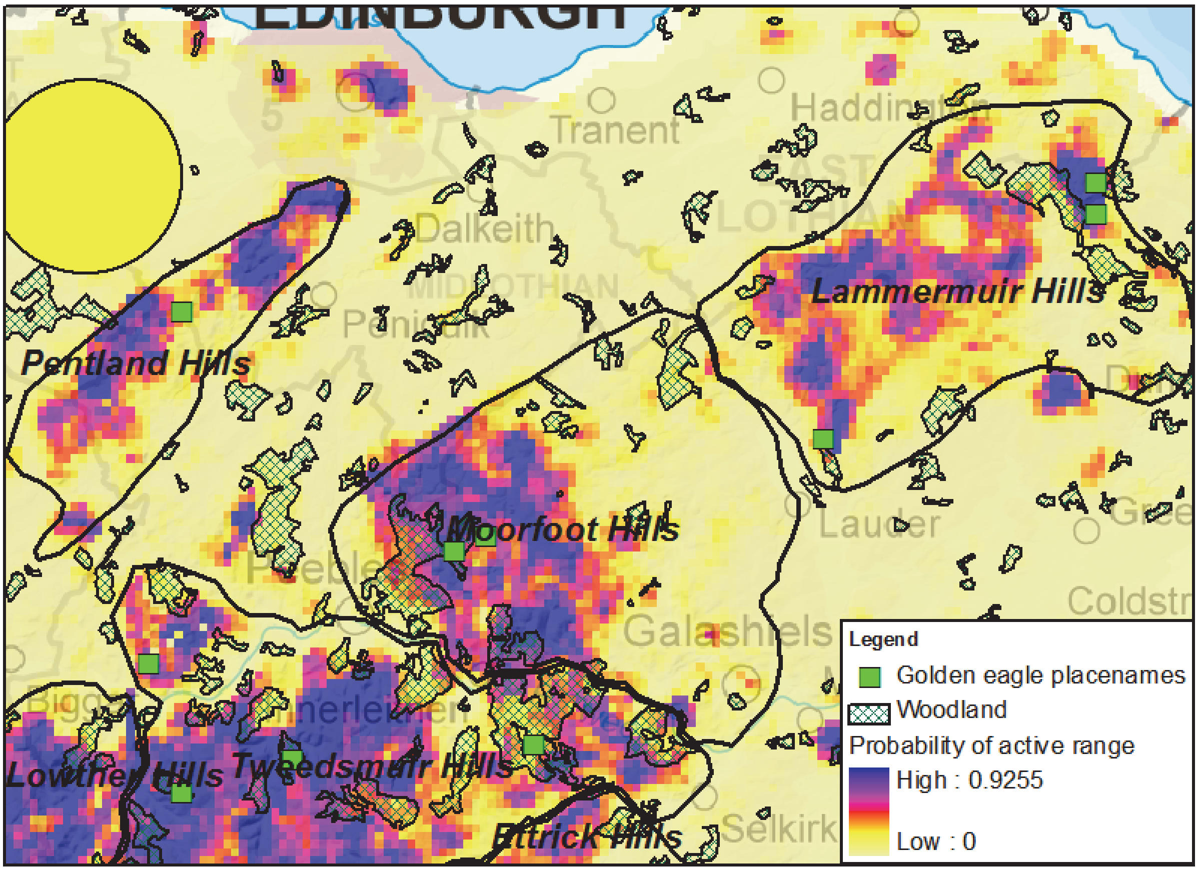


Figure 18. Moorfoot, Pentland and Lammermuir Hills regions. Yellow circle is a 6 km radius indicating maximum range size. The background (legend shown in inset) is the probability of breeding habitat from the random forest analyses overlain with current woodland. Contains Ordnance Survey data © Crown copyright and database right 2010.

5.8 Lammermuir Hills

There are no historic golden eagle nesting sites but there are three place names associated with eagles. However, because most of the existing wind farms in this region are north of the B6355 only the site in the south west corner seems currently suitable and there appears to be sufficient, contiguous space to support one pair of eagles (Fig. 18). Roxy visited some of this habitat in 2011 (Fig. 7b).

As with the adjacent Moorfoot Hills, the Lammermuir Hills have low scores on all of the wildness indicators. Their position in the far east of the region means that they have experienced relatively small increases in spring rainfall compared with the hills in the west (Fig. 9) and they have the highest mean NDVI (Table 14, Fig. 13) suggesting that prey may be more available than in the west. However, there are few nesting crags and this is a region where tree nesting is a more likely outcome.

Approximately 12% of ridge habitat has been lost to wind farms and woodland and this could rise to almost 20% if all planned wind farms are constructed.

Unfortunately this group of hills had the third largest number of recorded persecution incidents during 2000-2011 (Tables 16 & 17). Persecution of birds of prey has been an issue in this region and, unless it is controlled, it could affect eagle success.

Even if the region is not occupied by a pair it could be a significant area of habitat available to non-breeding birds if the southern Scotland population expands.

5.9 Cheviot Hills

Most of this hill group is in England and, as such, was excluded from this project. In the absence of detailed analysis it is only possible to note that, conservatively, there should be space for at least one pair.

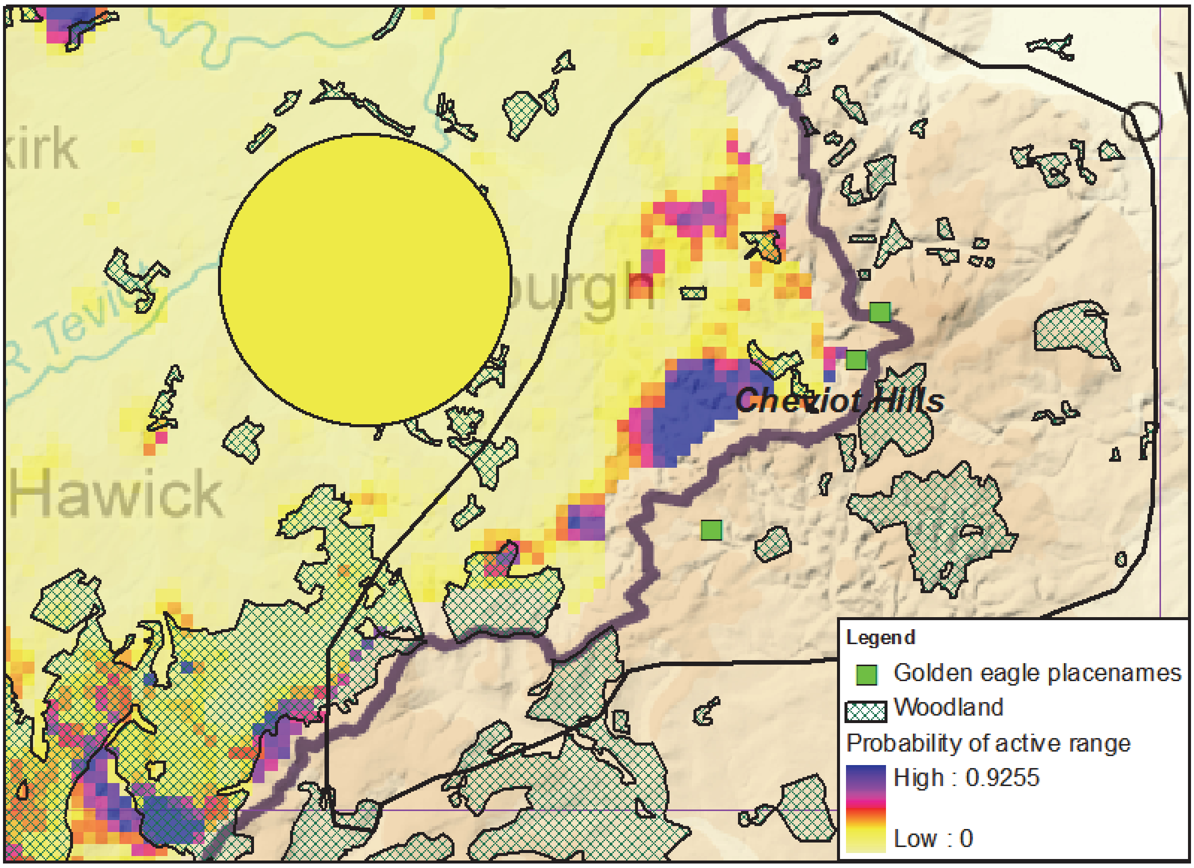


Figure 19. Cheviot Hills region. Yellow circle is a 6 km radius indicating maximum range size. The background (legend shown in inset) is the probability of breeding habitat from the random forest analyses overlain with current woodland. Contains Ordnance Survey data © Crown copyright and database right 2010.

5.10 Pentland Hills

There is some good, predicted golden eagle habitat in these hills (Fig. 18), and a single place name associated with eagles, but the predicted area is small and surrounded by a large expanse of unsuitable habitat. Although we lack definitive data it is also likely that there is considerable recreational pressure which, given their single ridge shape and proximity to Edinburgh, is likely to be concentrated in the small area suitable for eagles. On balance it seems unlikely that these hills will be occupied but they could become an area used by young birds.

5.11 Clyde Muirshiel Regional Park

This area is close to Arran and Cowal where there are many productive pairs. There is a single historic place name, Yearn Stane, although it seems more likely that this was a roost site rather than a nest site. Nonetheless, there appear to be several suitable crags marked on the 1:25,000 OS map and the region is an existing SPA and country park with active countryside rangers. Whilst the site is close to Largs, and developments along the south side of the Clyde, there does appear to be sufficient habitat to support a single pair. Even if the region is not occupied by a pair it could be a significant area of habitat available to non-breeding birds if the southern Scotland population expands.

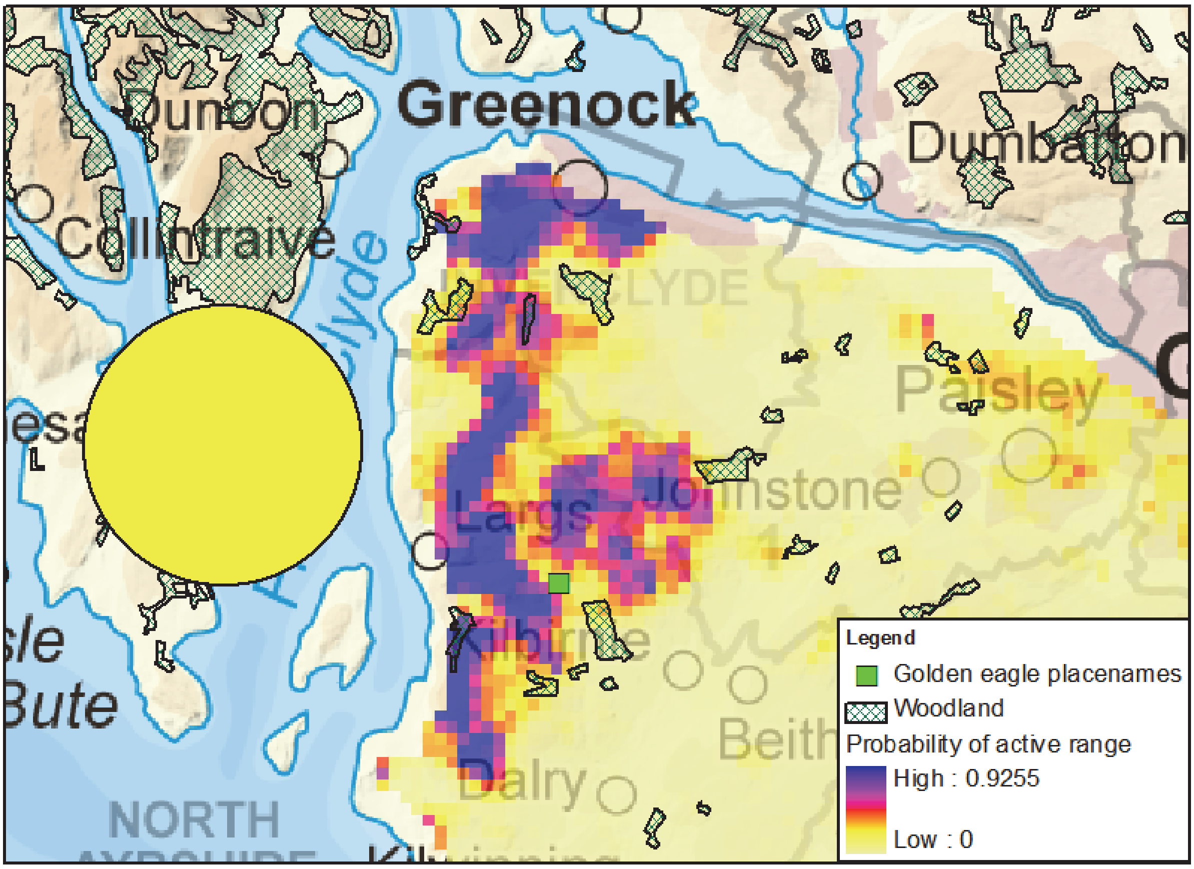


Figure 20. Renfrewshire Heights region. Yellow circle is a 6 km radius indicating maximum range size. The background (legend shown in inset) is the probability of breeding habitat from the random forest analyses overlain with current woodland. Contains Ordnance Survey data © Crown copyright and database right 2010.

6. CONCLUSIONS AND FURTHER WORK

6.1 How many pairs could be supported?

The regional summaries above suggest that southern Scotland could support 14-16 pairs, a figure which includes current ranges. A more conservative estimate, excluding the Moorfoot and Lammermuir Hills and the Renfrewshire Heights, would still leave 11-13 pairs. This would be a significant contribution to the Scottish population. However, the source of any new birds is uncertain and it would be very helpful if future research could focus on satellite tagging young birds in Argyll, Cowal and Arran in order to quantify the potential for natural recruitment from this area into Southern Scotland.

6.2 Broad predictors of the golden eagle's range

Only the region's potential to support territorial pairs was considered. It is impossible to determine the likely productivity of any future pairs without additional work. Nonetheless, a relatively small number of areas were highlighted as a focus for more targeted work.

The most important predictor of potential golden eagle breeding habitat was the **extent of moors and heathland.** Slope variability and maximum slope were the second and third most important predictors. Measures of altitude (mean and standard deviation) were also important. Golden eagle ranges are in the most topographically variable parts of the landscape. Distance to ridges, and its variability, was also important.

A map of predicted golden eagle habitat was a good fit to current and historic golden eagle ranges and it was also a very good predictor of the movements of the satellite-tracked sub-adult eagle Roxy in 2011 and 2012.

Analyses of **rainfall and growing degree days** changes since the early 1980s suggest that it will have become increasingly difficult for golden eagles to capture prey across the hill ranges. This is due to a combination of no, or very little, increase in the number of growing degree days combined with marked increases in rainfall totals.

Two measures of **potential recreational pressure** were investigated but the type of information needed for a robust investigation is unavailable. With the possible exception of the Pentland Hills and the Renfrewshire Heights, recreational pressure is not thought to be a significant constraint.

All of recently occupied golden eagle ranges have experienced significant reductions in potential ranging habitat because of forest expansion. However, some **woodland** would have been present while the ranges were occupied. If annual forest cover data were available for the periods while these ranges were occupied it would be possible to examine thresholds at which ranging losses were associated with range abandonment.

The average loss of ranging habitat, using the PAT eagle ranging model, differed markedly between ranges in different hill groups. In the Kielder and Carsphairn hill ranges the average loss was > 50% while in the Moorfoot Hills the average loss was >30%. Some of the new native woodland planting schemes, such as the Carrifran scheme, have the potential to improve golden eagle prey, at least in the short to medium term.

The amount of potential ranging habitat lost to golden eagles as a result of **wind farm developments**, assuming that golden eagles are displaced, varied between hill groups. As a percentage of all ridge habitat in a hill group, the Lammermuir, Lowther and Carsphairn Hills are predicted to have >10% loss. In the Lammermuir Hills a >10% loss is predicted for installed or approved wind farms. However, six hill groups have predicted losses of < 3% and these six hold almost 50% of the total ridge habitat. They also have very few, or no, predicted losses to currently installed or approved wind farms.

Combining the ridge habitat lost both to wind farms and woodland cover indicates that, apart from the Pentland Hills, large proportions of ridge habitat have, or will be, lost. In some hill groups the scale of loss depends on the future of wind farms in planning. The largest differences in loss calculations are in the Carsphairn and Lowther Hills.

If golden eagles are to become established as a productive population in southern Scotland they need a sufficiently robust and abundant **prey base**. Both the abundance and identity of food resources can influence the density and productivity of golden eagles. In several parts of Scotland, e.g. Morven, there is a relatively high density of eagles but productivity is very low almost certainly as a consequence of a low prey base. An adequate supply of carrion may be sufficient to enable pairs to survive for long periods without producing any young. However, a suitable supply of live prey is necessary for successful reproduction. Therefore, a more detailed understanding of prey resources is essential to target the best areas from those identified in this report.

The relationship between breeding productivity and **land management** is complex. In general, deer exert an indirect influence on prey abundance and availability through grazing pressure either on their own or in combination with sheep and burning. Unfortunately neither sheep statistics nor deer counts correspond to golden eagle range boundaries making it difficult to assess accurately the impacts of varying levels of grazing upon breeding productivity. Differing levels of grazing intensity are likely to have different impacts on the various key groups of potential prey, particularly hares and rabbits, and this in itself will vary from region to region.

Nest sites for the known ranges are a mixture of trees and crags. Given the undulating terrain it seems likely that crags will be unavailable over large areas. Although crags can be identified and quantified from OS map data it is difficult to assess the availability of tree nest sites and it is known that some nests in southern Scotland are in trees in shelter belts. It is possible that local knowledge could be used to create artificial nests in suitable areas with the aim of encouraging nesting attempts in those regions lacking crags.

If **persecution** is a serious problem in any region it does not alter that region's potential as suitable habitat or reduce the *potential* golden eagle population in southern Scotland. It could, however, act as a serious constraint to the occupation of suitable habitat in the immediate vicinity of incidents and, more generally, it could reduce the pool of birds available for other suitable regions.

6.3 Regional assessments

The **Galloway Hills** have always been central to the south of Scotland golden eagle population. Since the end of the second World War there have been up to four separate golden eagle ranges, although this is now reduced to two. The topography is similar to much of the more rugged highlands and there are many cliff nesting opportunities. Despite significant losses of open ground to forestry, sufficient habitat and potential breeding sites remain to support at least two pairs. However, it seems unlikely that current prey resources are sufficient to support a level of productivity that would turn this group of ranges from a sink to a source population. It has experienced a very large increase in spring rainfall and has the lowest mean NDVI (a measure of vegetation productivity). However, this region is one of the 'wildest' in southern Scotland and wind farms are unlikely to impinge on eagle habitat. It has very few recorded persecution incidents.

There are no recent golden eagle ranges in the **Carsphairn Hills** but place names suggest that parts were once occupied. A combination of forestry and wind farm developments suggest that there is now space for only one potential range in the hills south of Sanquhar and crag nesting locations may be limiting. This is one of the regions that Roxy has not visited, possibly because the habitat and/or prey resources are unsuitable. As with the Galloway Hills, it has experienced a very large increase in spring rainfall. It is not a particularly 'wild' region, only scoring above average for remoteness. Almost a third of its ridge habitat has been lost to a combination of woodland and wind farms and there is a possibility that additional wind farms could increase this to over 40%. It is unlikely that this would be one of the first regions occupied by territorial birds should the population expand.

Potentially the **Lowther Hills** is the most promising region for new golden eagle ranges. There is historic evidence, from place names, that it was used and, despite extensive wind farm developments, there is sufficient space for at least three ranges: one on each side of the A74/M74 and one to the north of the Clyde wind farm. This is also one of the regions that Roxy visited extensively. However, crag nesting sites may be limiting although there are some good crags and there is historical and recent use of some of these. As with the other hill groups to the west, spring rainfall has shown a large increase and the mean NDVI is the second lowest of all the hill groups, suggesting that prey availability may be an issue if any pairs become established. The region scores above average on all 'wildness' features and wind farms are unlikely to impinge on its eagle habitat. Unfortunately, it had by far the largest number of recorded persecution incidents. Persecution of birds of prey was certainly an issue in this region and, unless it ceases, could influence eagle success. Almost a quarter of the ridge habitat has been lost to woodland and wind farms which could rise to 30% depending on future developments.

Marquiss *et al.* (1985) noted that "*The history of the golden eagle in the Moffat-Tweedsmuir Hills is even vaguer, though there would be sufficient space and nesting habitat for 3-4 pairs*". Even with additional forestry and wind farm proposals there is still sufficient space for two to three ranges in the **Tweedsmuir Hills**, perhaps with a new range north of Megget Reservoir. Roxy visited this region extensively in 2011 and became increasingly attached to this hill group in 2012. Unlike some other regions, there is sufficient potential nesting habitat as both crags and mature trees. Although it has experienced an increase in spring rainfall this is less severe than the western hill groups. It has the highest score on all 'wildness' features suggesting that it could be good eagle habitat. Unfortunately, it had many recorded persecution incidents, including the only golden eagle poisoning recorded in southern Scotland in recent years. Almost a quarter of the ridge habitat has been lost to woodland and wind farms which could rise by an additional 4% depending on future wind farm developments.

The **Ettrick Hills** have space for only one range, in the vicinity of the historic range north of Langholm. Because this hill group is towards the east of the study area it has not experienced the same large increases in spring rainfall. Little ridge habitat has been lost to wind farms and it is unlikely that there will be much in the future because of the Eskdalemuir seismological recording station. However, over a third of the ridge habitat has been lost to woodland. It has an average score for its 'wildness', scoring highest for remoteness (third highest of all hill groups). There were two recorded persecution incidents during 2000-2011.

There are two place names associated with eagles in the **Moorfoot Hills**, and there is sufficient contiguous space to support one pair of eagles. These hills have low scores on all wildness indicators. Their eastern location means that they have experienced relatively small increases in spring rainfall compared with the west and they have the highest mean NDVI suggesting that prey may be more available than in the west. However, there are few nesting crags and this is likely to be a region where tree nesting is more probable. Sixteen percent of the ridge habitat has been lost to woodland, mainly, and wind farms with a potential for this to rise slightly if more wind farms are developed. Unfortunately this region had the second largest number of recorded persecution incidents, particularly those involving poisoning. Persecution of birds of prey has been an issue in this region and, unless controlled, it could affect eagle success. On balance this is more likely to become important habitat for non-breeding eagles rather than supporting a new range.

There are no historic golden eagle nesting sites in the **Lammermuir Hills**, but there are three place names associated with eagles. Because most existing wind farms are north of the B6355 only one site in the south west seems currently suitable and there is sufficient, contiguous space to support one pair. As with the adjacent Moorfoot Hills the Lammermuir Hills have low scores on all of the wildness indicators. Their position in the far east of the region means that they have experienced relatively small increases in spring rainfall and they have the highest mean NDVI suggesting that prey may be more available than in the west. However, there are few nesting crags and this is a region where tree nesting is more likely. Approximately 12% of ridge habitat has been lost to wind farms and woodland and this could rise to almost 20% if all planned wind farms are constructed. This group of hills has the third largest number of recorded persecution incidents. Persecution of birds of prey has been an issue in this region and, unless controlled, it could affect eagle success. Even if the region is not occupied by a pair it could be a significant area of habitat available to non-breeding birds.

Most of the **Cheviot Hills** are in England and were excluded from this project. Conservatively, it is estimated that there should be space for at least one pair.

The **Pentland Hills** has some good, predicted golden eagle habitat and a single place name associated with eagles. However, the predicted area is small and surrounded by a large expanse of unsuitable habitat. There is considerable recreational pressure which, given the Pentlands' single ridge shape and proximity to Edinburgh, is likely to be concentrated on areas that would be used by eagles. On balance it seems unlikely that these hills will be occupied but they could become an area used by young birds.

The **Clyde Muirshiel Regional Park** is close to Arran and Cowal where there are many productive pairs. There is a single historic place name although this may have been a roost site rather than a nest site. Nonetheless, there are several suitable crags and the region is an existing SPA and country park with active countryside rangers. Whilst the site is close to Largs, and developments along the south side of the Clyde, there may be sufficient habitat to support a single pair. Even if the region is not occupied by a pair it could be a significant area of habitat available to non-breeding birds.

6.4 Future considerations and further work

This work has only considered the region's potential to support range holding pairs. It is impossible to determine the likely productivity of any established pairs at this stage. However, if birds achieve the minimum survival rates recommended for favourable conservation status (Whitfield *et al.* 2006a,b) the region's productivity would need to be above 0.3 fledged per pair per year. If the productivity is below 0.3 the region would become a sink population in which birds from the rest of Scotland would be needed to replace adults dying. Historically, the region's productivity did exceed 0.3 but many things have changed since then, particularly the amount of habitat, its quality, the number of rabbits and the weather. If survival rates were below those required to achieve favourable conservation the productivity would have to be much higher than 0.3. Consequently, it is important that the region's future golden eagles do not experience the types of persecution that have been implicated in some other parts of Scotland (Whitfield *et al.*, 2003, 2004a, 2004b), which would reduce their survival rates.

The source of any new birds is uncertain and it would be very helpful if future research could focus on satellite tagging birds in Argyll, Cowal and Arran in order to quantify the potential for natural recruitment from these areas into S. Scotland. The data derived from the satellite tracked three-year old female golden eagle 'Roxy' (as at March 2014) has been invaluable in revealing the relative uses of suitable habitat in S. Scotland.

Clearly, if more golden eagles settle and are not disturbed, displaced or killed some may attempt to breed. We do not know if these birds would contribute to a self-sufficient or sink regional population, though any measures which improve the availability of live prey should benefit the viability and breeding success of the birds.

At this stage, three lines of work are needed. First, the currently occupied ranges need to be monitored, and the potential ranges identified in the report need to be surveyed for non-breeding as well as nesting birds. The Scottish Raptor Monitoring Groups appear to have this well in hand. Second, any work which can be carried out to reduce the constraints on golden eagles should be significant; this is especially important given the relatively recent wetter spring and summer climate, and impending losses of ridge habitats to wind farms, impose additional constraints on the birds. Hence, it is all the more important that risks to bird survival and health arising from persecution and lack of live prey are addressed. An action plan could be developed proposing practical work which could be undertaken by this report's stakeholders. Third, we need to develop our understanding of potential and actual recruits – where they come from, and their contribution to population viability; satellite tagging young golden eagles in areas specified above would be especially instructive.

The history of golden eagle occupation in S. Scotland is fascinating, and clearly many factors have given rise to the small outlying population we have today. We suggest that some more research and practical work could result in a step-change in fortunes for this population. This is, after all, one of the most westerly populations in Europe, and it may develop connections with the reintroduced small population in Ireland, and provide a source of birds for England.

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ANNEX 1: SPECIES DISTRIBUTION MODELLING BACKGROUND

Simple models assume a simple, linear relationship between the values of the response variable and predictor variables. For example, the probability that a species is present might increase as spring rainfall increases. However, ecological relationships are rarely simple over the complete range of biologically realistic values of a predictor variable. So, a species may be more likely to be present up to a certain amount of rainfall but then as rainfall increases it becomes less likely that the species would be present. This would be a non-linear relationship.

There has been a steady progression of new SDM techniques often promising to be 'solutions' to the SDM problem. Generally this progression has been driven by increasing computing power and software availability. It is less clear that ecological knowledge has played much of a role in this progression. The relatively recent adoption of the R software environment as the default choice by many ecologists has perhaps exacerbated the search for new methods. One outcome of the constantly evolving progression of statistical methods available in R is a stream of publications which either promote new methods or compare them to older, and now unfashionable, techniques. This can be seen by following the rise and fall of techniques as measured by their publication frequencies over time. For example, multiple regression was replaced by discriminant analysis which, in turn, was replaced by logistic regression. Logistic regression was the pioneer for a new batch of generalised linear models that have now been largely subsumed by generalised additive models.

It is clear that careful selection of the predictors should have a significant impact on SDM performance. Indeed, one of the main difficulties involved in creating effective SDMs is predictor selection. In general, refining the predictors, along with their measurement, is likely to yield bigger performance gains than making the SDM more complex. The aim is to select a small number of predictors that generate accurate predictions at minimum cost. MacNally (2000) listed four reasons why simple models should be sought.

1. They avoid model over-fitting, i.e. modelling noise in the data which degrades the model's performance with future data.
2. Future performance is generally lessened when there are too many predictors.
3. Simple models are thought to provide a better insight into causality.
4. Reducing the number of predictors reduces the economic cost of current and future data collection.

However, as Burnham and Anderson (2004) noted, there is a conflict between the need to produce a parsimonious model, that does not model noise, and the need to develop a model that is capable of representing the complexity within the data, i.e. there is a requirement to balance the SDM's bias against its variance. An SDM that is too simple may have a large bias while one with too much flexibility could have a high variance. Bias is a measure of the SDM's accuracy, i.e. the closeness of predictions to reality. Low bias implies high accuracy and is, therefore, a desirable property. Variance is a measure of precision or repeatability. If variance is high, accuracy will change markedly between different data sets. It is difficult to have confidence in the future performance of an SDM with high variance because the current accuracy may not be repeated with different sample data. Consequently, an SDM with low variance is also desirable. Although an ideal SDM would have both low bias and low variance there is an unfortunate trade-off such that one increases as the other declines. This is because low bias depends on an ability to adapt to differences in data sets, which is only possible if there are many predictors. Unfortunately a multi-parameter SDM is likely to have a high variance. This trade-off is reflected in the different relationships between training and testing error and SDM complexity. As an SDM's complexity increases errors within the training data should decline until some minimum is reached. However, although testing error will show an initial, parallel, decline with increasing model complexity it will begin to increase as the SDM passes its optimum complexity.

Variable selection always involves compromises but selections should be driven primarily by domain-specific knowledge. In reality, compromises are generally the consequences of cost and availability. In addition, if a large number of irrelevant predictors are used, Watanabe's (1985) 'ugly duckling' theorem will apply. The irrelevant predictors, which carry no information about probability of presence, tend to make mask differences between presence and absence locations and may degrade the SDM's performance, whilst also increasing the variance. As the number of predictor variables rise so do the number of possible models, especially if interactions and quadratic (squared) terms are also included. There are a number of automated techniques available for deciding which variables to include in a model, for example forward and backward selection after which, by using appropriate diagnostic statistics, the best model could be selected. Unless all of the predictors are orthogonal (uncorrelated), it is unlikely that any variable selection routine will select out the correct causal predictors, even if the selection produced a simple and accurate SDM. Identifying the optimum suite of predictors is only possible if all possible models are tested. Even then, procedures are needed to identify the 'best' of the resulting $2^{\text{predictors}}$ models and also estimating the independent effects of each predictor. Measures such as the Akaike and Bayesian Information Criteria (AIC and BIC) are often used to identify the best model by trading off model-fit against model complexity (number of predictors). However, it is important to distinguish between an efficient SDM, that has a statistically valid set of predictors, and an SDM that includes the predictors which have a causal relationship with presence and absence. While this means that variable and model selection algorithms are suitable for the generation of parsimonious models, the resultant models should not be interpreted as causal.

The main aim of an SDM should be to predict accurately the distribution of a species and a secondary, but ultimately very important aim, is to produce a model that can be understood outside of a small clique of post-docs. If a model is not understood by NGOs and government agencies involved in real conservation work it is unlikely that the model's results will inform conservation actions. Policy makers and many conservation managers may shun the esoteric in favour of simplicity and understanding while journal editors and referees will often reject a manuscript based on an older, and now unfashionable, technique. Altman and Royston (2000) summarized this succinctly in a medical context when they noted that "*usefulness is determined by how well a model works in practice, not by how many 0s there are in associated p values*". These, plus other concerns, lead to the general conclusion that an ideal SDM would be accurate, with utility and an ability to handle costs. Unfortunately these three terms are rather vague and open to different interpretations.

When predictions from a range of different SDMs have been compared there is often little to choose between them with respect to their accuracy. At best differences are marginal. Accuracy can be defined as "faithful measurement of the truth". However, this assumes that there is a truth against which predictions can be assessed. The robustness of the truth or gold standard against which accuracy is judged is an important, and often overlooked, issue. While accuracy measurement is unambiguous for situations such as forged versus valid passports, SDMs are used to predict the distribution of species that are almost always rare or endangered. When a population is below its carrying capacity there may be many suitable locations that are currently vacant. A simple comparison of an SDM's predictions against this current distribution is likely to result in a reduced accuracy. It is almost impossible to judge the true quality of this model unless, and until, the population expands and individuals occupy all suitable locations. It is important, in situations like this, to think carefully about how accuracy should be measured.

Utility is a measure of the total benefit or disadvantage to each of a set of alternative courses of action. When applied to an SDM it suggests that utility could be assessed from a list of the SDM's advantages/disadvantages. This would then allow fair comparisons to be made between SDMs, but what factors, apart from accuracy, contribute to the relative advantages and disadvantages? Four possible criteria are: speed of computation; comprehensibility of output; availability and complexity of software and, importantly, acceptability (by peers). These criteria can also be viewed as a cost framework. Although it is impossible to construct cost-free SDMs, it is possible, and usual for SDMs, to ignore costs. For example, failure to impose a misclassification cost structure implies that all misclassifications carry the same costs. Although it is often thought that costs are largely restricted to machine learning methods it is possible to incorporate them into standard statistical methods by adjustments to significance levels that alter the probability of type I and II errors. As Fisher stated in 1925, "*No scientific worker has a fixed level of significance from year to year, and in all circumstances, he rejects hypotheses; he rather gives his mind to each particular case in the light of his evidence and his ideas*". Unfortunately adjustments to the significance level are fraught with difficulties since alpha is a component of the power of a test and a frequently used measure of scientific acceptability. However, there is much more to SDM costs than misclassifications. There are costs associated with the predictors. Secondly there are computational costs, which include the time spent pre-processing the data and the computer resources needed to run the SDM. Third are the costs associated with the misclassified cases. Finally, there are the vague but real costs related to the acceptability of a piece of work by peers.

There is an implicit, or even explicit, assumption in many of the SDM comparison papers that some SDMs are better than others. So, the obvious question is which is the best? It is possible to phrase this question within two contexts. In the first the comparison would be between SDMs with different algorithms while the second compares different instances of one SDM, for example logistic regression, with different data sets. Such comparisons are fraught with difficulties, some theoretical and some more practical. In the first instance, Wolpert and Macready's (1995) no-free-lunch (NFL) theorem is a proof that there is no 'best' algorithm over all possible classification problems. This theorem implies that although one SDM may outperform another on problem A, it is possible that the ranking would be reversed for problem B. The second difficulty is more practical. Superficially it seems that comparing SDM performance should be simple. While between-SDM comparisons probably serve a useful purpose in the raising of awareness they sometimes oversimplify the process of comparison and generalise too much about the findings. It is not easy to demonstrate superiority of performance, if only because there is no single measure that should always be employed (Hand, 1997). Judging between SDMs depends on having sensible criteria and techniques for ranking their performance. In one comprehensive but non-ecological review, Lim *et al.* (2000) investigated the performance of 22 decision trees, nine statistical and two neural networks over 32 data sets. They showed that there were no significant differences in accuracy across most of the algorithms and any differences were so small that they had no practical significance. Their conclusion was that the choice of classifier must be driven by factors other than accuracy. This is reasonable since the existence of the NFL theorem means that other factors, such as size of the training set, missing values and probability distributions, are likely to be more important guides to the choice of classifier algorithm.

The R code for one of the random forest analyses used to generate the predicted distribution is shown in below.

```
#set the working directory
setwd("C:/Users/Alan/Desktop/SScotland_Eagles/model/")
#now read in the data file which is a tab separated text file
onekm <- read.delim("onekmdata.txt")

library(randomForest)
attach(onekm)
#get the variable we want to predict, in this example the class
y<-ACTIVE
#now choose the predictors - exclude the row ID field (field 1)
x<-onekm[,2:33]

#run the randomforest analysis
onekm.rf <-randomForest(y ~ ., data=x, importance=TRUE, ntree=2000,
votes=TRUE)
#look at the summary and the importance statistics
print(onekm.rf)
round(importance(onekm.rf), 2)

#create a data object with the original class and votes for the 3 possible
classes
compare<-cbind(onekm$ACTIVE,onekm.rf$votes)
#save a text file for import into a GIS and attachment to the sample
locations
write.table(compare,"compare.txt", sep="\t", dec=".")

#create an object of the importance statistics and save to a text file
onekmimp<-cbind(onekm.rf$importance,onekm.rf$importanceSD)
write.table(onekmimp,"importance_with_SSGEtraining.txt", sep="\t", dec=".")

#Now make predictions for the test data and save the file
sstest <- read.delim("testdata/sstest.txt")
sstestpredictions<-predict(onekm.rf,sstest,norm.votes=T, type="vote")
write.table(sstestpredictions,"testdata/sstestvotes.txt", sep="\t",
dec=".")
```

ANNEX 2: R RIDGE DETECTION AND DISTANCE-WEIGHTING CODE

This code is presented in two sections. The first identifies the ridges and the second calculates distances to the ridges and then attaches a weight depending on the distance,

```
#Ridge identification
#This code is intentionally verbose to ease understanding.
#It could be made much more efficient

library(raster)

#USER SUPPLIED VALUES
#The DEM as an ASC file.

#file paths need to be set to correct locations if files are to be saved and loaded
#set the working directory so that the full path is not needed again
#NOTE use / and not \ in file paths

setwd("C:/Users/Alan/Desktop/SScotland_Eagles/model/")

#dem_txt_file is the name of the DEM text file with no path but with file extension
dem_txt_file<-'demtest.txt'

#This is a text file that MUST have the asc extension, do not use .txt or .dat
ridgesave<-'tstridge.asc'

#Load the DEM into a raster layer called rdem
rdem <- raster(dem_txt_file)

#if an onscreen ridge map is required leave debug = T otherwise change it to F
debug<-T
#END OF USER SUPPLIED VALUES


# IDENTIFYING RIDGES
#First set a threshold value for the detection of ridges.
#This is used to compare the altitude of a putative ridge pixel against
#a mean calculated from a neighbourhood filter.
#Threshold is 26 m for 250 m (5 pixels) at 168 degrees
#(Tan 6 degrees = 0.1051, T=O/A so O = Tan A or 0.1051 x 250 m)
#But, there are two sides to a ridge so threshold is 54 (26+26 + 2)
#This setting seems to duplicate original PAT models
#and empirically this value creates #a visually acceptable representation of
#ridges when overlaid on to a 1:50,000 OS map.

threshold<-54

#Ridges are identified using the focal function from the raster package.
#first create two focal functions to sum the 5 cells to the left (west) and
#right (east) of the focal cell

leftrow<-
matrix(c(0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0),
nrow=3)
rrow<-matrix(c(0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0),
nrow=3)

# Combine the two EW filters and see if the combined difference is > threshold
hf <- ((rdem-focal(rdem, w = leftrow)))+(rdem-focal(rdem, w = rrow))>threshold

#Now the verticals (North – South)
lcol<-matrix(c(0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0),
nrow=11)
ucol<-matrix(c(0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0),
nrow=11)

# Combine the two NS filters and see if the combined difference is > threshold
```

```
vf <- ((rdem-focal(rdem, w = lcol)))+(rdem-focal(rdem, w = ucol))>threshold

#Now the diagonals
#nw corner
nwd<-
matrix(c(1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0),nrow=11)
#se corner
sed<-
matrix(c(0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
1),nrow=11)

nwsedf <- ((rdem-focal(rdem, w = nwd)))+(rdem-focal(rdem, w = sed))>threshold
#sw corner
swd<-
matrix(c(0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0), nrow=11)
#ne corner
ned<-
matrix(c(0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,
0), nrow=11)

# Combine the disgonal filters and see if the combined difference is > threshold
swnedf <- ((rdem-focal(rdem, w = ned)))+(rdem-focal(rdem, w = swd))>threshold

#a pixel is a ridge if one is detected vertically, horizontally or on a diagonal
ridge<-vf | hf | nwsedf | swnedf

#have a look at a plot of the ridges and save the file for importing into a GIS
if (debug) plot(ridge)
rfile <- writeRaster(ridge, filename=ridgesave, datatype='INT4S', overwrite=TRUE)

#tidy up
#remove(vf, hf, nwsedf, swnedf, leftrow, rrow, sed, swd, lcol, ucol, ned, nwd,
rfile)
```

Step 2 - distance weighting

```
#FIND DISTANCES FROM ALL PIXELS TO THE RIDGES
#These commands assume that a raster layer called ridge exists (i.e. is loaded)
#the ridge layer must have 1 for ridge pixels and 0 or NA for all other pixels
#It could be loaded from a saved .asc file
#If an onscreen ridge distance map is required leave debug = T
#otherwise change it to F

debug<-T

#The weighted distance map is saved as a text file in the working directory.
#This text file that MUST have the asc extension, do not use .txt or .dat
wtdist<-'wtdist.asc'

#Copy the ridge raster file and convert non-ridge values to NA
#The NA values are needed to enable distance calculations.
#The raster package distance function measures distances to non-NA values.

#The raster distance function measures distances to non-NA values.
rt2<-ridge
rt2[rt2<1] <- NA

#now do the distance calculation from ridges to all pixels.
```

```
#Note add 50 (PIXEL SIZE) otherwise there is an offset in the distances
rdist<-distance(rt2)+50

#have a look at the distances-to-ridges map
if (debug) plot(rdist)

#now convert ridge distances to 100m bands
r100m<-floor(rdist/100)

#now restrict distances to a 1200 m band as stated in the Ibis paper
r100m[r100m>12]<-NA
if (debug) plot(r100m)

#copy r100m to create a new raster for weighted distances
wr100m<-r100m

#create a raster based on the r100m raster and convert distance bands to weights
#assign the ridge distance weights based on the Ibis paper
#use large integer values to avoid floating point issues
wr100m[r100m==0]<-1000
wr100m[r100m==1]<-430
wr100m[r100m==2]<-249
wr100m[r100m==3]<-167
wr100m[r100m==4]<-110
wr100m[r100m==5]<-77
wr100m[r100m==6]<-70
wr100m[r100m>6]<-65
wr100m[r100m>12]<-0
if (debug) plot(wr100m)

#save the weighted distance to ridge file
rfile <- writeRaster(wr100m, filename=wtdist, datatype='INT4S', overwrite=TRUE)

#tidy up
rm(rdist, rt2)
```

ANNEX 3: R PAT MODEL CODE

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```
#PAT model for a single range
#Load the necessary R libraries
library(raster)
library(maptools)
library(spatstat)

#USER SUPPLIED VALUES, #NOTE use / and not \ in file paths.
#These are the range specific inputs needed to generate the PAT model
#set the name of working directory
wd<-'K:/Gisdata/PATModels/'
#The Weighted Ridge Distance file as an ASC file (see Annex 2)
#The nest file has a xTABy format and a final carriage return, no headers please
#A raster file of excluded pixels (e.g. lochs, forestry) is needed - see below
#A thiessen polygon shape file of the range boundary,
#talking account of neighbouring ranges if neeeded
      rangename<-'XYZ'
      wtdist_file <- 'xyzwtdist.txt'
      nestfile<-'xyznest.txt'
      excludefile<-'xyzexclude.txt'
      rangethiessen<-'xyzthiessent.shp'
#pixel size in m - needed for some calculations
      pixelsize<-50
#rinmax is the maximum radius of the RIN thiessen (range size)
      rinmax<-6000
#Range centres, a pair of X Y coordinates for each range read from a text file
      coords <- as.matrix(read.table(paste(wd,nestfile,sep='')))
#Number of ranges is found from number of XY coordinates
      ranges<-length(coords)/2
#Create the full file path name and load the weighted distance file
      wr100m_start<-raster(paste(wd,wtdist_file,sep=''))
#The exlude raster image pools all exclusion zones (e.g. water and forests).
#Exclusion regions must have values of NA with the rest being 0
      excluded<-raster(paste(wd,excludefile,sep=''))
#read in the range thiessen and plot it
v<-readShapePoly(paste(wd,rangethiessen,sep=''))
plot(v)

#covert the Thiessen polygon to a raster and use it to crop a 6km nest buffer
#An extent is needed for some cropping, use pixel size and max size of RIN
#to calculate the min and max values of an extent (a Raster parameter)
      xmn<-((coords[1,1]-rinmax)%/%pixelsize)*pixelsize
      xmx<-((coords[1,1]+rinmax)%/%pixelsize)*pixelsize
      ymn<-((coords[1,2]-rinmax)%/%pixelsize)*pixelsize
      ymx<-((coords[1,2]+rinmax)%/%pixelsize)*pixelsize
      ext<-extent(xmn,xmx,ymn,ymx)
      #get the weighted ridge distance and crop it to the extent from above
      wr100m<-crop(wr100m_start,ext)
      #Initialise a rasterised version of the RIN to the same size as wr100m
      rinraster<- rasterize(v, wr100m)
      plot(rinraster)
      #Find the nest centre and build a raster image that extends to 6000m
      nest<-cbind(coords[1,1], coords[1,2])
      nestras<-rasterize(nest, wr100m)

#First the nest has to have a NA value with everything else being 0 - needed
#for the distance function
      NAvalue(nestras)<-0
      nestras[nestras!=1]<-0
```

```
      nestras<-distance(nestras)
      nestras[nestras>rinmax]<-NA
      nestras[nestras>0]<-0
      plot(nestras)
      #Finally crop off any parts of the range Thiessen that are >6km from the nest
      #now need to crop them
      rinraster <- overlay(nestras, rinraster, fun=function(x,y){return(x+y)})
      wr100m<-overlay(rinraster,wr100m,fun=function(x,y){return(x+y)})
      plot(wr100m)


#NOW BEGIN THE PAT MODELLING
      #User supplied nest coordinate
         centre<-c(coords[1,1],coords[1,2])
      #find the extent of the rin and use it for cropping
         rinextent<-extent(rinraster)
      #Load the exclusion text file into a raster layer called rexclude and
      #ensure that the extents match, slight offsets in origin need to be corrected
         rexclude<-crop(excluded,wr100m)
         rexclude<-resample(rexclude,wr100m, method='bilinear')

#PART A
      #distances to the nest and number of 500 m bands - a function of RIN size
      #if intermediate maps are required leave debug = T otherwise change it to F
         debug<-T

      #find distances from the range centre to all pixels and crop it to the
      #spatial extent of the RIN
         cdist<-distanceFromPoints(wr100m,centre)
         cdist<-overlay(rinraster,cdist,fun=function(x,y){return(x*y)})
         if (debug) plot(cdist)
      #convert distances to 500m bands and remove any distances > 6000m (>12)
         r500m<-floor(cdist/500)
         r500m[r500m>11] <- NA
         if (debug) plot(r500m)

      #find the number of pixels in each band,1=0-500m, 2=500-1000m distance, etc
      #pixels is a count including NA cells
         pixels<-ncell(r500m)
      #How many NA cells are there?
         pna<-freq(r500m,value=NA)
      #Find the RIN area as the number of (Extent pixels - NA pixels).
      #pixel size as a proportion of 1 ha. Needed to convert pixel count ha
         pixha<-pixelsize/100*0.5
         rinarea<-round((pixels-pna)*pixha)
      #the number of 500 m bands from the maximum distance from the range centre
      #this is based on the RIN when r500 raster was masked with the rdem raster.
      #this should have a max distance of 6000m because of the RIN's construction,
      #otherwise it would be the max distance to the RIN boundary
      #use equation from Fig 3 of the Ibis paper
         bands<-round((rinarea*0.4049+2423.2)/500)
      #can't be more than 12 bands for a 6000m radius RIN
         if (bands>12) bands<-12
      #mask out any distances beyond maximum distance
         r500m[r500m>(bands-1)]<-NA

#PART B
#Construct the raw (no exclusions) PAT
#use the number of bands to find the initial percentage-use for each 500 m band.
#The calculation is a linear decay function
      baseuse_pct <- (136.59 * (bands^-0.89))
#and then the rate of use decay for each subsequent band (assumes linear decay)
      decayrate<-136.48 * (bands^-1.905)

#use-adjusted raster layer for distance from centre
      #no account taken of ridges at this point)
      baseuse<-(baseuse_pct-(r500m*decayrate))* 100000
      patbasesum<-cellStats(baseuse,'sum')
```

```
#find the number of pixels in each band, 1=0-500m dist, 2=500-1000m, etc
     r500m_pixs<-r500m
     for (j in 1:bands) r500m_pixs[r500m_pixs==(j-1)]<-freq(r500m,value=(j-1))
#now apply the weighted distance use to the base usage raster to adjust
#use-values to combine distances to the nest and ridges
     base_distwt<-wr100m*baseuse
#initialise 3 matrices with 0s to populate within the subsequent loop
      origbandbase<-matrix(c(0,0,0,0,0,0,0,0,0,0,0,0), nrow=1)
      wtbandbase<-matrix(c(0,0,0,0,0,0,0,0,0,0,0,0), nrow=1)
      bandratio<-matrix(c(0,0,0,0,0,0,0,0,0,0,0,0), nrow=1)
#now, following the ridge distance weighting, adjust the 500m distance bands
#to have the same sum as in the original baseuse map
     for (j in 1:bands) {
      baseuset<-baseuse
      tmpadj<-base_distwt
      baseuset[r500m!=(j-1)]<-NA
      tmpadj[r500m!=(j-1)]<-NA
      origbandbase[j]<-cellStats(baseuset,'sum')
      wtbandbase[j]<-cellStats(tmpadj,'sum')
      bandratio[j]<-origbandbase[j]/wtbandbase[j]
      }
     ratio<-r500m
     for (j in 1:bands) ratio[ratio==(j-1)]<-bandratio[j]

     pat<-base_distwt*ratio/r500m_pixs
     patsum<-cellStats(pat,'sum')
#normalise to sum to 10,000,000 to keep precision whilst converting to integer
     pat<-round((pat*10000000)/patsum)
     if (debug) plot(pat)
#save the raw PAT map and tidy up
rfile<-writeRaster(pat, paste(wd,rangename,"raw.asc",sep=''), datatype='INT4S',
overwrite=TRUE)
remove(baseuse,base_distwt,r500m_pixs,ratio,tmpadj,baseuset,origbandbase,wtbandbase
,bandratio)

#PART C
#Create the final PAT taking account of exclusions
#mask out excluded regions from the PAT with no exclusions
     tmp<-mask(pat,rexclude)
     #set the new 0 value cells to NA
     tmp[tmp==0]<-NA
     #tmp has the values and positions of the excluded pixels
     if (debug) plot(tmp)
     s3<-zonal(tmp,r500m, 'sum')
     #now do the same for the pat image
     s4<-zonal(pat,r500m, 'sum')
     #the loss in s3 has to be partitioned using the Ibis rules

     #find the use-per-band after exclusion and before redistribution of usage
     s1<-s4[,2]-s3[,2]
     #calculate usage redistribution categories to take account of excluded regions
     #1. retain 25% in the original band
     rd1<-s3[,2]*0.25
     retain<-rbind(rd1)
     #drop columns if needed, e.g. if there are 9 bands get rid of the outer ones.
     #if (bands<12) retain<-retain[,1:(bands+1)]
     #2. shift 25% out one band from the centre
     colno<-NCOL(retain)
     rd_out1<-matrix(nrow=1, ncol=colno)
     #3. shift 25% out two bands from the centre
     rd_out2<-rd_out1
     #4. shift 25% in one band towards the centre
     rd_in1<-rd_out1
     #now do the shifting
     for (j in 2:colno) rd_out1[j]<-retain[j-1]
     for (j in 3:colno) rd_out2[j]<-retain[j-2]
     for (j in 1:(colno-1)) rd_in1[j]<-retain[j+1]
     #get rid of NAs
```

```
rd_out1[1]<-0
rd_out2[1:2]<-0
rd_in1[colno]<-0
#5. tidy up for usage beyond last band and movement in from central band,
#spread this equally
rd_all<-((sum(retain)-sum(rd_out1))+(sum(retain)-sum(rd_out2)))/colno
#Finally add them all together
redistribute<-retain+rd_out1+rd_out2+rd_in1+rd_all

#Add these to the pat with exclusions to get new values for the bands.
#These band-use totals now have to be partitioned amongst the
#remaining (non-excluded) pixels with a distance-to-ridge adjustment
#make a temporary copy of the 500m distance band map
redistrib0<-r500m
#assign the redistributed use to each band
for (j in 1:bands) redistrib0[redistrib0==(j-1)]<-redistribute[j]
r500m_tmp<-r500m+rexclude
#cut out the exlcuded regions from the pat image
pat_tmp<-pat+rexclude
#start to create the redistributed pixels
#redistrib1 has the amount of use in each band to be shared between pixels
redistrib1<-redistrib0+rexclude
r500m_pixs_tmp<-r500m_tmp
#find the number of pixels in each band, 1=0-500m dist, 2=500-1000m, etc
for (j in 1:bands) r500m_pixs_tmp[r500m_pixs_tmp==(j-1)]<-
freq(r500m_tmp,value=(j-1))
#now divide the redistributed use by the number of pixels in a band
redistrib2<-redistrib1/r500m_pixs_tmp
#now adjust for distance from a ridge
redistrib3<-wr100m*redistrib2
redistrib3[redistrib3<0]<-NA
#find the sum of pixels in the distance-weighted redistribution
patsum2<-cellStats(redistrib3,'sum')
#find the actual sum of use to be redistributed
rsum<-sum(redistribute)
#normalise to the sum of redistributed use
patadj<-round(redistrib3*rsum/patsum2)
#last step - add this to the PAT with exclusion cut out and
#readjust total use to 100% (1000000)
pat2<-patadj+pat_tmp
pat2sum<-cellStats(pat2,'sum')
pat2<-round(pat2/pat2sum*1000000)
plot(pat2)
#tidy up
remove(redistrib0, redistrib1, redistrib2, redistrib3)

#Finaly write the finished PAT file
rfile <- writeRaster(pat2, paste(wd,rangename,"full.asc",sep=''),
datatype='INT4S', overwrite=TRUE)
```

ANNEX 4: PERSECUTION DATA

Poisoning incidents (count of incidents not the number of individuals) by hill group, species and type recorded in two time periods (all, up to 2011, and 2000-2011). (species codes: BO Barn owl; BZ Buzzard; C. Carrion crow; EA Golden eagle; GI Goshawk; MG Magpie; RN Raven; KT Red kite; RO Rook; SH Sparrowhawk; mammals also specified). None refers to species not recorded.

All years up to 2011

Hill group	None	BO	BZ	C.	EA	GI	MG	RN	KT	RO	SH	Cat	Dog	Fox	All
Cheviot Hills			**1**										**1**		**2**
Victim found			1										1		2
Ettrick Hills			**1**												**1**
Victim found			1												1
Galloway Hills									**1**				**1**	**1**	**3**
Victim & bait													1	1	2
Victim found									1						1
Lammermuir Hills	**2**		**5**					**3**							**10**
Bait found	2														2
Victim & bait			2												2
Victim found			3					3							6
Lowther Hills	**17**	**1**	**19**	**3**			**1**	**4**	**2**	**1**	**1**	**1**			**50**
Bait found	17														17
Victim & bait			7							1					8
Victim found		1	12	3			1	4	2		1	1			25
Moorfoot Hills	**3**		**17**					**2**	**3**						**25**
Bait found	3														3
Victim & bait			1												1
Victim found			16					2	3						21
Renfrewshire			**3**										**1**		**4**
Victim found			3										1		4
Tweedsmuir Hills	**1**		**2**		**1**	**1**									**5**
Bait found	1														1
Victim & bait			1			1									2
Victim found			1		1										2
Total	**23**	**1**	**48**	**3**	**1**	**1**	**1**	**9**	**6**	**1**	**1**	**1**	**3**	**1**	**100**

2000-2011

	None	BO	BZ	C.	EA	GI	MG	RN	KT	RO	SH	Cat	Dog	Fox	All
Cheviot Hills			**1**												**1**
Victim found			1												1
Ettrick Hills			**1**												**1**
Victim found			1												1
Galloway Hills									**1**						**1**
Victim found									1						1
Lammermuir Hills	**1**		**5**					**3**							**9**
Bait found	1														1
Victim & bait			2												2
Victim found			3					3							6
Lowther Hills	**17**		**17**	**3**			**1**	**4**	**2**			**1**			**45**
Bait found	17														17
Victim & bait			5												5

Victim found			12	3			1	4	2			1			23
Moorfoot Hills	**2**		**16**					**2**	**2**						**22**
Bait found	2														2
Victim & bait			1												1
Victim found			15					2	2						19
Renfrewshire			**1**												**1**
Victim found			1												1
Tweedsmuir Hills	**1**		**1**		**1**	**1**									**4**
Bait found	1														1
Victim & bait						1									1
Victim found			1		1										2
Total	**21**	0	**42**	**3**	**1**	**1**	**1**	**9**	**5**	**0**	**0**	**1**	**0**	**0**	**84**

Non poisoning incidents (count of incidents not the number of individuals) by hill group, species and type recorded in two time periods. (species codes: ML Merlin; BZ Buzzard; GI Goshawk; HH Hen harrier; K. Kestrel; PE Peregrine falcon; KT Red kite; SE Sort-eared owl; SH Sparrowhawk; TO Tawny owl).

All years up to 2011

	None	ML	BZ	GI	HH	K.	PE	KT	SE	SH	TO	All
Carsphairn Hills							**2**					**2**
Shot							2					2
Cheviot Hills	**2**		**1**				**1**				**1**	**5**
Set crow trap in illegal circumstances	1											1
Shot			1				1				1	3
Unset spring trap in illegal circumstances	1											1
Ettrick Hills	**1**				**1**							**2**
Nest destroyed					1							1
Use of live decoy to take birds	1											1
Lammermuir Hills	**5**	**1**	**1**	**1**	**1**	**1**		**1**				**11**
Bird caught/died due to illegal crow trap		1				1						2
Set Larsen trap in illegal circumstances	1											1
Set trap in illegal circumstances	1											1
Shot			1	1	1			1				4
Unset pole-type trap	1											1
Unset trap in illegal circumstances	2											2
Lowther Hills	**2**		**6**	**1**	**3**	**1**	**5**		**3**			**19**
Bird caught/died due to illegal crow trap			1	1		1						3
Nest destroyed							4					4
Shot birds			4		3				3			10
Unset pole-type trap	1											1
Unset trap in illegal circumstances	1											1
Moorfoot Hills	**3**		**1**									**4**
Shot			1									1
Unset pole-type trap	1											1

Unset spring trap in illegal circumstances	2											2
Pentland Hills							**4**					**4**
Nest destroyed							4					4
Renfrewshire					**1**		**2**			**1**		**4**
Nest destroyed					1							1
Shot							2			1		3
Tweedsmuir Hills	**1**		**1**	**3**			**5**					**8**
Nest destroyed				1			3					4
Set Larsen trap in illegal circumstances	1			1								2
Shot			1	1								2
Total	**14**	**1**	**10**	**5**	**6**	**2**	**19**	**1**	**3**	**1**	**1**	**59**

2000-2011

Row Labels	None	ML	BZ	GI	HH	K.	PE	KT	SE	SH	TO	All
Cheviot Hills	**2**						**1**				**1**	**4**
Set crow trap in illegal circumstances	1											1
Shot							1				1	2
Unset spring trap in illegal circumstances	1											1
Ettrick Hills	**1**											**1**
Use of live decoy to take birds	1											1
Lammermuir Hills	**4**			**1**				**1**				**6**
Set Larsen trap in illegal circumstances	1											1
Set trap in illegal circumstances	1											1
Shot				1				1				2
Unset trap in illegal circumstances	2											2
Lowther Hills	**1**		**4**		**2**	**1**	**4**		**3**			**13**
Bird caught/died due to illegal crow trap			1			1						2
Nest destroyed							3					3
Shot birds			2		2				3			7
Unset trap in illegal circumstances	1											1
Moorfoot Hills	**1**		**1**									**2**
Shot			1									1
Unset pole-type trap	1											1
Pentland Hills							**3**					**3**
Nest destroyed							3					3
Tweedsmuir Hills				**1**			**4**					**3**
Nest destroyed							2					2
Shot				1								1
Total	**9**		**5**	**2**	**2**	**1**	**12**	**1**	**3**		**1**	**32**

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All of nature for all of Scotland
Nàdar air fad airson Alba air fad