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IMPROVING PREDICTION OF GOLDEN EAGLE (*AQUILA CHRYSAETOS*) RANGING IN WESTERN SCOTLAND USING GIS AND TERRAIN MODELING

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ABSTRACT.—A current model for predicting range use of Golden Eagles (*Aquila chrysaetos*) in western Scotland is derived from observed ranging behavior, a central point, and elevation. An improvement to this model is described that incorporates terrain features. Ridges are modeled as an assumed surrogate for deflected updrafts of air currents. Golden Eagles preferred areas close to ridges and close to the center of the range described by mean nest site location in the past 10 yr. The new model is an assemblage of the observed relationships between ranging points and the range center and ridge features, with an elevation cutoff, applied to a locally-derived range center and range boundary.

KEY WORDS: *Golden Eagle*; Aquila chrysaetos; *home range*; *ranging behavior*; *range model.*

Mejorando la predicción del rango del águila real (*Aquila chrysaetos*) en el oeste de Escocia usando SIG y modelamiento de terrenos

RESÚMEN.—El modelo actual para predecir el uso del rango del águila real (*Aquila chrysaetos*) en el oeste de Escocia se deriva del comportamiento de rango observado, un punto central, y la elevación. Se describe un mejoramiento a este modelo incorporando las características del terreno. Las cordilleras son modeladas como un sustituto adoptado para desviar los movimientos ascendentes de las corrientes de aire. Las águilas reales prefieren áreas cercanas a las cordilleras y cerca al centro del rango descrito por la media de la localización del sitio nido en los últimos 10 años. El nuevo modelo es un ensamblaje de las relaciones observadas entre los puntos del rango, el centro del rango y las características de las cordilleras, con un corte en la elevación, aplicado a un centro de rango derivado localmente y a un limite de rango.

[Traducción de César Márquez y Victor Vanegas]

The conversion of large tracts of open upland habitat to plantations of dense stands of conifer trees is one of the most significant land-use changes in Scotland over the last 50 yr (Avery and Leslie 1990). Concern over these changes prompted several studies of the effects of commercial forestry on birds, including the Golden Eagle (*Aquila chrysaetos*) (Marquiss et al. 1985, Watson et al. 1987, Watson 1992). This work demonstrated a link between reduced breeding success of eagles and commercial tree planting and suggested that breeding pairs may abandon ranges if extensive planting occurred close to range centers.

McGrady et al. (1997) evaluated the impact of forestry on Golden Eagles by systematically collecting observations of Golden Eagle range use by radiotagged birds in Argyll, Scotland. Their aim was to explicitly identify important areas for eagles and to develop a generalized range prediction model so that future forestry proposals could be judged for their likely impacts on eagle ranging where data on range use did not exist. This model is commonly known as the RIN model after the series of Research Information Notes in which it was published. It provides a simple prescription to estimate the likely boundaries and the core area of an eagle range based on knowledge of the range center, described by the average nest site location, and the centers of neighboring ranges. While eagles may range 6–9 km from their range centers, the "core area" of the range is within 2–3 km of the range center and represents the area where eagles are expected to spend 50% of their time. The model also gave general guidance on where to site new forest planting. It suggested that tree planting in core areas could be detrimental to eagles, and that such planting usually should be avoided or at least kept below the 40% of landcover within 4 km level indicated by Watson et al. (1987) as having a negative impact on eagles. It also recommended that plantings in low areas had less impact on eagles than those at middle elevations.

The simplicity of the RIN model and its foundation in field observations, together with the growing recognition of the need to protect Golden Eagles away from designated protected sites in the "wider countryside" (Watson and Whitfield, this volume), has led to its increasing adoption by foresters and conservationists alike. This paper describes some of the results of ongoing research to improve modeling techniques for predicting Golden Eagle ranging behavior using a Geographic Information System (GIS). It also illustrates several areas of conservation management where the predictive capabilities of range modeling could be applied and suggests further directions for model development. Here, we present a simple overview of the direction of this range modeling. More detailed information (McLeod and Whitfield 1999) and results are published elsewhere (Whitfield et al. 2001).

MODEL DEVELOPMENT

Development of a range prediction model requires data on known ranging behavior, coupled with data on environmental factors, including physical features of eagle ranges. If ranging behavior is affected by environmental factors, then it should be possible to predict behavior from knowledge of the environmental factors alone. The success of the predictive model will depend on the strength of association between behavior and environment and how successfully the environmental factors to which Golden Eagles respond can be incorporated into the model.

DATA ON RANGING BEHAVIOR

The modeling process described here employs the same ranging data used to derive the RIN model (McGrady et al. 1997). The field study area was north Argyll in the western Highlands of Scotland (Fig. 1). From 1992–96, 9 adult Golden Eagles were radiotagged in six home ranges and tracked Birds were located with the aid of the radio tags and triangulated visual sightings were made by at least two observers and recorded relative to geographical location as X-Y coordinates. One day constituted an observation session. Out of each session, a location was chosen randomly for inclusion in the analysis. Additional points within a session were used if they were >1 hr earlier or 1 hr later than the original random location. This process was repeated until selection spanned the entire day-long observation period and had included all observation days. Only records during the nonbreeding period were included in the analysis, and if both birds in a pair were tagged, the combined observations were used to define the overall range of the pair (Marzluff et al. 1997). An example of the range use data is illustrated in Fig. 2. It was not known if the radio tags affected range use, although no effect was obvious.

ENVIRONMENTAL FACTORS: RANGE CENTER AND BOUNDARIES

Observations were clustered around a few localities, notably a "central" area within 2–3 km of nests and were distance-limited in distribution (i.e., over 98% of range use observations were within 6 km of the range center) (Fig. 2). The environmental factor that provided the best fit to the home range center was the mean nest location within the past 10 yr (McGrady et al. 1997). Eagle locations were generally closer to the range center when other territories were immediately adjacent. Hence, when neighboring range centers were <12 km apart, range boundaries could be estimated reasonably by delineating equidistant points between adjacent range centers. In the absence of neighbors, we estimated range boundaries at 6 km from range centers (McGrady et al. 1997). These two environmental factors, range center and influences on range boundary, are fundamental to both the RIN model and the new modeling direction, and their influence is assumed for present purposes (McGrady et al. 1997). Even though the new model is founded in and represents an extension of the RIN model, to differentiate it from the RIN model, it is called the PAT (Predicting *Aquila* [*chrysaetos*] Territory) hereafter.

ENVIRONMENTAL FACTORS: TERRAIN

Golden Eagles are large birds that exploit air currents for much of their activity (Watson 1997),

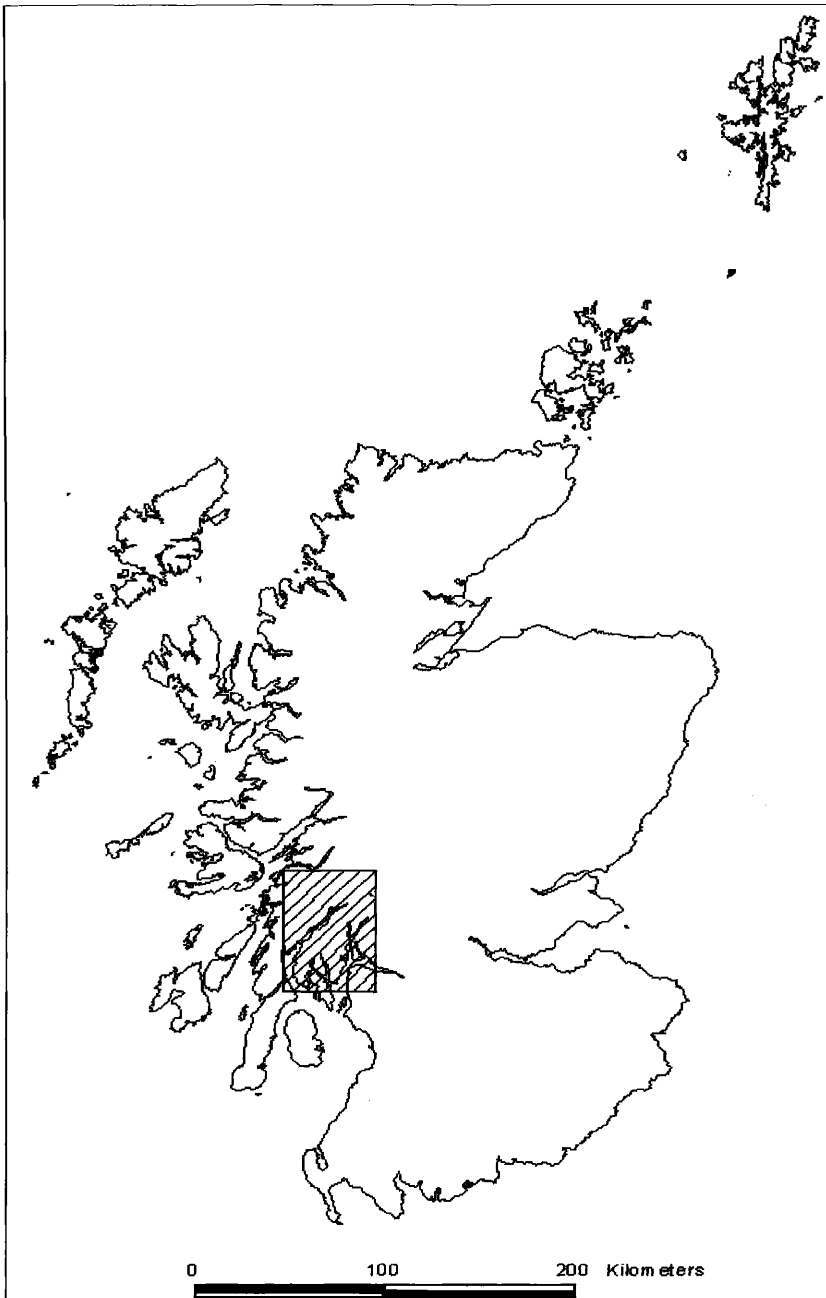

Figure 1. Study area in Argyll, Scotland.

but in the relatively cool climate of the Scottish Highlands thermal updrafts are rare. In a thermal-poor environment, ridges provide upward deflected air where eagles can soar and help determine ranging behavior. Chalmers (1997) demonstrated that Golden Eagles in western Scotland showed significantly positive selection for ridge features in ranging behavior. It is also likely that Golden Ea-

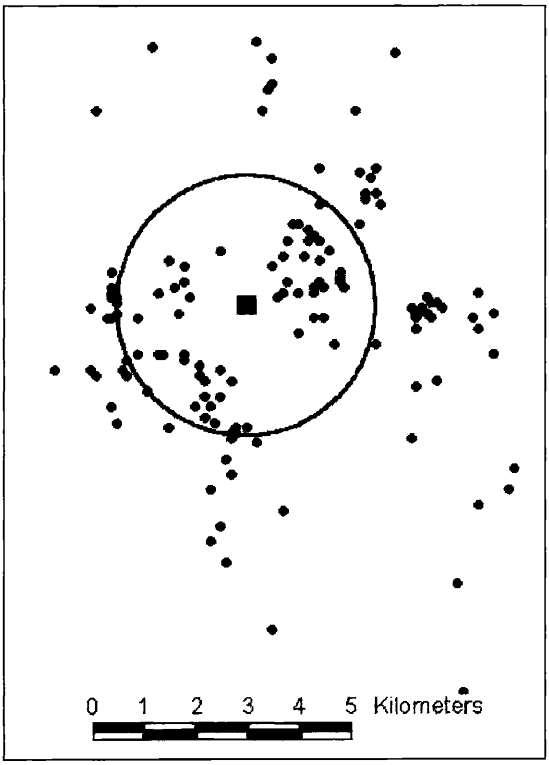

Figure 2. Example of observations of radiotagged Golden Eagles used in the development of the range use model, shown in relation to the estimated range center (square) and a 2.5 km radius about the center.

gles do not favor low elevations both because they are poor in airflow and may be more likely to be centers of potential human disturbance or unsuitable habitat (Watson and Dennis 1992, González et al. 1992). Novel features of the PAT modeling process partially reflected such considerations. These features were incorporation of ground according to coarse distance decay functions in relation to the range center (i.e., a decreasing range of elevations was assumed to be used by eagles with increasing distance from the center) and preferential inclusion of ground close to ridges. The PAT also excluded all elevations below a value derived from the mean and variance that were available within the range being modeled (Watson and Dennis 1992). Golden Eagles prefer certain land cover or habitat types (McGrady et al. 1997), at least in part because of prey availability (Marzluff et al. 1997).

All modeling was undertaken in a raster environment using ArcView Spatial Analyst. Environmental data included terrain (the UK Ordnance Survey, OS) and range center, taken as the mean coordinate for nests used in the past 10 yr.

RANGE USE RELATIVE TO THE CENTER

The range center was calculated and Thiessen polygons were constructed for each range for which we had telemetry data. Concentric annuli, 500 m in width, were circumscribed around the center of each range (i.e., annuli 1 = 0–500 m, annuli 2 = 500–1000 m, etc.). The amount of land available within each annulus was then calculated for each range and then summed for each distance class across all ranges. Ranging data were aggregated for all ranges and the distance to the center was calculated for each data point. Ranging data were assigned to distance categories defined by the annuli and these were aggregated from all ranges. The number of ranging points observed within each annulus, or distance class, was then represented as a proportion of the number that would be expected if all ranging points were randomly distributed according to the land available within each distance class (Fig. 3). Values >1 indicated that observed use was greater than expected and values <1 indicated that observed use was less than expected. Eagles showed an increasing "preference" for areas closer to range centers and increasingly "avoided" areas beyond 2.5–3 km from centers (Fig. 3). The transition from positive to negative use at 2.5–3 km was consistent with the core concept described by McGrady et al. (1997). Eagle use preferences, according to their distance from centers, were used to assign a weighting for each pixel within the Theissen polygon.

USE OF TERRAIN: ELEVATION

The RIN model assumes that all elevations within the core range are exploited by eagles whereas only those >150 m elevation are exploited outside the core (subject to regional modifications) (McGrady et al. 1997). A number of less coarse methods were explored to incorporate local variation in a lower ranging elevation threshold into the PAT. The method that appeared to best match observations calculated the mean and variance of the elevations available within 2.5 km of range centers. It then took a value equal to a single standard deviation below the mean as the lower elevation threshold across the whole range. The PAT as-

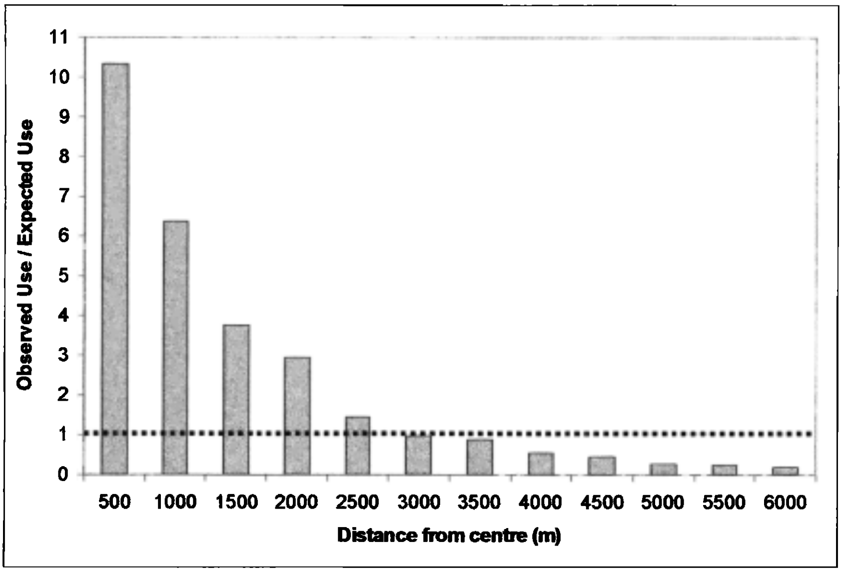

Figure 3. Observed use of range/expected use of range according to distance from the range center for six Golden Eagle ranges in Argyll. Broken line is where observed use equaled expected use.

1	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	3
0	1	0	0	0	0	0	0	2	0	0	0	0	0	0	3	0
0	0	1	0	0	0	0	0	2	0	0	0	0	0	3	0	0
0	0	0	1	0	0	0	0	2	0	0	0	0	3	0	0	0
0	0	0	0	1	0	0	0	2	0	0	0	3	0	0	0	0
0	0	0	0	0	1	0	0	2	0	0	3	0	0	0	0	0
0	0	0	0	0	0	1	0	2	0	3	0	0	0	0	0	0
0	0	0	0	0	0	0	1	2	3	0	0	0	0	0	0	0
4	4	4	4	4	4	4	4		4	4	4	4	4	4	4	4
0	0	0	0	0	0	0	3	2	1	0	0	0	0	0	0	0
0	0	0	0	0	0	3	0	2	0	1	0	0	0	0	0	0
0	0	0	0	0	3	0	0	2	0	0	1	0	0	0	0	0
0	0	0	0	3	0	0	0	2	0	0	0	1	0	0	0	0
0	0	0	3	0	0	0	0	2	0	0	0	0	1	0	0	0
0	0	3	0	0	0	0	0	2	0	0	0	0	0	1	0	0
0	3	0	0	0	0	0	0	2	0	0	0	0	0	0	1	0
3	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	1

Figure 4. Grid representing individual elevation pixels within the raster GIS, and the process used to determine ridge features. The black square is a source pixel and the four orientations (1–4) in which elevation comparisons were made. If the elevation was lower in all neighbors in any one orientation then the source pixel was classed as a ridge pixel. This process was repeated for all pixels within the range area.

sumes that Golden Eagles do not use areas below this elevation threshold.

USE OF TERRAIN: RIDGES

Ridges can be defined in a number of ways, such as river catchment boundaries, but a method was required that would allow the future incorporation of scale factors, such as distances between ridges, and more qualitative definitions, such as their steepness. In a raster GIS, the method that identified ridges best compared the elevation of each pixel against its neighbors in each of four orientations (NE-SW, N-S, SE-NW, E-W: orientations 1 to 4, respectively, Fig. 4). If the source pixel was higher than all of its neighbors in all directions then it was a local peak; if the source was higher than its neighbors on both sides in at least one orientation then it was classed as a ridge pixel. This process produced some "noise" in the form of isolated "ridge" pixels, but these were filtered out as a post-processing operation to produce defined ridge features.

The vast majority of land was <4 km of a ridge feature and was split into 100 m distance bands from the nearest ridge. The amount of land available within each distance class was then calculated for each range and then summed across ranges and yielded an expected distribution of ranging behavior if it was neutral with respect to ridge fea-

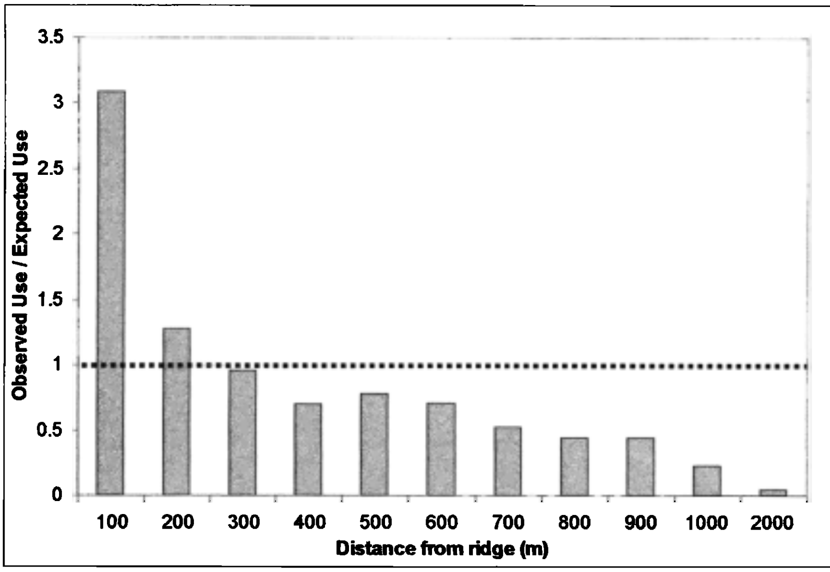

Figure 5. Observed use of range/expected use of range in relation to distance from a ridge feature for six Golden Eagle ranges in Argyll. Broken line is where observed use equaled expected use.

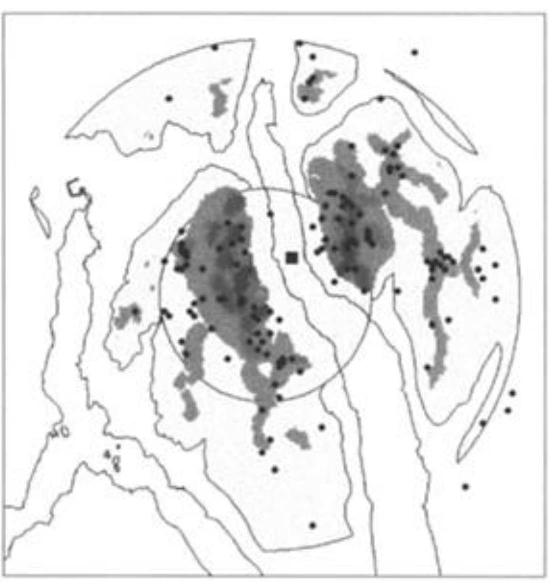

Figure 6. Example of the predicted Golden Eagle range according to the PAT model (darker shading), in relation to observations of actual range use (solid circles), the range center (square), and predicted range according to the RIN model (lighter shading = inner core and outer range boundary).

tures. The number of ranging points in each distance class was then calculated to give an observed distribution of ranging behavior with respect to ridges. The number of ranging points observed within each distance class was represented as a proportion of the number that would be expected if all ranging points were randomly distributed according to the land available within each distance class (Fig. 5). Since values >1 indicated preferential use, it was apparent that Golden Eagles made more use than expected of areas <200 m from a ridge. Eagle preferences, according to distance from a ridge, were incorporated into the model to provide an appropriate weighting for each pixel within the Theissen polygon.

THE PAT MODEL

In the raster GIS with a range center, range boundary and ridge features in place, every pixel had weighting due to its distance to the center and its distance to the nearest ridge. These weightings were added together to give a single probabilistic value for each pixel. Applying the elevation threshold cut-off to all pixels was the final step in the PAT model output (Fig. 6).

For the six ranges in Argyll the fit of the PAT model's predictions to the ranging observations were encouraging and a marked improvement on those of the RIN model (Fig. 6). However, a more rigorous test would be against ranging observations collected away from the study area.

FUTURE MODEL DEVELOPMENT

The PAT model is a modeling direction, and not a single model. There are a considerable number of future developments to the modeling approach that would be desirable. First is the need to address some of the restrictions inherent in the ranging observations. Behaviors associated with the observations would help to refine the modeling process as Golden Eagles can use different parts of their range for different purposes. Range boundaries, for example, may be visited primarily for territorial display purposes (Watson 1997), and so features that may be important in the rest of the range (e.g., food availability) may be irrelevant in this context. Second, it is important to note that both the RIN and PAT models relate to the nonbreeding season only and Golden Eagle range use can vary with breeding activity (Marzluff et al. 1997, J. Stacey unpubl. data). It is highly likely that the core of the nonbreeding range becomes even more important during the breeding season, but this should be quantified and incorporated into the modeling process. Third, inclusion of land cover information would probably improve the predictive capability of the model, as the radiotagged birds displayed habitat preferences that were probably related to prey availability (McGrady et al. 1997). The apparent predictive success of the PAT model, albeit within a limited set of comparisons, is perhaps surprising without any explicit reference to or surrogate for vegetation type or prey. The preference for ridgelines may nevertheless be at least partly related to prey or habitat availability as well as improved airflow.

Clearly there is a need to examine the model's abilities in a range of other types of Golden Eagle territories and, in all likelihood, adapt it accordingly. A means of recognizing "dead ground" within the modeling environment should be possible and may improve predictions too, given that eagles can exploit such features to surprise their prey (Watson 1997). A more intractable problem may be predicting the use of highly localized and range-specific "honey pot" prey supplies such as rabbit (*Oryctolagus cuniculus*) or seabird colonies. In the absence of any supplementary local information, the best that may be possible under such circumstances would be to exercise additional caution in interpreting model predictions for low-lying or coastal pairs.

THE GOLDEN EAGLE GIS

The PAT model is one component of a larger GIS application implemented within ArcView and Microsoft Access. It provides a powerful tool for assisting with the management of, and research into, Golden Eagles.

The 1992 National Survey of Golden Eagles (NSGE) (Green 1996) has been entered into an Access database, and includes data on range occupation and breeding success. The Access database has been dynamically connected to ArcView to enable better management, visualization, query, and analysis of these data, as well as ensuring security of the NSGE data. The GIS includes customized and standard research, analysis, and model development capability.

The modeling software allows implementation of range modeling across large areas of Scotland. This facility allows more strategic planning for conservation issues related to Golden Eagles. For example, rather than assessing the impact on Golden Eagles of individual forest planting proposals on a case-by-case basis, as is current practice, areas that are important to Golden Eagles and where there may be conflict with commercial forestry can be predefined across large areas. Similarly, wind farms can potentially pose risks to Golden Eagles (Whitfield 2000). Predefinition of sensitive areas for Golden Eagles will allow their incorporation much earlier into the costly wind farm planning process.

The influence of changes in environmental factors on Golden Eagle numbers and breeding success can be tracked efficiently within the GIS, and when coupled with an ability to model those areas where environmental change is most likely to affect Golden Eagles, it becomes a powerful research tool.

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