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Spatial association as an indicator of the potential for future interactions between wind energy developments and golden eagles *Aquila chrysaetos* in Scotland

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ABSTRACT

Despite their environmental benefits in generating electricity without emission of 'greenhouse' gases, wind farms have attracted controversy with regard to their impacts on birds, especially golden eagles *Aquila chrysaetos*. Evidence from USA studies suggest eagle fatalities through collision with turbines may be the main potential impact whereas for breeding eagles in Scotland, displacement from wind farm areas (indirect habitat loss) may be the primary impact. In this study, we examined the co-occurrence potential for golden eagles and wind farms in Scotland by documenting the spatial association between wind farm proposals and breeding eagle territories and areas potentially suitable for non-breeding eagles. Although there were records for over 500 wind farm proposals at various stages of development, relatively few coincided with eagle territories (ca. 4% of territories had a proposal within 3 km of territory centre). Similarly, only 2% of habitat predicted to be suitable for non-breeding eagles overlapped with proposed or installed wind farm areas. Moreover, estimates of the potential for electricity generation from all wind farm proposals, with respect to government targets for renewable energy supplies, suggested most proposals were unlikely to be constructed. We conclude that in comparison with other constraints on Scotland's golden eagles, notably persecution, wind farms should not represent a serious concern if best practice in planning their location and minimising their impact are maintained. Potential future regional pressures on breeding eagles from wind farms are highlighted, however, and uncertainty of impact with respect to displacement or collision fatalities requires continued scrutiny.

1. Introduction

Increasing numbers of wind farms are being constructed in many parts of the world as a response to concern over the climatic effects of 'greenhouse' gases, because increasing the contribution of renewable sources of energy supplies is seen as a means of reducing outputs of greenhouse gases. Despite the environmental benefits driving their construction, considerable controversy has accompanied wind farms and their effects on birds. Wind farms may have at least three potentially adverse impacts on birds (e.g., Gill et al., 1996; NWCC, 2000; Bern Convention, 2003):

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- Fatality through collision with wind turbine blades and associated power lines (although the latter is a potential factor for most forms of electricity generation).
- Displacement of birds around turbines or the wind farm site, including so-called 'barrier effects', as a result of disturbance (effectively indirect habitat loss).
- Direct habitat loss through the construction of the wind farm and ancillary structures (not considered influential at most wind farms as the scale of habitat loss is usually negligible, e.g., Bern Convention, 2003).

Much of the current controversy surrounding wind farm impacts have been prompted by the findings from one of the earliest large wind farms (several thousand turbines) at the Altamont Wind Resource Area (WRA) in California where many birds of prey have been found killed by strikes with turbine blades (e.g., Smallwood and Thelander, 2004). Particular concern has been expressed over fatality rates of golden eagles *Aquila chrysaetos* due to its legal status (e.g., Hunt, 2002). In the only study of a wind farm on the population of any bird, results suggested sufficient eagles were being killed at Altamont WRA to have an effect on local population abundance, but the lack of any observed change in population abundance may have been because many sub-adults killed came from migratory populations to the north (Hunt et al., 1997, 1999; Hunt, 2002). Studies at other sites in the USA, however, have not recorded comparable golden eagle fatalities (Erickson et al., 2001), and detectable impacts on populations were highly unlikely. Many of the fatality differences may be accounted for by site differences in eagle activity levels (Smallwood and Thelander, 2004), suggesting improved wind farm site selection following the installation of Altamont WRA (Johnson et al., 2000; Young et al., 2003).

Due to the antagonistic nature of displacement and turbine collision risk (Band et al., in press) collision risk declines if displacement occurs. At Altamont WRA there were no pre-construction studies of golden eagle activity levels, so definitive conclusions on the occurrence of displacement are not possible (Smallwood and Thelander, 2004). The available post-construction evidence, however, suggested that neither non-breeding sub-adults (which are the majority age class within the WRA) nor breeding adults were obviously displaced (Hunt et al., 1997, 1999; Hunt, 2002). Initial studies following construction of the Foote Creek Rim wind energy facility in Wyoming, USA indicated activity levels of golden eagles were similar to pre-construction observations: both non-breeding subadults and breeding birds were present (Johnson et al., 2000). Most other studies at USA wind farms on golden eagles and other birds of prey also suggest that displacement is not an influential factor (Madders and Whitfield, 2006).

By contrast, studies at a smaller Scottish wind farm within a golden eagle breeding territory indicated that the resident pair probably avoided the wind farm (Walker et al., 2005). The difference between Scotland and the USA may lie in a prolonged history of human persecution and greater use of remote areas away from human influence for eagles in Scotland (Whitfield and Coupar, in press) or that because turbines at Scottish sites typically are not arranged in 'strings' there are no obvious gaps where birds could 'feel safe' in entering the wind turbine arrays. If the latter argument is correct, future wind farms with larger turbines (and hence larger separation distances) may not be avoided in Scotland. As yet there are no studies in Scotland to indicate the reaction of non-breeding eagles to wind farms.

There were an estimated 443 occupied golden eagle territories in Scotland during 2003 (Whitfield et al., 2006; Eaton et al., in press) with territory occupancy, breeding productivity and survival rates varying regionally (Whitfield et al., 2004a,b, 2006; Eaton et al., in press). Conservation status also varies regionally, with only some sub-populations in regions of the western Highlands and Islands in favourable condition (Whitfield et al., 2006). Watson and Whitfield (2002), in deriving the concept of a conservation framework for Scottish golden eagles, noted several constraints (negative influences on abundance, distribution and demography) which act on golden eagles in Scotland, including afforestation, persecution by humans, grazing and recreation. The influence of these constraints varies regionally, so that, for example, grazing by sheep and/or red deer *Cervus elaphus* likely causes reduced productivity and jeopardises occupation of several territories in some western Highland regions through its effect on herbivorous prey of eagles (Watson, 1997; Watson and Whitfield, 2002; Whitfield et al., 2006). Historically, habitat loss through commercial conifer afforestation has also caused reduced productivity and territory abandonment in western Scotland (Watson, 1997; Watson and Whitfield, 2002) although this appears to be much less influential in recent years (Whitfield et al., 2006, in press). The most serious constraint, however, is the effect of persecution on some moorlands managed for shooting red grouse *Lagopus lagopus scoticus* in the central and eastern Highlands (and, likely, south of the Highlands) through its influence on eagle demography (Watson, 1997; Watson and Whitfield, 2002; Whitfield et al., 2003, 2004a,b, 2006, submitted). Persecution is strongly implicated in the vacancy of numerous otherwise suitable territories and in placing the national population at risk of decline (Whitfield et al., 2004a,b, 2006, submitted).

Watson and Whitfield (2002) indicated that wind farms may present a potential future constraint for the golden eagle and recommended their consideration within a national conservation framework. If resident eagle pairs are displaced by wind farms then indirect habitat loss could lead to range abandonment, reduced productivity or have little effect (Whitfield et al., 2001, in press). The impact of habitat loss on eagles is difficult to predict at the territory level (Whitfield et al., 2001, in press) and thus practically impossible to predict nationally (moreover, mitigation measures may often accompany installation, e.g., Madders and Walker, 2002). If displacement does not occur, national scale of analyses, uncertainty over the precise effects of wind farms on eagles generically and site-specifically, and that precise details of most wind farm schemes are currently unknown, precludes prediction of any population effects of any collision fatalities for resident pairs.

For non-breeding eagles, as for resident pairs, wind farms may effectively cause habitat loss or collision fatality. Previous analyses had suggested that subadult non-breeding eagles may move from areas where persecution does not occur into areas where persecution occurs (Whitfield et al., 2004a), creating a potential ecological trap or population sink (Delibes et al., 2001). Hence, if significant areas of non-breeding habitat in regions safe from persecution are lost to wind farms through displacement this could lead not only to local impacts but also lead to an increased threat to the national population by encouraging emigration to regions with persecution even if no active territories are affected. It is also probable that there is heterogeneity in the suitability of potential habitat for non-breeding eagles, and that 'settlement areas' are especially important (Ferrer, 1993; Penteriani et al., 2005a,b); thus, the loss of such areas is liable to have greater population consequences. Also, obviously, if displacement does not occur, then collision fatalities are far more likely if wind farms are located in such settlement areas. However, as for resident pairs, whilst such considerations are clearly important, they are beyond the scope of current capabilities because of the required scale of analyses, absence of knowledge on the existence and location of 'settlement areas', and uncertainty over the nature of windfarm impacts on non-breeding eagles and precise details of most wind farm schemes.

Frankly, we doubt if it will ever be possible to predict future regional or national impacts of wind farms on eagles to a degree where population implications could be modelled: such an exercise is even very difficult (and rarely undertaken) at the level of a single wind farm proposal with detailed site-specific information. Nevertheless, this does not preclude gaining a picture (albeit crude) of the extent to which wind farms may represent a potential threat by simply documenting the potential for wind farm development in areas used by eagles. If the number of prospective wind farms in 'eagle habitat' is small, then the implication is that the threat may not be serious (especially when through the planning process the effects of any specific proposal may be manageable through mitigation or proposal rejection). Conversely, if the number is large then the implication is that wind farms may represent a serious threat, thereby requiring even greater scrutiny of proposals and an urgent appraisal of locational and capacity strategies for wind farm development.

Our primary objective, therefore, was to provide an overview of the extent to which wind farms may be a potential constraint for golden eagles nationally and regionally by documenting the current and future potential for spatial co-occurrence of wind farm proposals in areas known (resident pairs) or liable (non-breeding birds) to be used by golden eagles. A similar approach has been adopted for other potential constraints on golden eagles (Watson and Whitfield, 2002; Whitfield et al., 2004a,b, 2006). Hence, a further objective was to discuss wind farms in the context of other constraints which may be acting on the Scottish golden eagle population. Such an approach has not been considered before for any species which may potentially co-occur with wind farms.

The main driver of the current expansion of terrestrial wind farms in Scotland is government policies to increase the share of renewables in energy output: the latest decision is to have 40% of Scotland's energy requirements from renewable sources by the year 2020 (Scottish Executive, 2003). Depending on the impact of energy efficiency measures, this will require about 3000–5000 MW of installed wind energy generation, assuming a 50% contribution of wind energy to the target, according to an industry estimate (SRF, 2005). Another source has estimated 3600 MW as a possible wind energy capacity if the government target for renewable energy is to be met mainly by onshore wind energy (SNH, 2003). It is reasonable to assume that once the renewable energy target is reached the likelihood of further wind farms will be substantially reduced as, presumably, government incentives to encourage appropriate installations will also be reduced or removed. Consequently, some schemes are more likely to co-occur with golden eagles simply because they are more likely to be installed before the government target is reached, and assuming all schemes will be installed would exaggerate our assessment of potential interactions between wind farms and golden eagles. Our final objective, therefore, was to examine broad trends in the potential installed capacity with respect to the government target.

2. Methods

We obtained data on wind farm schemes from two main sources. The first was the Casework Recording System (CRS) of Scottish Natural Heritage (SNH: a statutory consultee for schemes in Scotland in its position as the advisor to government on natural heritage issues) (SNH, 2003, 2004). Schemes are recorded and updated in CRS according to the following stages in the development planning process: pre-application (proposals at the earliest stage of development which have not entered the planning system), scoping (schemes registered with the planning authority in order to seek a direction or 'scoping opinion', about the nature of any environmental assessment needed), application (schemes for which planning permission has been sought), approved (schemes with planning consent), refused (rejected by the planning authority) and installed (operational). Data were collated as of the end of December 2004. The second data source was the Gazetteer of Wind Power in Scotland (SWAP, 2005). Data in Scottish Wind Assessment Project (SWAP) had a number of origins, similar to those behind CRS and were collated to 9 January 2005. If there was a doubt about possible duplication between data sources, only one record, from CRS, was included: we believe that duplication within our combined national dataset was no more than a handful of cases, at most.

Scheme parameters recorded by CRS and SWAP included 'installed capacity' (the energy output capacity in MW if or when the scheme is installed), the number of turbines, and the dimensions of turbines (CRS only). Data on installed capacity or turbine numbers were available for a lower proportion of pre-application schemes (85/282 = 30.1%) than for schemes at other stages (scoping, at 78/88 = 88.6%, was the next worst). Geographical grid location was also recorded, although for schemes in the earliest stages of development these could be crude which should temper any conclusions reached.

The area covered by a wind farm, or its 'footprint', was estimated from predictors derived from regression relationships between known turbine parameters of installed or proposed schemes and footprint. This assumes that footprint is a function of turbine or blade size and turbine number, and separation between turbines is a function of their metrics, with larger turbines having a greater separation distance to prevent wind interference (separation distance approximately six times the diameter of turbine blade disc, as measured from maps of five installed schemes). Thus, a footprint area was approximated by number of turbines × (6 × blade diameter)^2, and a circular buffer of a wind farm location = $\sqrt{}$(farm area/π). From 89 schemes where there were data on installed capacity, turbine number and blade disc diameter, we then derived a predictive relationship between installed capacity and footprint: footprint (ha) = 8.15 + (8.62 × installed capacity) ($R^2 = 0.90$: Fig. 2), which allowed us to estimate footprint (and an appropriate circular buffer) for those schemes where only data on installed capacity was available. For schemes with no information on turbines or installed capacity we assigned a nominal buffer of 100m around the given grid reference (209 pre-application schemes). We examined the effect of using several different buffer values for these 209 schemes, and it made relatively little difference to the results (since it mainly influenced the extent of overlap with potential subadult eagle habitat – see later). Hence, we opted for a notional value which represented the likelihood that, with no information on capacity, these 209 schemes were the most speculative and least liable to be constructed. Pre-application schemes were also more likely to be small (<5 MW) than schemes at later stages in the planning process. For especially large schemes over 150 MW at application stage, where a simple circular footprint was unlikely to represent appropriately the footprint shape with respect to overlap with eagle territories, we examined relevant environmental statements (ESs: reports on the environmental assessment of impacts which accompany applications) to better gauge footprint area with respect to territorial boundaries.

To predict broad future changes in the installed capacity and number of turbines, and allow us to fulfil our objective of examining these projections in relation to the government renewable energy target, we had to estimate parameter values for those schemes where there were incomplete data on capacity and/or turbine number. Hence, where we had data on number of turbines or installed capacity, but not both parameters, we used a simple predictor derived from linear regression (using schemes where we knew both parameter values), so that number of turbines = 1.57 + (installed capacity × 0.417) ($R^2 = 0.93$, $n = 233$). For pre-application schemes with no data on capacity or turbine number we assumed median values derived from other schemes at the same stage, and for scoping cases we assigned median values derived from scoping schemes below 50 MW, as we assumed that all scoping schemes above 50 MW had been lodged with government authorities in accordance with planning legislation.

To derive likely estimates of the number of operational wind farms in the future we assumed that not all proposals would enter the planning system due to withdrawal and not all schemes in the planning system would seek or would be granted planning permission. We assumed an installation rate of 50% for pre-application schemes, which was probably conservative. We also assumed relatively low installation rates of 65% and 75% for scoping and application schemes, respectively (values which according to CRS underestimate installation rates currently: see also BWEA, 2003) but we anticipated that the rate may drop in the future as more wind farms are constructed. We assumed that 95% of approved schemes will be constructed, which again was probably conservative.

The collated data represented 527 schemes associated with a geographical grid reference which were entered as a layer in a Geographical Information System (GIS) (ArcView®). As a means of examining regional differences in parameters we used the bio-geographical divisions of Scotland derived by SNH (SNH, 1998). The SNH zonal programme has identified 21 Natural Heritage Zones (NHZs) that reflect the variation in biological and landscape qualities across Scotland (Fig. 1). NHZ boundaries were created as an additional layer in the GIS.

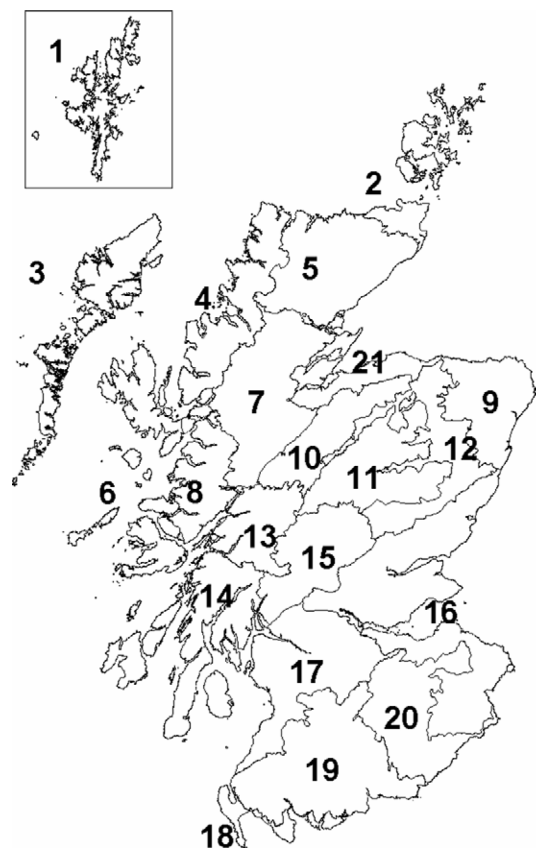

Fig. 1 – Biogeographic zones of Scotland, termed Natural Heritage Zones (NHZs), developed by Scottish Natural Heritage (SNH, 1998). 1 = Shetland, 2 = North Caithness and Orkney, 3 = Western Isles, 4 = North West Seaboard, 5 = The Peatlands of Caithness and Sutherland, 6 = Western Seaboard, 7 = Northern Highlands, 8 = Western Highlands, 9 = North East Coastal Plain, 10 = Central Highlands, 11 = Cairngorms Massif, 12 = North East Glens, 13 = Lochaber, 14 = Argyll West and Islands, 15 = Breadalbane and East Argyll, 16 = Eastern Lowlands, 17 = West Central Belt, 18 = Wigtown Machairs and Outer Solway, 19 = Western Southern Uplands and Inner Solway, 20 = Border Hills, 21 = Moray Firth. For further details in the context of the golden eagle in Scotland see Watson and Whitfield (2002) and Whitfield et al. (2006).

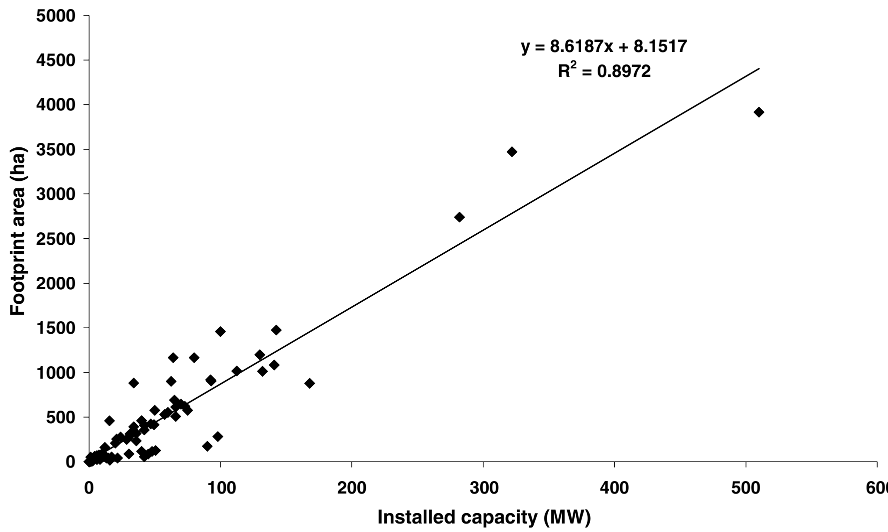

Fig. 2 – Graphic representation of the estimated relationship between installed capacity of a wind farm and its approximate footprint, with linear trend line, derived from 89 schemes with data on installed capacity, turbine number and blade disc diameter, and utilising the relationship: footprint = number of turbines × (6 × blade diameter)^2. Although forcing the relationship through a 0 intercept was logical we did not exploit this option because it made virtually no difference for schemes >5 MW which were primarily those which may co-occur with golden eagles.

Data were obtained on the distribution of occupied and vacant golden eagle territories from the 2003 national survey (Eaton et al., in press; Whitfield et al., 2006, submitted). This census attempted to visit at least twice in the same season every known golden eagle territory in Scotland. A first visit to a territory (home range) involved checking if it was occupied by a pair prior to egg laying (i.e., direct observation of a pair, or of a built up nest), with a second visit during the incubation phase to check for any evidence of birds having laid eggs or, if a territory was not found to be occupied on the first visit, to provide a second check for territory occupation. For occupied territories a third visit was made later in the breeding season to record the number of any young that had fledged or had reached an age where fledging could safely be assumed (Steenhof, 1987; Steenhof and Kochert, 1982).

For each known territory in the census recognised as a contemporary or former breeding territory, we calculated a territory centre from the eyrie location used in 2003 or, if an eyrie was not used in 2003, the most recent eyrie used or the mean location of all used alternative nest sites (those used during a maximum period of 11 years, 1982–1992) from previous 1982 to 1992 censuses. Crude estimates of territory boundaries were made by using Dirichlet tessellation and the production of Thiessen polygons (e.g., McGrady et al., 2002; McLeod et al., 2002). In the absence of a neighbouring territory boundary we assumed a maximum limit of 6 km from the centre (McGrady et al., 1997). This method has an advantage over simple circles around a territory centre in that it is responsive to differences in nesting density and does not produce any overlap in estimated territory use (McLeod et al., 2002). Territory centres and boundaries were entered as a layer in the GIS which was overlapped with the wind farm scheme layer. When looking for spatial associations between wind farm schemes and territories we used two distances around territory centres, based on telemetry data collected in western Scotland (McGrady et al., 1997): within 3 km or, in the absence of a neighbouring territory boundary, within 6 km. McGrady et al. (1997) found that most ranging was within 6 km of the territory centre, and the ‘core’ of the territory (50% of activity) was within 3 km. McGrady et al. (1997) also indicated that habitat loss was more likely to be detrimental within the core than outwith the core. Hence, in effect, we used the extent and location of overlap in the GIS between wind farm schemes and the ‘RIN’ model of eagle territory use (McGrady et al., 1997, 2002; McLeod et al., 2002; Fielding et al., 2003) as a crude indication of potential interaction.

Golden eagles tend to avoid commercial conifer forests (e.g., Marquiss et al., 1985; McGrady et al., 1997; Whitfield et al., 2001, in press) and therefore any effect of displacement of eagles from wind farms will be minimal for proposals in commercial conifer forests. In order to examine the occurrence of schemes with respect to forests we created a forest layer in the GIS from the Land Cover of Scotland 1988 (LCS88: MLURI, 1993) and the National Inventory of Woodland Trees (a forest-specific update to LCS88 conducted by Forestry Commission for 1995). LCS88 includes broad categorisation of woodland age, indicating areas recently felled, prepared for planting, open canopy young plantation, and closed canopy plantation. Hence, although the data were not obviously contemporaneous with other datasets we used, new forests around planting identified in LCS88 would have reached an age where they would affect eagles during our study (Whitfield et al., 2001) and commercial forests are almost always restocked after felling. As a check against the possibility that LCS88 was seriously outdated with respect to documenting forest cover in the years involved in our analyses, Landsat 7 images from 2000 to 2001 were downloaded as georeferenced Tif images from the Global Landcover Facility website (http://glcf.umiacs.umd.edu/data/landsat/). GeoTif files were converted to grid files and re-projected from their original UTM projection to the British National Grid using Huber's Reproject Grids (v4.0) extension (www.quandec.com, available as AS11368.zip from www.arcscripts.esri.com) and entered in the GIS. Re-projected images were clipped to remove unwanted regions such as large areas of sea or overlap with other images. False colour composite images, using Bands 3, 5 and 7, were used to detect commercial forest cover. Comparison of LCS88 with these images in a number of areas known to be used by eagles (Whitfield et al., in press) suggested a very similar picture of the extent and location of woodland (probably because relatively few new commercial forests have been planted in recent years: Reid, 1997; SEDDESB, 2005), and hence at the scale of our analysis the use of LCS88 was reasonable.

For all schemes whose location occurred within 3 km or 6 km of an active territory centre we considered that there was a potential impact. We assumed schemes proposed within commercial forests would not have a potential impact (the assumption was based on displacement being a more likely effect than collision risk for eagle pairs in Scotland – see Section 1) and we ignored schemes which had probably been withdrawn or which were less than 5 MW. For those schemes within eagle territories at the installed and approved stages we examined ESs, planning decisions and any post-construction site monitoring materials in order to inform better the 'residual' impact i.e., the likely impact based on site-specific observations and/or after enhancement through counteractive habitat management. For application schemes we also examined ESs, distance of scheme from territory centre and extent of scheme as a means of gaining an idea of the likely impact of such schemes although we considered it as presumptuous to draw anything other than speculative conclusions from such site-specific examinations prior to a planning decision being reached.

We assumed that non-breeding eagles (principally subadult birds) used open upland habitat which was not commercial conifer forest, standing open water bodies, or territories occupied by resident pairs (Watson, 1997). We used a definition of upland habitats derived from LCS88 (Whitfield et al., 2003) in the GIS with the addition of three 'bare rock and cliff' LCS88 habitat classes. For every active golden eagle territory in the 2003 national survey we ran the GIS-based PAT model which predicts resident golden eagle range use (McLeod et al., 2002; Fielding et al., 2003) and assumed that non-breeding eagles could only use upland habitat outside the predicted 95% range use of resident eagles. We used the PAT model of range use prediction rather than the more simple RIN model (McGrady et al., 2002; McLeod et al., 2002; Fielding et al., 2003) to allow incorporation of the observation that the periphery of eagle territories can be used by non-breeding eagles (Watson, 1997). The resulting layer in the GIS was also 'clipped' to remove commercial forest cover and standing water bodies to create a series of patches of varying size and shapes. The layer was then subject to several 'cleaning' operations which removed connections between patches which were less than 100 m wide and removed patches less than 1 km^2, as we conservatively assumed that eagles would not use such areas, to produce a final 'non-breeding eagle habitat' layer that was overlaid with the layer of wind farm scheme footprint areas to derive estimates of area overlap.

We did not consider whether a wind farm scheme overlapped with any statutory protected sites, such as Special Protection Areas (under the EC Wild Birds Directive) so our study should not be taken as a comment on the suitability of any proposal with respect to the protective requirements imposed by such site classifications.

3. Results

For proposals or developments in the planning system (i.e., excluding pre-application schemes), there was a trend for more recent schemes to be larger (Table 1). In part this was due to a smaller proportion of more recent schemes being small wind farms, which are typically concerned with providing local power supplies and so are often promoted as community or private landowner proposals. Hence, when excluding schemes of less than 5 MW, the temporal trends in scheme capacity were reduced in strength, the change being particularly marked for installed operational schemes since a large proportion of installed schemes involved small wind farms with less than 5 turbines (Table 1). Considering only schemes of over 5 MW, few of the temporal differences in installed capacity were significant; the only marked differences (Mann–Whitney U tests) were between installed and application schemes ($N = 63$, $U = 131$, $P < 0.001$), and scoping and pre-application schemes ($N = 112$, $U = 1233.5$, $P = 0.052$). Temporal trends in turbine numbers for schemes over 5 MW were less marked than for installed capacity, largely because more recent schemes were associated with turbines of larger capacity, reflecting recent technological and engineering advancements (Table 1). It was clear, nevertheless, that unless there is a correspondingly greater rejection or withdrawal rate

Table 1 – Median estimates of installed scheme capacity for all known onshore wind farm schemes, number of turbines per scheme, individual turbine capacity per scheme, and installed scheme capacity for schemes greater than 5 MW capacities

Stage of development	Scheme capacity (MW)	Number of turbines	Turbine capacity (MW)	Scheme capacity >5 MW (MW)
Pre-application (282)	24.0 (72)	10 (50)	2.0 (37)	39.1 (57)
Scoping (88)	49.8 (66)	26 (68)	2.0 (56)	50.0 (57)
Application (80)	40.0 (64)	16 (78)	2.0 (64)	48.9 (53)
Approved (39)	12.0 (37)	7 (39)	1.8 (37)	29.2 (24)
Installed (42)	1.7 (39)	2 (42)	0.6 (38)	19.4 (14)

Sample sizes are in parentheses.

for larger wind farms, then the size of new wind farms in the future will probably increase with respect to those currently installed, under construction or with planning approval.

The number of installed turbines at the time of analysis was 385, and based on median turbine capacity (Table 1) and total installed capacities (Table 2) for each stage of development the total potential number of turbines in the future could potentially be about 10,400 if all schemes are installed or about 6470 at the assumed reduced installation rates. Whereas at the date of analysis there were 42 operational wind farms, in the future with the assumed installation rates there could potentially be an estimated 337 operational wind farms with a total installed capacity of 13,199 MW (Table 2). Our estimates of the capacity potential were greater for most development stages than in another review (SNH, 2004) because we extrapolated capacity estimates for schemes without information on capacity or turbine numbers rather than ignore them.

Relatively few schemes coincided with the core (<3 km from centre) of active golden eagle territories (Table 3). At the time of analysis only three schemes had been approved or installed in the core of eagle territories. At two of these sites habitat enhancement measures had been introduced to compensate for any displacement of eagles from the wind farm and initial monitoring studies indicated no post-construction change in eagle territory occupation or fecundity at one of these sites (Walker et al., 2005). The third scheme was constructed on ground that was apparently unsuitable for golden eagles, and confirmed by site-specific observations. Thirteen other schemes were proposed within the core of eagle territories, but it is unlikely that all of these schemes will progress or be approved, or have a 'residual' impact (i.e., the impact following site-specific assessments and any mitigation measures put in place) (Table 3). Two of the three scheme applications with a potential impact were associated with habitat enhancement proposals.

Only two schemes with approval were within the 3–6 km distance band within an eagle territory and site-specific observations concluded minimal use of the two scheme areas by eagles. One scheme was also on the extreme periphery of the presumed territory boundary, so we assumed minimal residual impact for these two schemes. Thirty-one other active territories coincided with a scheme proposal outwith the core territory, but not all of these schemes will progress or be approved, or have a residual impact (Table 3). For those eight territories potentially impacted by schemes at application stage, four involved schemes which were at the extreme periphery of the presumed territory and at least two included a package of habitat enhancement for eagles.

Some schemes had a disproportionate potential impact compared to others: one large pre-application scheme had an indicative distribution that coincided with at least seven active territories and two others coincided with three and four territories, respectively. Most or all other schemes apparently coincided with one territory, although certainty was difficult for several schemes where information was incomplete.

From a regional breakdown, there were few NHZ where more than 10% of territories (the total on a national basis) were associated with a wind farm scheme (Table 4). Although estimates were based on all existing and potential schemes,

Table 2 – Estimates of installed capacity of onshore wind farms at the time of analysis (January 2005) and potential installed capacity in the future according to stage of development

Stage of development	Total capacity (MW)	Assumed installation rate (%)	Total capacity × installation rate (MW)
Pre-application (282)	9356.9	50	4678.5
Scoping (88)	5603.9	65	3642.5
Application (80)	4671.3	75	3503.5
Approved (39)	1064.9	95	1011.7
Installed (42)	362.3	100	362.3
Total	21059.3		13198.5

Actual or potential number of schemes at each stage of development is given in parentheses.

Table 3 – Estimates of the number of wind farm schemes which are proposed or occur within 3 km or 6 km of the centre of an occupied golden eagle territory in Scotland and which therefore may have a potential impact (i.e., simple co-occurrence between a wind farm proposal and an eagle territory)

Stage of development	Number of territories			
	Potential impact	Residual impact	Potential impact	Residual impact
	<3 km	<3 km	3–6 km	3–6 km
Pre-application	8	–	21	–
Scoping	2	–	2	–
Application	3	–	8	–
Approved	1	0[a]	2	0[a]
Installed	2	1[b]	0	0

For those schemes which have been approved or installed the presumed 'residual' impact (i.e., presumed impact following site-specific pre-construction investigations and/or initial monitoring of range occupation and breeding performance) is also given.
a Distance from territory centre and/or site specific observations indicated minimal use of area by eagles.
b Monitoring in initial years of turbine operation at one site indicated continued occupation of territory, although there was evidence of avoidance of wind farm area by pair (Walker et al., 2005). Territory enhancement through habitat management plan has occurred as a means of potentially counteracting any such displacement (Madders and Walker, 2002). No recent information was available from the second site.

Table 4 – Regional breakdown of the numbers of wind farm schemes at all stages of development within 3 km or 6 km of an active eagle territory, together with the number of active territories in each region and the percentage of eagle territories in each region associated with a scheme

NHZ	Number of territories with proposal			Active territories	Percentage of territories
	<3 km	3–6 km	Total[a]		
3	4	8	11	81	14
4		2	2	46	4
5		5	5	18	28
6	3	2	5	74	7
7	1	1	2	43	5
8	1	4	5	51	10
10		1	1	12	8
11	1	1	1	28	4
12			0	3	0
13		1	1	25	4
14	6	8	9	44	20
15			0	12	0
16			0	1	0
19			0	2	0
20			0	3	0
Total	16	33	42	443	10

Refer Fig. 1 for NHZ names and locations.
a Some territories were potentially impacted by more than one scheme so totals are not the sum of 3 km and 6 km numbers.

and so should be qualified with the strong likelihood that many schemes will probably not be approved, it was apparent that in two regions relatively high proportions of territories were associated with interest in wind farm development: West Argyll (NHZ 14) and the Peatlands of Caithness and Sutherland (NHZ 5) (Fig. 1, Table 4). Notably, on the Argyll mainland of NHZ 14 (i.e., excluding islands: Fig. 1), where there were 22 active territories, 7 territories (32%) were associated with at least one wind farm scheme.

Table 5 – Estimated number of patches and area of non-breeding eagle habitat, the number of wind farm schemes (at all stages of development) within non-breeding eagle habitat, and extent of overlap between schemes and non-breeding eagle habitat in each NHZ

NHZ	Eagle habitat		Wind farms (n)	Overlap	
	Patches (n)	Area (km^2)		(km^2)	Percentage
3	54	1115.4	7	29.1	2.6
4	46	1541.3	8	11.9	0.8
5	27	3132.5	42	26.9	0.9
6	66	709.3	6	13.3	1.9
7	63	2018.8	8	29.0	1.4
8	52	459.2	4	3.7	0.8
10	28	1493.4	11	14.6	1.0
11	30	1911.3	2	0.3	0.0
12	58	786.0	8	5.4	0.7
13	26	903.6	1	0.03	0.0
14	79	1007.2	12	15.3	1.5
15	45	1339.9	20	28.7	2.1
16	28	218.5	17	10.3	4.7
17	41	448.4	27	49.9	11.1
19	86	1617.5	25	51.2	3.2
20	52	1735.8	34	88.9	5.1
21	7	37.1	0	0	0.0
All	788	20,475.2	232	378.5	1.8

Refer Fig. 1 for NHZ names and locations.

Of a total national estimate of 20,475 km^2 of habitat potentially suitable for non-breeding eagles, an estimated 378 km^2 was overlapped by 232 of the 527 potential wind farm schemes (Table 5). The greatest potential overlap (and therefore potential effective habitat loss should displacement occur) was in those NHZ where there were few or no active eagle ranges (Table 5, cf. Table 4). The overall extent of overlap nationally was about 2%.

4. Discussion

In order to meet the target of 40% of Scotland's electricity supply to be from renewable sources by 2020, an installed capacity of up to 5000 MW is the current maximum estimate of what may be required from wind energy, although this requirement depends on the degree of contributions from non-wind energy sources (SRF, 2005). Based on the present analyses, clearly there is a large excess of potential schemes because about 3626 MW would be required from schemes which have not yet been approved or installed to meet the indicative target for terrestrial wind energy, and with relatively conservative installation rates 7146 MW could be installed from scoping and application schemes only. Thus, theoretically, approval of only about 35% of the installed capacity of those schemes currently in scoping or application stages would be required, even without any contribution from schemes at the pre-application stage. This argument is overly simplistic as it ignores the relative suitability of schemes at different stages, and the capacity of wind farms necessary for the government target on renewables to be reached is far from clear. It does confirm, however, that there is probably an excess of wind farm proposals over requirements (SNH, 2003, 2004) and so our simple logging of the number of schemes which coincide with eagle territories and areas potentially used by non-breeders will overestimate the potential impact.

There were relatively few wind farm schemes within the core of eagle territories, where potential impact may be greatest (all else being equal). Site-specific features of territory usage aside, wind farm schemes outwith the core of territories should have less potential impact. Hence, although the number of territories with a scheme outwith the core was greater than the number with schemes within the core, the potential impact of any given proposal should be less. In practice the number of schemes within eagle territories will be less than our results indicated because all proposals are unlikely to be approved. For example, based on the simple argument presented earlier on wind energy requirements in relation to government renewable energy targets, in the future there may only be an additional six or seven eagle territories with wind farm schemes not yet approved or installed. Moreover, as illustrated by operational and approved schemes, actual impact may be minimal following site-specific assessment and potential mitigation. When associated with positive habitat management, wind farms can present potential opportunities to enhance previously degraded habitats for eagles and other bird species (Madders and Walker, 2002).

Our analysis suggested that the extent of habitat potentially suitable for non-breeding eagles which would be lost to wind farms if displacement occurs was minimal, with an overall loss of about 2% even if all schemes will be installed, which is most unlikely (although there was a caveat that for some schemes there was no information to allow derivation of wind farm footprint). The implication was that any national impact, in terms of effective habitat loss should displacement occur, is likely to be small. Potential habitat loss through wind farms would also appear to be negligible with respect to encouraging further non-breeding birds to move from regions free from persecution (typically in the western Highlands) to areas further east where persecution is more prevalent (Whitfield et al., 2003, 2004a) further jeopardising the long-term security of the national population (Whitfield et al., 2004b).

However, the results are probably best viewed as a qualitative guide, and do not replace site assessments which may reveal areas of particularly high non-breeding eagle activity or 'settlement areas' (Ferrer, 1993). Importantly, it also does not account for the possibility that the higher risk to non-breeding eagles will be through collision with turbines or associated masts and power lines, if displacement does not occur. There are no studies from non-breeding eagles in Scotland to indicate similarity or otherwise with findings from the USA, which suggest non-breeding eagles are probably not displaced from wind farms (e.g., Johnson et al., 2000; Hunt, 2002; Smallwood and Thelander, 2004). Until such Scottish studies are available, precaution may be required in some circumstances, especially as initial findings from a Scottish wind farm do not suggest similarity with USA findings of non-displacement for resident pairs (Walker et al., 2005).

The results of the present study should not be used as justification for attention to drift from wind farms as a potential constraint on golden eagles, especially given the poor knowledge surrounding habitat use by non-breeding birds and the need for more studies of how eagles react to wind farms in Scotland. It seems clear, nevertheless, at least on current information, that wind farms pose a far less serious national threat to golden eagles than some other constraints (Watson and Whitfield, 2002; Whitfield et al., 2006), notably persecution (Whitfield et al., 2004a,b) which appears responsible for numerous range vacancies, reduced breeding productivity, reduced survival rates and placing the national population at risk of decline (Whitfield et al., 2004a,b, 2006, submitted). Maintaining best practice in wind farm proposal site selection and impact assessment, increasing knowledge of wind farm impacts on birds and utilising counteractive management of any perceived impacts, which should include avoiding sites of particular importance to eagles, should ensure that future residual impacts stay low nationally.

A key feature of wind farm developments, unlike many other potential constraints on golden eagle populations (Watson and Whitfield, 2002) is that they are controlled by a planning system and so subject to rejection if unsuitable or to conditions of consent if residual impacts may remain but can be counteracted. Being subject to the planning system, wind farms are in the public domain and so have a high profile as a potential problem for eagles. Other constraints are not so overt or, at least, obvious to the public (indeed much persecution is covert due to its illegality: Whitfield et al., 2003) but public profile does not necessarily reflect ecological influence. A good example of this disparity is served by the golden eagles of the central and eastern Highlands (zones 10, 11, 12, 15: Fig. 1). Here, there was a loss of 15 active territories between 1992 and 2003 which was most consistent with evidence of persecution (Whitfield et al., 2006, submitted), and even before these losses there was a significant association between territory vacancies and persecution (Whitfield et al., 2003, 2004a), with 85 vacant territories by 2003 (61% of known territories), the highest regional level of vacancies in Scotland. By contrast, in this region there were only two active eagle territories with three wind farm schemes by early 2005, and none of these schemes had progressed beyond pre-application. Even nationally, it is difficult to conceive that wind farms could approach this scale of impact. Clearly this indicates that there is probably much to be done in raising the public profile of persecution as an issue for golden eagles in Scotland.

Of course, simply because other constraints are more influential on a population does not necessarily justify the introduction of an additional population constraint. If the novel influence can be planned to be negligible, however, which should be possible for wind farms in Scotland, then such justification is credible. An exception to this could be if other constraints have eroded regional conservation status, so that in Scotland wind farm development should arguably be less likely to proceed in eagle territories where the regional population's conservation status is already poor due to persecution. This argument also suggests that by restricting the purported economic benefits of wind farm development (e.g., SRF, 2005) persecution of eagles incurs an additional, hitherto unappreciated economic cost (apart from a likely effect on wildlife tourism revenue).

Although nationally the picture for wind farm development does not give grounds for serious concern, regionally there were potential pressures which may build on occupied territories from wind farms in the future, notably in mainland Argyll (part of NHZ 14) in the southwest Highlands and in the Peatlands of Caithness and Sutherland (NHZ 5) in the northern Highlands. Particular care in planning wind farm schemes and in assessing cumulative impacts is needed in these regions. It is important that these regional pressures, and any others which may develop, are monitored. Clearly also, the nature of impacts, especially with respect to whether collision fatality or displacement is the most pertinent issue, requires careful monitoring, and should feed back into future assessments.

Around the world, wind farms represent a novel and potentially significant land use in many areas formerly free from development pressures. This study shows the value in maintaining records of wind farm proposals which can be used in conjunction with GIS as simple tools to assist in identifying future trends in potential impacts, in planning for any impacts, and in placing those potential impacts in the context of other constraints which may be acting on features of conservation interest.

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