"The Answer, My Friend, is Blowin' in the Wind..."

The Unintended Consequences of Wind Energy:

A Case Study of the Griffon Vulture *Gyps fulvus* in Spain

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INTRODUCTION

In an era of growing concern regarding the processes and implications of energy production, wind energy is emerging as a popular, clean, and sustainable resource. In fact, electricity generated from wind energy has one of the lowest carbon footprints, especially when compared to energetically expensive (and not to mention controversial) methods such as hydraulic fracking (Parliamentary 2006). While all forms of electricity generation require an initial investment for manufacturing and construction with varying amounts of energy expenditures, electricity produced through wind turbines essentially only requires steel for the physical structure, concrete for the base and a blend of fiberglass, epoxy and other materials for the blades (Parliamentary 2006). According to the report compiled by the UK Parliamentary Office of Science and Technology (2006), the fabrication, transportation, and synthesis of these materials represents 98% of the total carbon dioxide emissions produced by an average single wind turbine during its lifetime. That is to say, once a wind turbine is installed and in operation, very little energy (only 2% of the total energy costs accrued during the entire "lifetime" of a wind turbine) is used for maintenance (Parliamentary 2006). Considering the relatively small ecological footprint, an average, industrial-grade wind turbine can easily "pay for itself" well within its lifetime of 20-30 years (Parliamentary 2006).

In order to address increasing social demand and governmental pressure for clean, renewable energy sources, installations of wind farms increased by 45% in the United States between 2005-2009 (Martínez-Abraín et al. 2011). Currently, 39,000 utility-scale wind turbines are installed in the U.S. and while these turbines only produce 2.9% of U.S. electricity, a 2008 study found wind could feasibly provide 20% of U.S. electricity by 2030 (Center 2012). While the U.S. has been taking progressive steps to incorporate and expand the green energy sector of its economy, the European Union has pursued a far more aggressive approach. From 2005-2009, the installations of wind farms increased 74% in the European Union, with Spain in the lead (Martínez-Abraín et al. 2011; de Lucas et al. 2012b). In fact, by the end of 2004 the Spanish wind power industry produced 800 MW with the aim to reach 40,000 MW towards the end of the 5-year

Spanish Plan of Renewable Energy (Tellería 2009). Spain is now the world's third largest wind energy market with 16.8 GW of installed electric generation capacity (Ferrer et al. 2012).

Since expansive wind farms are a relatively new form of energy production, there is limited research available and a relatively poor understanding of the impacts of these installations upon the surrounding environment. However, four effects have been observed and documented: wind farms create noise, destroy plant cover, have an aesthetic impact on the landscape, and have a negative impact on flying fauna, especially birds (Farfán et al. 2009). In Spain, the Griffon Vulture (*Gyps fulvus*) has experienced the highest mortality rates of any bird species affected by wind farms (de Lucas et al. 2012a). The aim of this paper is to explore the Griffon Vulture's vulnerability to turbine-related death as well as future implications and suggestions for wind energy mitigation in Spain and other nations engaged in wind energy expansion. The predicament of the Griffon Vulture highlights the unintended consequences and threats posed by quickly-expanding wind farms that can lead to population declines and even local extirpations.

SETTING THE SCENE: WIND POWER IN SPAIN

Covering more than 505,370 square kilometers, or nearly twice the size of Oregon, Spain is the largest country in Europe after France (Central Intelligence 2013). As mentioned before, the wind energy sector of Spain is increasing quickly, approximately 30% annually (Graber 2005). Spain is truly the wind energy "capital" of the world as it houses the world's leaders in both turbine manufacturers and wind farm operators. Currently, there are over 737 wind farms in Spain consisting of a total of 16,842 turbines which produce 16.8 GW of electricity annually (de Lucas et al. 2012a). Recently, wind energy produced more electricity than any other power source in Spain for the first time (The Guardian 2013). In January of 2013, Spain delivered over six terawatt hours of electricity from wind farms (The Guardian 2013).

The area around the Strait of Gibraltar has one the greatest potentials for producing wind energy (de Lucas et al. 2012a). However, this area also happens to be one of the most important locations for migrating Palearctic birds and there is a growing concern about the effects of existing and future wind farms upon (migrating) birds. Thousands of small and large birds are killed annually by wind turbines in Europe; turbine-related mortality rates in Spain have been determined at 21.2 birds per turbine per year (Farfan et al. 2009; Tellería 2009). Raptors seem to be particularly susceptible and raptor collision rates in Spain are far higher than collision rates of raptors observed in wind farms of the United States (1.33 birds/turbine/year in Spain as compared to 0.001-0.065 birds/turbine/year in the US); (de Lucas et al. 2012a; Ferrer et al. 2012). The Griffon Vulture is the most common victim at 0.41 birds/turbine/year, but local mortality rates could be much higher (Tellería 2009). For example, at the Salajones wind plant in Navarre 63.1% of all bird fatalities were Griffon Vultures, with a local mortality rate of approximately 8 Griffon Vultures/turbine/year (Tellería 2009).

SETTING THE SCENE: THE GRIFFON VULTURE IN SPAIN

The Griffon Vulture is part of the Old World Vultures (a group comprised of eagles, buzzards, hawks, and kites that fall under the Accipitridae family) which mainly feed upon the carrion of large animals, such as wild ungulates (Encyclopedia of Life 2013; Mateo-Tomás & Olea 2009). Its distribution extends from the Mediterranean countries to India as well as parts of north Africa (Mateo-Tomás & Olea 2009). Griffon Vultures are relatively flexible in terms of habitat (preferring grasslands as well as Mediterranean-type shrubland) and can be found in a range of altitudes and environments from plains to low and high mountains. They are partially migratory; during the fall migration, approximately 4,000-5,000 Griffon Vultures cross the Strait of Gibraltar to winter in Northern Africa (BirdLife International 2013).

Over 80% of the European population of Griffon Vultures resides in Spain, with about 25,541 breeding pairs in the Iberian Peninsula (García-Ripollés & López-López 2011). Currently, the IUCN lists this species as Least Concern, but in the early 1980's the Griffon Vulture was considered threatened due to the spread of epidemic livestock diseases (specifically bovine spongiform encephalopathy, African swine fever, and foot and mouth disease) and the total number of breeding pairs dropped to only 3,000-5,000 (BirdLife International 2012). However, from 1989 to 1999, the Spanish population of Griffon Vultures experienced a sharp increase, growing from 8,064 to 22,455 breeding pairs (Parra & Tellería 2004). Moreover, both breeding colonies and non-breeding populations are still on the rise (Parra & Tellería 2004). Yet, the spatial patterns of relative abundance and aggregations of birds (whether in breeding colonies or communal roosts) have remained the same (Carrete et al. 2012).

Griffon Vultures nest in large, dense colonies ranging in size from 20-250 pairs with individual pairs and nests located often less than 20 meters apart from one another (Kemp & Newton 2003). Breeding colonies are located in rocky (limestone) cliffs (BirdLife International 2012), which seem to determine their overall spatial distribution (Parra & Tellería 2004). The breeding season extends from late December/early January until July with a typical brood consisting of only one chick (Mateo-Tomás & Olea 2009). The low reproductive output in combination with delayed maturity and a long life span makes the population of Griffon Vultures in Spain, although no longer threatened, still quite vulnerable to human-related disturbances (Martínez-Abraín et la. 2011).

While New World Vultures tend to have enlarged olfactory lobes and can locate isolated carcasses through smell, Old World Vultures like the Griffon Vulture rely upon their acute eyesight (Kemp & Newton 2003). They take to the air in spacious, scattered flocks and once a carcass is spotted by one vulture, it will begin to descend and draw in the birds around it. This occurs so quickly that crowds of twenty or more vultures will form within minutes. Groups of this size can strip down the carcass of a small animal (such as a deer) in as little as twenty minutes (Kemp & Newton 2003). As such, Griffon Vultures and vultures in general play a very important role in the ecosystem: they represent the “cleaning crew” (Mateo-Tomás & Olea 2009).

In Spain, their role as scavengers has led to the development of a mutually beneficial relationship with livestock farmers, dating back hundreds of years, whereby farmers dispose of dead cattle at specific sites called “muladares” (or “vulture restaurants”) where the vultures have access to a reliable source of food. Traditionally, many muladares were located in the remote interior of Spain, where disposing of dead animals in this manner was both a sanitary and an economical solution (García-Ripollés & López-López

2011; Martínez-Abraín 2011). However, during the late 20th century intensive cattle raising expanded rapidly throughout the Spanish countryside, followed by a similar increase in muladares. At the same time many of the larger animals that the Griffon Vulture depended on in the past either declined or disappeared altogether because of economic development and habitat fragmentation. As a result, Griffon Vulture populations came to rely heavily on the growing number of muladares (García-Ripollés & López-López 2011; Martínez-Abraín 2011), which now, inadvertently, control population growth. Indeed, the sharp population increase of Griffon Vultures over the 1990's closely matches the expansion of these food sources (Parra & Tellería 2004).

The dependency of Griffon Vultures on muladares also makes them vulnerable to the presence of harmful substances in the carcasses, such as diseases, biocides, or lead from spent ammunition (Kemp & Newton 2003; Mateo-Tomás & Olea 2009). In 2001, a deadly outbreak of the neurodegenerative disease Bovine Spongiform Encephalopathy (BSE) or "mad cow disease" resulted in the closure of many muladares throughout Spain in order to curb the spread of this illness (García-Ripollés & López-López 2011; Martínez-Abraín 2011). The effect was immediate, especially in regions where muladares were common. Since the outbreak of BSE, food shortages have led to reduced breeding success, decreased juvenile survival, and marked population declines in some Griffon Vulture colonies over the last decade (García-Ripollés & López-López 2011). Without remedial action populations are expected to crash (Parra & Tellería 2004) and the Griffon Vulture may once again become a threatened or endangered species.

BLOWING IN THE WIND: THE GRIFFON VULTURE ON A COLLISION COURSE

Several different hypotheses have been put forth to explain the increased mortality rates of the Griffon Vulture in relation to wind turbines.

1. Limited Field of Vision

Griffon Vultures, like many other raptors and vultures, are known to have some of the highest measured visual acuities. Martin et al. (2012) tested the field of vision of two *Gyps* vulture species (including the Griffon Vulture) using ophthalmoscopic reflex techniques and constructed two- and three-dimensional visual fields for these birds that show monocular, binocular and blind sectors of vision (Figure 1). Griffon Vultures have a relatively small area of binocular vision which extends from approximately 55˚ (slightly above eye level) to 135˚ (slightly below bill level), giving a total range of 80˚ (Martin et al. 2012). However, below 55˚ degrees and above 135˚, Griffon Vultures have a large “blind spot” (Figure 2). While the binocular vision of *Gyps* vultures (such as the Griffon Vulture) is larger than that of the Kori Bustard (*Ardeotis kori*) also shown in Figure 2, it is much smaller than that of the Cattle Egret, whose binocular sector includes nearly 180˚ (Martin et al. 2012).

Binocular vision mainly serves to control the position of the bill and feet in relation to relatively close objects (Martin et al. 2012). To use their binocular vision in flight, Griffon Vultures typically pitch their head forward at an eye-tip angle of at least 60˚ as they scan the ground at low altitude (<200 meters); (Figure 3). Consequently, *Gyps* vultures acquire both comprehensive binocular visual coverage of the terrain below and extensive monocular visual coverage laterally. However, they become effectively sightless in the direction of travel due to the blind spots in their field of vision and are thus vulnerable to collision with objects such as wind turbines, which intrude into otherwise empty airspace. Any efforts to increase the conspicuousness of wind turbines would achieve only marginal gains because the wind turbine itself is simply not seen by these birds in flight (Martin et al. 2012).

2. Flight Behavior and Topography

As part of the “soaring birds,” Griffon Vultures tend to exhibit a flight behavior that exploits both topography and related wind currents. They take advantage of vertical air currents or thermals, ridge updrafts and other sources of lift and thus move in a more or less predictable manner across the landscape (de Lucas et al. 2012b). However, areas of greater wind flow also tend to be the most desirable locations by wind energy developers. Wind turbines are generally arranged in parallel rows along mountain ridges, coasts and other areas with reliable wind currents, which are often the same wind currents used by soaring birds (Barrios & Rodríguez 2004; Tellería 2009; Figure 4). In addition, Griffon Vultures have low maneuverability in flight and a low capability for powered flight (de Lucas et al. 2008), making it more difficult to avoid wind turbines.

Griffon Vulture mortality also seems to follow a seasonal pattern. During a study from 1993-1994, Barrios and Rodríguez (2004) found that 66.7% of the observed Griffon Vulture deaths took place during the winter (December-February). This seasonal mortality can be attributed changes in flight behavior in response to different weather conditions. Griffon Vultures rely on thermals to gain height. However, during the winter months, thermals become less prevalent and Griffon Vultures have to exploit updrafts along slopes and ridges in order to gain elevation, venturing often in close proximity to wind farms (Barrios & Rodríguez 2004).

In the PESUR wind farm (located in southern Spain near the Strait of Gibraltar), Griffon Vultures circle upwards on weak updrafts created by a series of gentle, short slopes which puts them on a collision course with the wind turbines on the ridges. In fact, most of the Griffon Vulture deaths at PESUR occurred in two particular rows of wind turbines with very little space between consecutive units (Barrios & Rodríguez 2004). De Lucas et al. (2012b) also noted that Griffon Vulture deaths tended to be concentrated around particular turbines. Through wind tunnel predictions and models, de Lucas et al. (2012b) found that specific locations can be identified as high risk areas for collision even though the relative density of Griffon Vultures may be low. Vice versa, other locations were found to be safe even with higher densities of birds in the wider area, a key observation that refutes the assumption currently used in wind turbine risk assessments that higher bird densities result in higher wind turbine related collisions (de Lucas et al. 2012b).

3. Changes in Food Availability

As wind farms steadily expanded and an outbreak of BSE forced many muladares to shut down, local Griffon Vulture populations began to decline (Martinez-Abrain et al. 2011). To determine the cause of this decline, Martínez-Abraín et al. (2011) followed a population of Griffon Vultures in eastern Spain from 2005-2009. For this particular population, the muladares were closed from April of 2006 to October of

2007; wind turbine development began in September of 2006. In 2007, breeding pairs in this study population decreased by 24.1%. Moreover, the greatest decrease in fecundity (35%) took place when both disturbances (wind turbine development and food scarcity) occurred; however, wind farms appeared to have a greater effect upon fecundity than food availability (Martínez-Abraín et al. 2011). With the muladares closed, Griffon Vultures began to change their foraging behavior and exploit other food sources: landfills. However, a wind farm was located on the main flight path to the landfill. As expected, this wind farm was the main cause of vulture mortality and the observed population crash in 2007 of the Griffon Vulture study population (Martínez-Abraín et al. 2011). The study shows that manipulating food sources can unintentionally expose vultures to wind turbine collision.

4. Environmental Assessment Procedure Shortfalls

Whenever a wind project is proposed, an environmental impact assessment (EIA) must be conducted as required by the European Union (Ferrer et al. 2012; de Lucas et al. 2012). The EIA must address the impact the wind farm is likely to have on local bird populations. Moreover, the EIA creates a framework for mitigation of and compensation for potential negative environmental effects of the project and may include restoration or conservation plans (Ferrer et al. 2012; Carrete et al. 2012).

Ferrer et al. (2012) analyzed the predicted risk and the actual recorded bird mortality at 53 potential wind farm locations in southwest Spain and found that there was no clear relationship between the predicted risk identified during EIAs and the actual mortality of birds (specifically Griffon Vultures) after wind farms had been constructed. While the construction of only 20 of the 53 proposed wind farms was eventually approved, the study showed that environmental administrations may have issued licenses for wind farms based on inaccurate data and incorrect criteria, thereby allowing wind farms to be constructed in locations that could potentially threaten vulnerable bird species (Ferrer et al. 2012).

EIAs often use predictive collision risk models (CRMs) which are based on a positive relationship between mortality and bird abundance (de Lucas et al. 2008). However, various studies have shown that there is no positive relationship between these two factors: high mortality may occur at relatively low bird densities and vice versa (Barrios and Rodríguez 2004; de Lucas et al. 2012b; Carrete et al. 2012). Other inaccurate procedures in EIAs include the use of “risk areas” mapped around breeding sites using a set “risk radius” (Carrete et al. 2012), which are often determined arbitrarily or based on outdated information. In addition, EIAs tend to use the distance of a wind turbine or wind farm to a breeding colony as a factor when evaluating a location, which has, as Carrete et al. (2012) found, a very low predictive power for bird mortality. Griffon Vultures can have very large home ranges, about 7,400 km^2 (as calculated by Minimum Convex Polygon) with 95% and 50% kernel contours of about 4,000 km^2 and 500 km^2, and therefore cover large areas—far from colonies and roost sites (García-Ripollés et al. 2011; Carrete et al. 2012). A better indicator to evaluate the risk of collision would be to identify areas where birds tend to aggregate (flight paths, roost sites) in the immediate vicinity of the proposed wind farm site (Carrete et al. 2012).

In summary, Griffon Vulture mortality can be attributed partly to the incompatibility of wind farms and the flight behavior of the vultures, and partly on human error in evaluating collision risk as well as human induced changes in their main food source (i.e. muladares). Vultures cannot be trained to avoid wind turbines, so efforts to reduce or eliminate collisions need to focus on the factors within human control: avoiding high risk areas, managing food sources, and changing turbine design.

MITIGATION STRATEGIES AND THE FUTURE

Although the current population of Griffon Vultures in Spain is not in danger, the future of this species is far from certain. The continued expansion of wind farms can have detrimental effects on this vulnerable species and its survival. To reduce wind turbine related mortality, several strategies can be adopted.

1. Avoiding High Risk Areas

Concern over the increased mortality rate of Griffon Vultures has resulted in a number of useful suggestions for improving the environmental risk assessment of future wind farms and wind-related developments. Any such assessment needs to include current information on the distribution and abundance of sensitive species, a thorough study of wind patterns in relation to the topography of the proposed site, and a post-construction evaluation to allow for adjustments by (temporarily) turning off or dismantling “risky” turbines (Carrete et al. 2012; de Lucas et al. 2012a, 2012b).

For Griffon Vultures in particular, their home and foraging range may be one of the most useful, biological guidelines in determining wind farm locations on a larger scale (Carrete et al. 2012). While it has been shown that Griffon Vultures continue to use foraging areas and muladares after wind farms have been built, it is not known to what extent and how many other wind farms Griffon Vultures may encounter as they visit various food sources (Martínez-Abraín et al. 2011).

Wind tunnel tests with a model of the proposed wind farm will provide some indication where the main concentrations of soaring birds are likely to occur (de Lucas et al. 2012b). Since Griffon Vultures usually exploit predominant wind flows (specifically the routes where the least amount of flight effort is needed) formed by the topography of the land, certain locations of wind turbines (rather than the wind farm as a whole) could be very dangerous even when there is a relatively low density of birds in the vicinity of the wind. Not only is this tool useful for simulating the possible flight routes of Griffon Vultures and other soaring birds, it is also helpful in positioning individual turbines in less risky locations (de Lucas et al. 2012b).

A post-construction survey of actual wind turbine collision deaths on a per-turbine basis will determine where modifications need to be made. For instance, individual wind turbines with high mortality rates compared to surrounding wind turbines may be turned off during times when collision is more likely to occur, such as during the winter months from December to February, or completely dismantled (Ferrer et al.2012). Based on data from de Lucas et al. (2012a), turning off select wind turbines can decrease the mortality of Griffon Vultures by half with only a 0.07% reduction in energy production.

2. Managing Food Sources

Since Griffon Vultures are greatly dependent on muladares and similar man-made concentrations of food, managing food sources can, indirectly, contribute to a reduction in mortality rate due to wind turbine collisions. Changing the location of muladares away from wind farms or establishing other scattered (and somewhat unpredictable) food sources to mimic historical conditions, could lead to the development of more robust populations while reducing their exposure to wind turbines (Martínez-Abraín et al. 2011). Others have suggested that hunting, especially of red deer and wild boar, can play a role in maintaining local Griffon Vulture populations when or where the use of muladares is prohibited (Mateo-Tomás & Olea 2009).

3. Wind Turbine Design

The technology of wind turbines itself has improved over the last decade and there are several interesting developments on the horizon. Tubular towers are more now commonly installed rather than lattice towers, which were often used by Griffon Vultures and other raptors for perching and even nesting (Barrios & Rodríguez 2004). One novel idea, as put forth by de Lucas et al. (2012a), would be to develop an automatic system capable of stopping the blades of the turbine if the trajectory of a flying birds leads directly towards it. Perhaps the most promising innovations are those detailed in Alex Steffen's *WorldChanging* (2006). Greater wind speeds are generally located at higher altitudes, so over time the trend has been to develop taller wind turbines. Companies such as Sky WindPower and Magenn are now in the process of building "flying windmills." Some models feature propeller blades high up in the jet stream that are tethered to the ground, while other smaller prototypes feature simple blimp-like designs with scoops that rotate around a horizontal axis (Steffen 2006). Both of these designs are still in developmental phase, but there is a growing interest in flying windmills with the hope that these will greatly reduce the negative effects of current wind farms on flying fauna.

Wind energy has long been touted as the newest, greenest, and cleanest form of energy production. Indeed, wind energy production has greatly increased globally over the last decade, but the case study of the Griffon Vulture in Spain shows that wind energy can have unexpected and unintended consequences. Turbine blades claim the lives of 7,000 or more Griffon Vultures per year, which is, in comparison to total a population of more than 25,000 breeding pairs, a disconcerting amount. Now that a substantial amount of research is available, it is paramount that the results are taken into account at every level of development, from the initial design of the turbine, to assessment of the wind farm as well as monitoring and seasonal adjustment once construction has been completed. The case of the Griffon Vulture has demonstrated that the effects of a wind farm extend far beyond its immediate vicinity, sometimes hundreds of kilometers. Currently, the most efficient way to prevent collision of vultures, and by extension other soaring birds, would be to conduct an extensive wind pattern analysis of the proposed site, which is already part of the development of a wind farm, and adjust the location of each turbine so as to minimize interaction with sensitive species. For existing wind farms, continued monitoring and adjustment may reduce mortality rates at specific, potentially high-risk locations.

APPENDIX

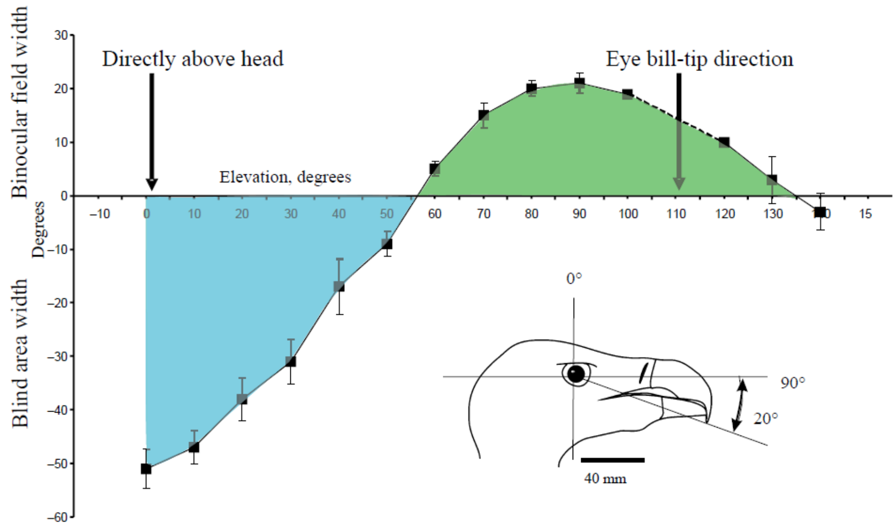


Figure 1. Mean angular separation of the retinal field margins as a function of elevation in the median sagittal plane in *Gyps* vultures.
Positive values indicate overlap of the field margins (binocular vision), and negative values indicate the width of the blind areas.
Note: Martin, G. R., S. J. Portugal, and C. P. Murn. 2012. Visual fields, foraging and collision vulnerability in *Gyps* vultures. Ibis 154:626-631.

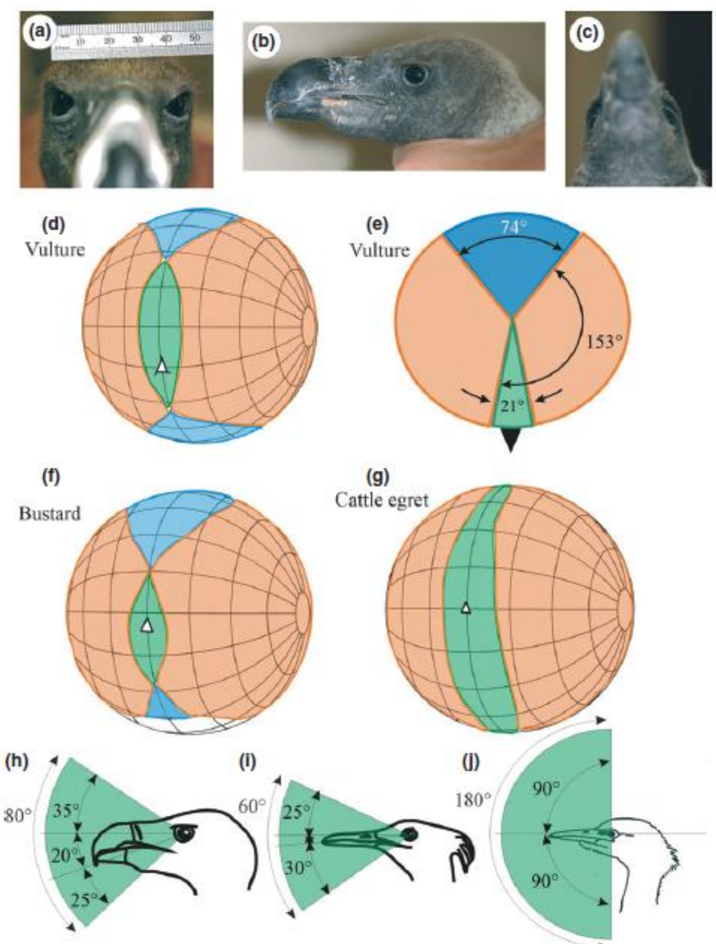


Figure 2. Visual fields of *Gyps* vultures.
The figure shows data for the vultures but also allows interspecific comparisons with the visual field of Kori Bustards *Ardeotis kori* (i) and Cattle Egrets *Bulbulcus ibis* (j). The top row shows photographs of the head of an African White-backed Vulture *Gyps africanus* (closely related to the Griffon Vulture); note the prominent eye ridge. (d) Perspective views of orthographic projections of the boundaries of the retinal fields of the two eyes and the line of the eye-bill tip projection (indicated by a white triangle). It should be imagined that the bird's head is positioned at the center of a transparent sphere with the bill tips and field boundaries projected onto the surface of the sphere with the heads in the orientations shown in (b). Green areas, binocular sectors; pink areas, monocular sectors; blue areas, blind sectors; downward pointing black arrowhead in (e) indicates direction of the bill.
Note: Martin, G. R., S. J. Portugal, and C. P. Murn. 2012. Visual fields, foraging and collision vulnerability in *Gyps* vultures. Ibis 154:626-631.

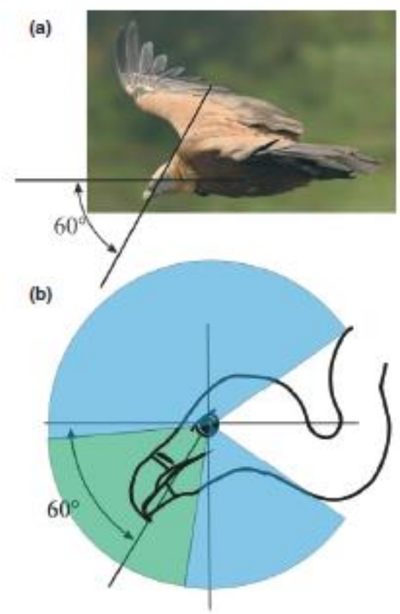
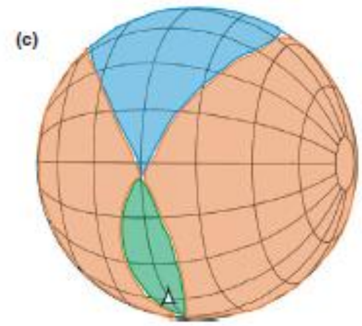


Figure 3. Visual fields and foraging in *Gyps* vultures. (a) Photograph of a bird in foraging flight showing the typical angle of the eye-bill tip projection when foraging (60 ˚ with respect to the horizontal). (b) Projection of the binocular and blind areas in the sagittal plane and (c) perspective view of orthographic projections of the visual field, when the head is held at the eye-bill tip angle depicted in (a). Green, binocular sector; blue, blind sector. *Note*: Martin, G. R., S. J. Portugal, and C. P. Murn. 2012. Visual fields, foraging and collision vulnerability in *Gyps* vultures. Ibis 154:626-631.



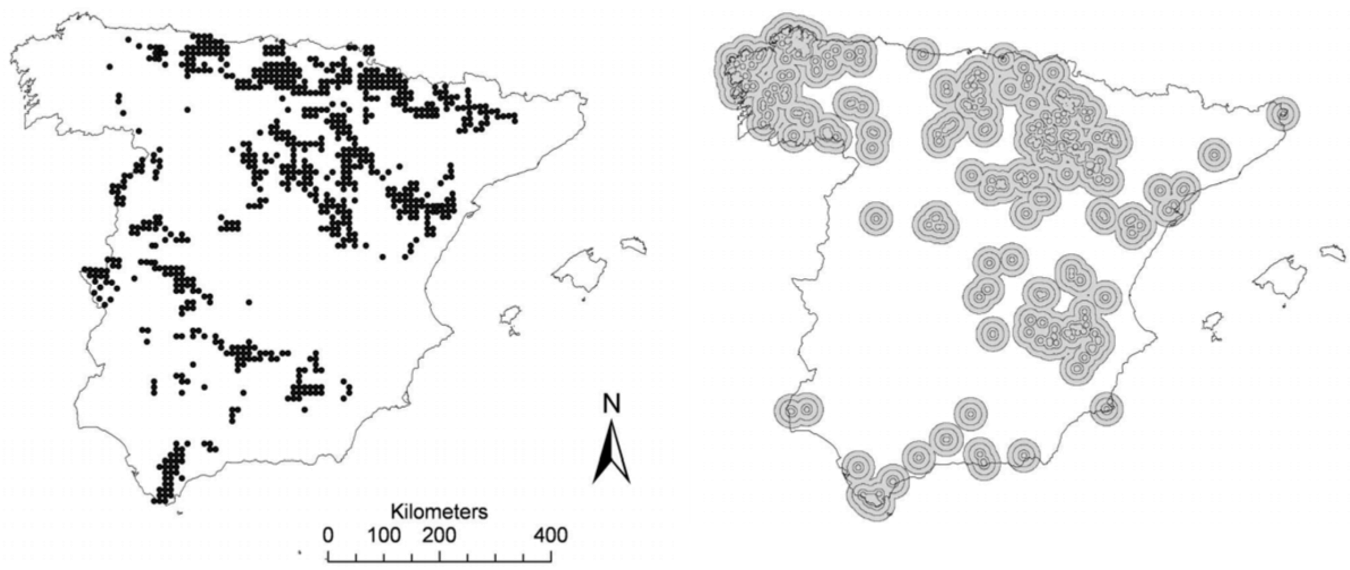


Figure 4. Distribution of 10 x 10 km UTM squares with breeding colonies of Griffon Vultures in Spain (left) and of 5, 10, 20, and 30 km buffer areas around wind plants (right). *Note*: Tellería, J. L. 2009. Overlap between wind power plants and Griffon Vultures *Gyps fulvus* in Spain. Bird Study 56:268-271.

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