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Adverse impacts of wind power generation on collision behaviour of birds and anti-predator behaviour of squirrels

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Summary

Wind power is a fast-growing energy source for electricity production, and some environmental impacts (e.g. noise and bird collision) are pointed out. Despite extensive land use (2600–6000 m^2/MW), it is said that most of these impacts have been resolved by technological development and proper site selection. The results in this paper suggest that: (i) wind farms kill millions of birds yearly around the world, and the high mortality of rare raptors is of particular concern; (ii) wind farms on migration routes are particularly dangerous, and it is difficult to find a wind power site away from migration routes because there is no guarantee that migration routes will not vary; (iii) according to the presented model of collision probability, the rotor speed does not make a significant difference in collision probability; the hub is the most dangerous part, and large birds (e.g. raptors) are at great risk; and, (iv) based on the field observation of squirrels' vocalisation (i.e. anti-predator behaviour), there are behavioural differences between squirrels at the wind turbine site and those at the control site. Noise from wind turbines (when active) may interfere with the lives of animals beneath the wind turbines.

US Government guidelines and the Bern Convention's report have described adverse impacts of wind energy facilities on wildlife and have put forward recommendations. In addition to these documents, the following points derived from the discussion in this paper should be noted for the purpose of harmonising wind power generation with wildlife conservation: (i) engineers need to develop a turbine form to reduce the collision risk at the hub; (ii) institute long-term monitoring, including a comparison between bird mortality before and after construction; and (iii) further evaluate impacts of turbine noise on anti-predator wildlife vocalisations.

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Introduction

The first wind-powered electricity was produced by a machine built by C. Brush in 1888. This machine had a rated power of 12 kW (DWIA, 2003). During the 1980s, installed capacity costs dropped considerably and since then wind power has become an economically attractive option for commercial electricity generation (ITDG, 2005). Large wind farms or wind power stations have become a common sight in many western countries; e.g. Denmark alone had 2000 MW of electricity generating capacity from more than 5700 wind turbines in 2001, representing ~15% of their national electricity consumption (ITDG, 2005). Wind energy is being adopted in more and more countries, with 58,982 MW installed worldwide in 2005 (World Wind Energy Association (WWEA), 2006).

The global rate of growth of wind power increased to 24% in 2005, up from 21% in 2004; with this trend continuing to increase, 120,000 MW is projected to be installed worldwide by 2010 (WWEA, 2006). This dynamic increase shown in Figure 1 can be justified as follows: since wind is a clean, renewable form of energy and a free source of electricity, it will reduce energy dependence on imported fossil fuel and reduce the output of greenhouse gases (e.g. CO_2) and other pollution (e.g. SO_2, NO_x, etc.). Therefore, many public organisations are promoting the construction of vast wind farms, encouraging private companies with generous subsidies and regulatory support, requiring utilities to buy from them, and setting up markets for the trade of green credits in addition to actual energy.

Wind power seems to be environment friendly. However, some considerations need to kept in mind when planning a wind power scheme. Disadvantages of wind power may hinge on the extensive land use required for wind farms, and possible demerits can be evaluated according to a multi-criteria matrix (e.g. Gamboa & Munda, 2006): income issues, number of jobs, visual impact, forest loss, noise, CO_2 reduction and installation capacity. The evaluation criteria encompass economic, sociological, socio-ecological and technical issues, but wildlife impacts are not included. In spite of extensive land use (2600–6000 m^2/MW), wildlife impacts including noise have not been sufficiently taken into account in wind power schemes. The following reasons are reported: (i) the sounds emitted by modern wind turbines are usually masked by other natural sounds in the area (The Office of Energy Efficiency and Renewable Energy (OEERE), 2005; WRA, 2005); and (ii) current wind turbine technology offers a solid tubular tower to prevent birds from perching on it, and turbine blades rotate more slowly than those of earlier design (OEERE, 2005; WRA, 2005).

There have been few comprehensive studies and even fewer published scientific papers on wildlife impacts of wind power, and many studies suffer from a total lack of assessment of relevant factors, e.g. collision risk, differences in bird behaviour, etc. (Birdlife International, 2003). In light of the significant increase in the use of wind power (see Figure 1), it seems worthwhile to assess whether wildlife impacts from wind power generation are really negligible. This subject is discussed based on the collision behaviour of birds and the anti-predator behaviour of squirrels. The purpose of this paper is not to criticise wind power generation but to discuss relevant impact factors in great detail. The main purpose is to take a general view of the data and establish a fundamental concept in order to encourage an environment friendly relationship between wildlife and wind power generation. Therefore, the description of each topic is simple, followed by a general principle for linking strategies for nature conservation with those for renewable energy. The principles of wind power generation are outlined first, followed by the main discussion.

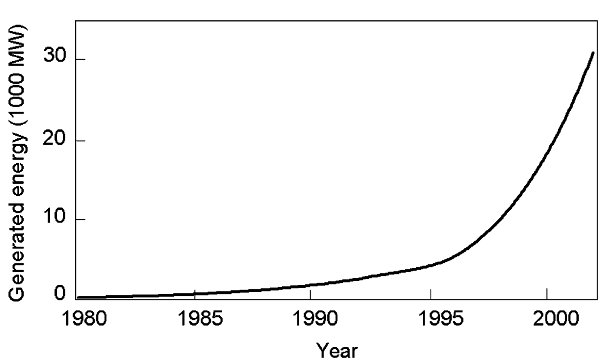

Figure 1. Worldwide energy generated by wind power (reviewed by Podolsky, 2003).

Principles of wind power generation

Wind power plants (or wind farms as they are sometimes called), are clusters of wind machines used to produce electricity. A wind farm usually has dozens of wind machines scattered over a large area. A simple overview of the technology for wind power generation is provided by Bockris (1977), Adachi (1997), Pereira (1998) and ITDG (2005).

Basic theory

Wind (air in motion) is a form of solar energy, that is, it is caused by the uneven heating of the earth's surface by the sun. The earth's surface is made up of different types of land and water, so it absorbs the sun's heat at different rates. Today, wind energy is mainly used to generate electricity. Wind is called a renewable energy source because the wind will blow as long as the sun shines. The power (P in watts) in the wind is proportional to the windmill area being swept by the wind (A in square metres), the wind speed (V in metres per second) and the air density (in kilograms per cubic metre), so the following formula is used to calculate the power: $P = (AV^3)/2$. However, the power extractable from the wind is significantly less than the power calculated from the above formula. This low availability is known as the Betz limit; in practice, the power available from a wind machine is usually around 45% of the theoretical maximum available for a large electricity-producing wind turbine.

Wind machines

Today's wind machines use blades to collect the wind's kinetic energy; most turbines have either two or three blades, and the wind flows over the airfoil-shaped blade causing lift, like the effect on airplane wings, causing them to rotate. The blades are connected to a drive shaft that turns an electric generator through a gear box. Gears connect the low-speed shaft to the high-speed shaft and increase the rotational speeds from about 30–60 rpm to about 1200–1500 rpm, the rotational speed required by most generators to produce electricity. The gear box is a costly (and heavy) part of the wind turbine and engineers are exploring a direct-drive generator that operates at lower rotational speeds and does not need gear boxes. There are two types of wind machine used today – the horizontal axis type and the vertical axis type. These two types are illustrated in Figure 2.

The terms used will be explained first (refer to Figure 2): nacelle – the rotor attaches to the nacelle, which sits atop the tower and includes the gear box, low- and high-speed shafts, generator, controller, and brake; towers are made from tubular steel or steel lattice because wind speed increases with height – taller towers enable turbines to capture more energy and generate more electricity; rotor – the blades and the hub together are called the rotor; and pitch – blades are turned, or pitched, out of the wind to keep the rotor from turning in winds that are too high or too low to produce electricity.

The horizontal axis device is the type most commonly used. A typical horizontal wind machine stands as tall as a 20-story building and has three blades that span ~100 m across (the largest wind machines in the world have blades longer than a football field). Wind machines stand tall and wide to capture more wind. Vertical axis wind machines make up just a few percent (probably ~5%) of the wind machines used today. Vertical axis wind machines have blades that go from top to bottom. The typical vertical wind machine stands ~50 m tall and 25 m wide.

Advantages and disadvantages

Wind energy is fueled by the wind, so it is a clean energy source. Wind energy does not pollute the air like thermal power plants that rely on combustion of fossil fuels such as coal or natural gas. Wind turbines do not produce atmospheric emissions that cause acid rain or greenhouse gasses (GHGs). Wind turbines can be built on farms or ranches, thus benefiting the economy in rural areas, where most of the best wind sites are found.

Although wind energy is a clean source and may be economically feasible, the serious problem remains of what to do when the wind is not blowing; that is, it does not always blow when electricity is required, and wind energy cannot be stored (unless batteries are used). Environmental concerns include: (i) aesthetic (visual) impact; (ii) the noise produced by the rotor blades; and,

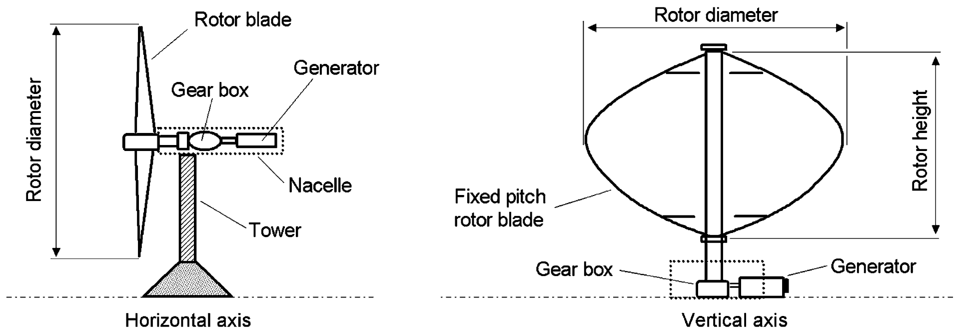

Figure 2. Schematic of wind turbine (redrawn from AWEA, 1998).

(iii) the occasional killing of birds that have flown into the rotors. Most of these problems have been resolved through technological development and/or by properly siting wind plants (OEERE, 2005; WRA, 2005) (see also the Introduction).

The Bern Convention (September 1979) is a binding international legal instrument in the field of nature conservation, which covers the whole of the natural heritage of the European continent and extends to some states of Africa. Its aims are to conserve wild flora and fauna and their natural habitats and to promote European co-operation in that field. A report written on behalf of this Convention identifies three major hazards to wildlife from wind farms (Birdlife International, 2003): (i) disturbance leading to displacement (or exclusion) including barriers to movement; (ii) collision mortality; and (iii) loss of (or damage to) habitat resulting from wind turbines and associated infrastructure. There is doubt as to whether wildlife impacts (including noise) have really been almost solved or greatly reduced; this subject is therefore further elaborated upon in the following section.

Wind turbine and bird collision

The Altamont Pass is a mountain pass in California (USA) about 90 km east of San Francisco, and this pass is known as the largest wind energy facility (~7000 wind turbines) in the world (Smallwood & Thelander, 2004). The wildlife risk in terms of turbine-caused fatalities in this area is reported as follows: a bird mortality of 0.05 deaths per wind turbine per year (Howell & Didonato, 1991) and a raptor mortality of 0.03 deaths per wind turbine per year (Howell, 1997). Considering these data, wildlife impacts of wind power generation may be minimal. Another observation was conducted at the Mountaineer Wind Energy Center located along the Appalachian plateau in West Virginia, and the results show a bat mortality of 38 deaths per turbine for the 6-week study period (Bats and Wind Energy Cooperative (BWEC), 2004). It is estimated that 1356–1980 bats were killed by 44 wind turbines in this 6-week period (BWEC, 2004). As seen above, mortality rates per turbine are variable because collision probability depends on a range of factors such as bird or bat species, numbers, behaviour, weather conditions, topography and the nature of the wind farm itself (Drewitt & Langston, 2006).

Europe is the world leader in wind energy; a few years ago, Europe accounted for some 75% of the global market (DWIA, 2006). With ~6300 MW of installed capacity, Europe accounts for more than 50% of the world's new wind power capacity (DWIA, 2006). Table 1 shows the mean avian mortality rate by collision at some wind farms in Europe.

The mortality rates shown in Table 1 are calculated mainly from observations in spring and autumn, originally expressed as birds per turbine per day; the rates over a year-long period could be lower.

Interpretation of mortality

It cannot be generalised that a low mortality rate is correspondent to a low risk. As stated above, collision-caused mortality depends upon a range of

Table 1. Mean avian mortality rate by collision at some wind farms in Europe (reviewed by Everaert, 2003)

Country	Place (wind farm)	Number of turbines	Avian victims per turbine per year	Study period
Belgium	Schelle	3	18	1 year
	Oostdam	23	24	2 years
	Boudewijinkan	14	35	1 year
Spain (Navarre)	Salajones	33	35	1 year
	Izco	75	26	1 year
	Alaiz	75	4	1 year
	Guerinda	145	8	1 year
	El Perdon	40	64	1 year
UK	Blyth	9	1.34	2 years
Netherlands	Zeeland	5	2–7	1 year
	Ooasterbierum	18	22–33	1 year
	Urk	25	15–18	1 year

The studies used correction factors (predator removal and search efficiency rates) to adjust the figures. This is only the number of large birds. Small birds are not included because they were not surveyed.

factors. For example, the mortality rate may increase in a place with many large birds (e.g. swans) with poor maneuverability that are generally at great risk of collision with a structure (Brown et al., 1992). Species that habitually fly at dawn and dusk (or at night) are less likely to detect and avoid wind turbines (Larsen & Clausen, 2002). The Spanish local government reports that the Navarre wind farms (see Figure 3) killed about 7150 birds, including 409 vultures and 29 eagles, in one year (Lekuona, 2001). The high mortality of raptors, such as the Griffon Vulture (*Gyps fulvus*) and Golden Eagle (*Aquila chrysaetos*), is of particular concern because they are relatively rare and long-lived species which have low reproductive rates and are vulnerable to additive mortality.

In the Spanish case, extensive wind farms were built in topographical bottlenecks where large numbers of migrating and local birds fly through a relatively confined area due to the nature of the surrounding landscape, for example through mountain passes, or use rising winds to gain lift over ridges (Barrios & Rodriguez, 2004). In the case of Altamont Pass, mortality rates (per turbine per year) are low, but overall collision rates are high because of the large number of wind turbines (~7000 turbines). Thus, it is estimated that ~80 Golden Eagles and ~400 Griffon Vultures are killed annually by turbine collision at Altamont Pass. The raptor population is declining in this area, and the cause is thought to be at least in part due to collision mortality (Hunt, 2001).

Direct mortality or lethal injury of birds can result not only from collisions with rotors, but also with towers, nacelles and associated structures such as guy cables, power lines and meteorological masts (Drewitt & Langston, 2006). Birds may also be forced to the ground as a result of being drawn into the vortex created by moving rotors (Winkelman, 1992). The majority of studies of collisions caused by wind turbines have recorded relatively low levels of mortality (e.g. reviewed by Erickson et al., 2001). This is perhaps largely a reflection of the fact that many of the studied wind farms are located away from large concentrations of birds (Drewitt & Langston, 2006). It is also important to note that many records are based only on corpses found, with no correction for corpses that are overlooked or removed by scavengers (Birdlife International, 2003). Accepting that many wind farms result in only low levels of mortality, even these levels of additional mortality may be significant for long-lived species with low productivity and slow maturation rates, especially when rare species of conservation concern are affected. In such cases there could be significant effects at the population level (locally, regionally, or in the case of rare and restricted species, nationally), particularly in situations where cumulative mortality takes place as a result of multiple installations.

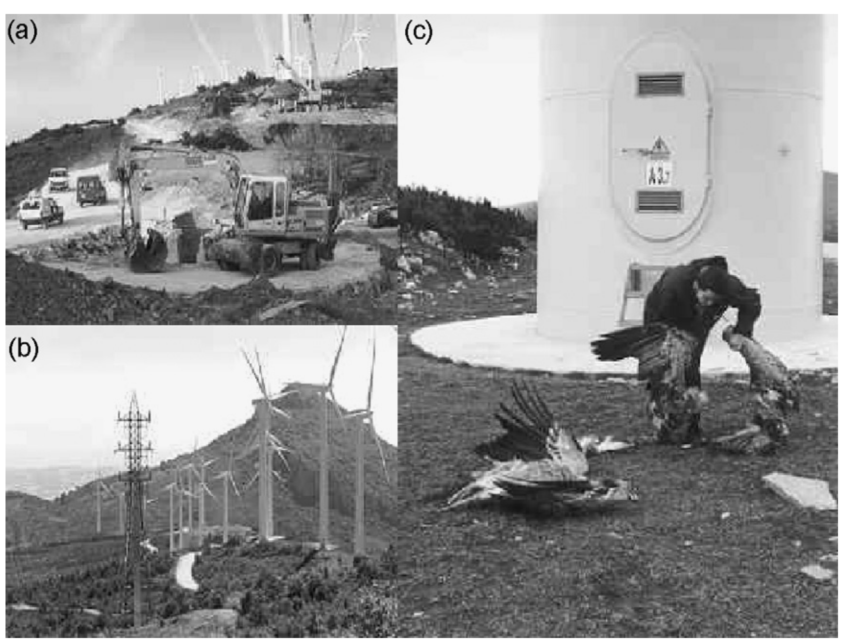

Figure 3. Birds and wind farm at Alaiz in Spain (courtesy Gurelur – Fundo Navarro para la Proteccion del Medio Natural): (a) construction work of wind farm; (b) overview of wind farm; and (c) several dead vultures.

Perception and collision

The most dangerous wind turbines (i.e. those with the highest mortality rate) are located at the ends of rows, and wind turbines that are more isolated from other turbines kill disproportionately more birds in Altamont Pass; by contrast, wind turbines situated in the interior of wind turbine clusters are safer for birds (Smallwood & Thelander, 2004). This observation suggests that birds recognise wind turbines and towers as obstacles, and they take measures to avoid wind turbines, such as attempting to fly around the turbines at the ends of strings, and flying lower to the ground or higher from the ground around the end turbines. Nevertheless, dangerous flights are still made. Raptors perform disproportionately more of their perching and flying within 50 m of wind turbines, despite the evidence that they generally attempt to avoid wind turbines while perching and flying. Red-tailed hawks and American kestrels appear to attempt to avoid end-of-row wind turbines, which happen to be where they get killed more often. Raptors are more likely to fly close to wind turbines that have slower-moving rotor blades and are mounted on tubular towers, as well as to vertical axis turbines. They also are more likely to fly close by wind turbines that are more widely spaced apart.

As stated above, birds may recognise wind turbines; however, they have some problems in avoiding them. These problems are summarised based on the published data (Duchamp, 2003):

(i) *Vision* – the eyes of most birds are located on each side of the head, and their eyes can cover a field of vision nearing 360° in order to detect predators coming from any angle. On the downside, their quality of perception is mediocre at the limit of the 180° covered by each eye; i.e. right in front of the bird, right behind, right above and right below. This is compensated for by the flexibility of their necks which are easily twistable. But unless their heads happen to be twisted around to see what is above (or sideways to see what is in front), their vision of the wind turbines that they are flying into will be rather poor. Rabbits and non-predatory mammals usually have the same problem: for this reason, it is easy to capture them in nets. Low-flying nocturnal migrants, such as many species of songbird, are especially prone to collision with man-made structures. Nocturnal bird kills are virtually certain wherever an obstacle extends into the air space where birds are flying in migration (Weir, 1976). Raptors' vision is superior to that of other birds, e.g. a peregrine falcon can spot a pigeon flying 3.5 km away. As raptors hunt, they often focus their eyes at great distances to detect prey. When the lens is focused on a far-away point, twigs moving in the forefront are barely visible. The danger is heightened by the fact that their eyes are fastened on the prey.

(ii) *Group* – there is a possibility that flying in flocks may increase the percentage of casualty. The reasons are obvious: law of numbers; breadth and depth of the flock; and, the birds flying behind others have a reduced vision of what is in front.

(iii) *Weather* – it is expected that birds will accidentally venture on the trajectory of a turbine blade when visibility is impaired by bad weather such as rain, or in darkness.

(iv) *Flight pattern* – raptors glide most of the time to save energy. They use ascending air currents which often form along slopes and ridges, where wind plants are often located for the same reason. They drift on the wind itself, the same wind that flows through the turbines. Some raptors (e.g. Golden Eagle) practice contour flying, i.e. close to the ground. Often they pass under the turbines, but sometimes they are not low enough, especially if a gust of wind sends them upwards.

(v) *Perching* – birds of prey commonly perch on tall structures. When the blades are standing still on days without wind, turbines become perching sites and will attract raptors. Having perched once, they will tend to come back to the site, whether the blades are moving or not. Even tubular-tower turbines may attract them for that purpose, e.g. sea-gulls were seen perching on turbine nacelles at the Tuno Knob offshore wind farm in Denmark (Birdlife International, 2003).

(vi) *Instinct* – birds, like any other animal, can distinguish between living creatures (e.g. prey) and inanimate objects. Their instinct sometimes does not warn them against television towers, tension lines, or wind turbines.

(vii) *Migration* – observation at the Flanders wind farms in Belgium indicates that the number of collision victims is relatively high on the routes of local migrations (Everaert, 2003). The effect of the barrier is also pointed out (Birdlife International, 2003). This effect is of concern because of the possibility of increased energy expenditure when birds have to fly farther as a result of avoiding a large array of turbines, and the potential disruption of linkages between distant feeding, roosting, moulting and breeding areas otherwise unaffected by the wind farm (Drewitt & Langston, 2006). Erecting wind turbines on migration routes is particularly dangerous for the birds; night-flyers, with greatly reduced visibility, may not even see the rotors. Daytime migrants which tend to fly higher, and out of reach of the rotors, during good weather become more vulnerable in poor weather conditions. They also fly closer to the ground when they skirt mountain crests, which are preferred locations for wind farms. A migration route is as wide as a country; Spain, Italy, and Israel are the natural highways to Africa for most European birds (Holden & Langman, 1994). These routes are so wide that even if it is desirable to site a wind farm away from them, it is very difficult to find a place for such a wind farm. In addition, night migration routes (e.g. routes used by many songbirds) are currently not well known (Birdlife International, 2003). Preliminary research covering one or two years would be insufficient to assure that a proposed location is not potentially dangerous because there is no guarantee that migration routes will not vary from one year to another. As for migratory birds, the European Union Directive 79/409/EEC (Birds Directive) lists the threatened and vulnerable species of Europe; member states are therefore required to undertake special conservation measures for these species, e.g. classification of protection areas.

Collision risk model

Wind turbines create powerful air disturbances in their wake and around the blades themselves. These can easily throw a bird or a bat to the ground, or otherwise impair its flight. Unlike approaching cars, the blades of a turbine do not maintain a straight course; they travel on orbit. The result is that their flying victims do not notice the blade-tip until it suddenly appears above their heads, or underneath them, and strikes in a split second. It is obviously necessary to consider the effect of turbine design on bird mortality. Although there are many factors such as tower type, wind wall and so on, some factors are selected for discussion in this paper. As stated above, there is a difference in the mortality rate between a turbine at the end of a row and a turbine in the interior of a turbine cluster (i.e. congestion). There is no clear pattern between mortality and tower height in Altamont Pass (Smallwood & Thelander, 2004). In Flanders, the number of collisions is lower in proportion to the generation capacity (kW) of the wind turbines, but it is dependent on the number of passing birds (Everaert, 2003). A high risk of collision clearly exists when a bird is in flight within the rotor's swept area (i.e. the circular area delineated by the rotating blades) and/or may be affected by the rotor's turbulence, so the following factors are selected: location of rotor (radius – hub and tip); and, rotation (rpm) and flight speed of the bird (relative to the body size). A probabilistic/kinetic model has been developed to simulate bird collision at a wind farm (for further technical details, refer to Podolsky, 2003, 2005). The output of this model is collision risk probability, which is denoted by (collision flight paths)/(total flight paths). It is necessary to consider behavioural information concerning the proportion of the population that avoids turbine blades and the proportion that is attracted to turbine blades, but real behavioural data on avoidance and attraction are unknown. Assuming that the proportion of the population attracted to turbines is small, the values 0.999 representing the proportion that avoids turbines and 0.001 representing the proportion that is attracted to turbines are adopted to run the model. The results obtained from the model run are summarised in Figure 4.

The model has two basic sets of data inputs. The first set of inputs characterise the bird, and these input data are shown in Figure 4. Each bird speed is constant in Figures 4a and b, and the collision probability as a function (8–34 m/s) of the bird speed is shown in Figure 4c. The second set of inputs characterise the design of the wind farm; 38.5 m rotor radius, 10.5 m radius at the widest point on the rotor, 2.0 m blade width at the hub, 0.1 m blade width at the tip, 2.6 m blade width at the widest point and three rotor blades (single turbine). There are two cases concerning birds' angle (direction relative to the rotor plane) of approach to the wind farm: a worst case – approach perpendicular to the rotor plane; and, a best case – approach parallel to the rotor plane. The difference between the above-mentioned two approach angles (i.e. perpendicular approach and parallel approach) is not as high as one might expect; it would be best to avoid the turbines altogether (Podolsky, 2003, 2005). It follows from Figure 4 that: (i) the hub is the riskiest part of the turbine to negotiate, even though the tip is moving faster (best to fly towards the tip) (see Figure 4a); (ii) the rotor speed does not make a significant difference in collision probability (see Figure 4b); and, (iii) bird speed also does not make a significant

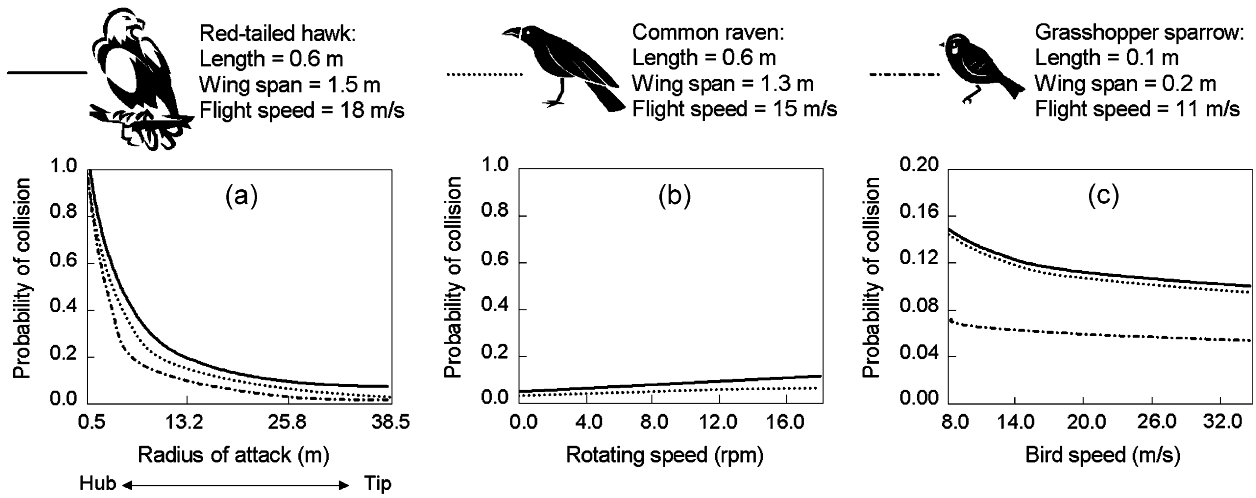

Figure 4. Risk probability of bird colliding with rotating turbine (based on Podolsky, 2003, 2005): (a) probability of collision vs. radius of attack (38.5 m blade, 14 rpm); (b) probability of collision vs. rotating speed of rotor (at 20 m for a 1.8 MW wind machine); and (c) probability of collision vs. bird speed.

difference; but larger birds are at greater risk (see Figure 4c).

Noise and anti-predator behaviour

As stated in the Introduction, the noise of a wind turbine can be considered a wildlife impact; however, it is reported that the sounds emitted by modern wind turbines are usually masked by other natural sounds in the area (OEERE, 2005; WRA, 2005). As a wind farm occupies extensive land (2600–6000 m^2/MW), there is a possibility that animals living on hillsides close to a wind farm may be affected by the acoustically changed environment. The European Union Directive 92/43/EEC (referred to as Habitats Directive) aims to conserve natural habitats and wild fauna and flora; it is therefore important to consider the acoustic effect of wind farms on natural habitats. This subject is discussed based on a field survey conducted in Altamont Pass during August to September 2001 (Rabin et al., 2005, 2006).

Alarm calls and sciurid vocal communication

When danger in the form of a predator is spotted, animals may call in a pattern that is interpreted by other individuals as a warning. Upon hearing an alarm call, individuals typically react by freezing, heading swiftly towards cover, or ceasing all activity. Sometimes the alarm call of one species produces a reaction in individuals of other species (Sullivan, 1985). Ground-dwelling sciurids (e.g. squirrels) emit vocalisations in response to predators (Macedonia & Evans, 1993). An interesting feature of sciurid vocal communication systems is that many species use both non-repetitive and repetitive call types. In the former, a discrete acoustic element is produced in temporal isolation from other vocalisations; in the latter, similar elements are produced repeatedly, with intervening silences of similar duration to the elements themselves. The alarm vocalisations produced by adult California ground squirrels (*Spermophilus beecheyi*) in response to mammalian and avian predators have been well described (see Owings & Leger, 1980; Owings & Virginia, 1978). In response to terrestrial mammalian predators, squirrels typically produce multi-note vocalisations (i.e. chatter), retreat to burrows and mount promontories where they monitor the activity of the intruder. In contrast, squirrels typically respond to avian predators by producing single-note calls (i.e. whistle) followed by an immediate dash to a refuge.

Noise characterisation

As part of the above-mentioned field survey in Altamont Pass (Rabin et al., 2006), sound pressure levels were measured at each site: one set of readings was taken at the control site; and, two sets were taken at the turbine site – one while the turbines were active and the other while the turbines were inactive. Recordings of ambient noise at each site were also made at ground level near ground squirrel burrows. Ambient noise at the

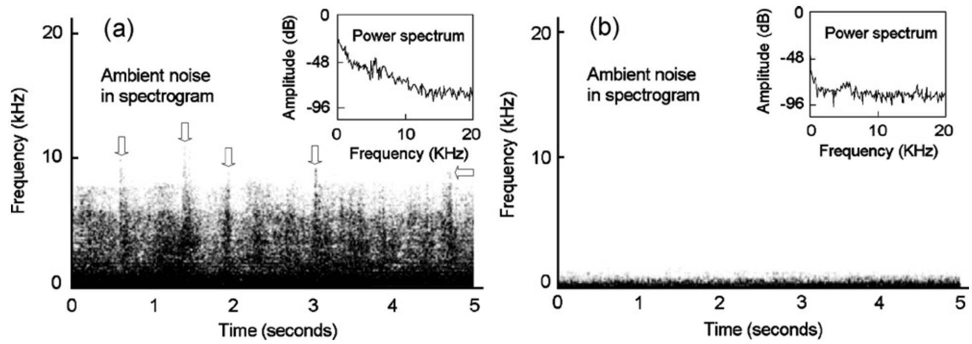

Figure 5. Spectrograms and power spectra of ambient noise at turbine site and control site (redrawn from Rabin et al., 2006): (a) turbine site ambient noise and its power spectrum. Arrows mark the spectral signatures (swoosh) of the turbine blades as they rotate; and (b) control site ambient noise and its power spectrum.

turbine site was recorded once when all turbines surrounding the site were active and again when no turbines were active. The noise characterisations at the turbine site and the control site are summarised in Figures 5a and b.

As seen in Figure 5, the average decibel level (power spectrum in Figure 5b) for ambient noise at the control site is substantially lower than that at the turbine site during turbine activity (power spectrum in Figure 5a). When the turbines are active, the turbine site has a complex spectral signature with amplitude noise extending as high as 6–8 kHz. The swooshing sound of the sweeping wind blades is identified by arrows on the spectrogram in Figure 5a. The ambient noise spectrum at the control site is much simpler, with noise produced mostly at very low frequencies by wind.

Behavioural responses

An experiment carried out in Altamont Pass (Rabin et al., 2006) is summarised in the following paragraph. A series of alarm calls were recorded from ground squirrels in the field immediately after exposure to a domestic dog simulating a carnivorous predator. Eight different series from squirrels of different ages and sex classes were used. Four of these series were obtained from four different squirrels at two turbine sites (moderate to high turbine activity) and are referred to as turbine-call-series. Another four call series were obtained from four different squirrels at a non-turbine site and are referred to as control-call-series. Predator abundance, vegetation type and vegetation density appeared to be similar for the two sites. Alarm calls were broadcast at ground level from a speaker array during a playback experiment. As alarm calls reliably elicit anti-predator responses in squirrels (Owings & Leger, 1980; Owings & Virginia, 1978), behavioural responses to playbacks were compared with baseline behaviour. Two variants of the experimental design were performed – focal squirrels were played a control-call-series; in the other variant, a turbine-call-series was broadcast. Behaviour differences between the turbine and control sites are summarised in Table 2.

The statistic terms used in Table 2 will be briefly explained (refer to Motulsky, 1995). The *F* value is known as an *F* statistic which is commonly expressed by $\{s_1^2/\sigma_1^2\}/\{s_2^2/\sigma_2^2\}$ where σ is the standard deviation of population and *s* is the standard deviation of the sample drawn from population. If variances have the same size in different groups, the *F* value is zero. The *P* value is the probability with a range from zero to one, and this value is compared with the significance level. If it is smaller, the result is significant; according to the Michelin Guide scale, $P<0.05$ (significant), $P<0.01$ (highly significant) and $P<0.001$ (extremely significant). Table 2 shows clear statistical differences in squirrel behaviour between the turbine site and the control site. The results shown in Table 2 are interpreted as follows: regardless of site, squirrels increase their vigilance in response to playback samples when compared with baseline (as indicated by the variable of alertness). However, squirrels at the turbine site are more vigilant overall than squirrels at the control site. Squirrels at the turbine site have a greater tendency to return to the area immediately around their burrows during playback (as indicated by the variable of shelter proximity). A high level of overall alertness at the turbine site indicates that turbine squirrels perceive themselves to be under higher risk than control squirrels. As stated above, the other conditions (predator abundance and vegetation) are similar for these two sites; in light of behavioural differences between the turbine site and the control site, it may be concluded that turbine noise affects the behaviour of squirrels.

Table 2. Behavioral differences of squirrels between turbine site and control site (derived from Rabin et al., 2006)

Behavior (variable)	Baseline vs. playback		Turbine site vs. control site	
	F-value	*P*-value	*F*-value	*P*-value
Alertness	21.353	<0.001	4.938	0.038
Proximity to shelter	–	–	9.238	0.006
Group size	8.048	0.015	0.598	0.454

Discussion and recommendations

Wind energy is being presented as a strategy for addressing problems associated with the emission of greenhouse gases (e.g. CO_2) and high energy dependence, thus, wind energy has a favourable image. However, the extensive land use required for wind farms (2600–6000 m^2/MW) causes negative impacts on nature conservation. It is reported that wind farms kill millions of birds yearly around the world, and many of them are eagles, swans, geese, storks and other protected species (Duchamp, 2004) (also see Table 1).

According to data published in Europe (DWIA, 2006): Spain has the largest capacity of wind power in Europe, with approximately 10,000 MW installed at present; Portugal is the third largest market of wind power in Europe, and the target for wind power is ~4000 MW by 2010; and, in France, the installed capacity (390 MW) in 2005 was about three times that in 2004. Considering the Birds Directive (79/409/EEC) and the Habitats Directive (92/43/EEC) of the European Union (EU), these European countries in particular should be attentive to adverse impacts of wind power on wildlife. For example, the following points are made in the Birds Directive: no further population decline of EU bird species; more species to have a favourable conservation status; the share of long-distance migrants (161 species) with favourable conservation status is increased from 35% (current level) to at least 50% by 2010; and the population trend of declining farmland birds is reversed by 2010.

Guidelines (Ref. no. FWS/DEPA/BFA, May 2003) from the US Fish and Wildlife Service and a report by the standing committee of the Bern Convention (Birdlife International, 2003) have clarified adverse impacts of wind energy facilities on wildlife and stated recommendations for impact abatement; the US guidelines and the Convention report should be referred to for detailed information. In addition to these recommendations, the following points derived from the discussion in this paper are advisable to harmonise wind power generation with wildlife conservation from an environmental viewpoint:

(i) Turbine blades currently rotate more slowly than those of earlier design (WRA, 2005), but this measure does not contribute to effectively reducing the collision risk (see Figure 4b). Though the rotor's tip moves fast, the hub is the most dangerous part. Engineers should develop a turbine form (e.g. spiral type) to reduce the collision risk at the hub.

(ii) Correct selection of appropriate sites for wind farms can minimise the environmental effect of wind-generated electricity (WRA, 2005). The problem of how to select proper sites remains because migration routes may vary from one year to another (see the section Perception and collision). Short-term research would be insufficient to confirm that a proposed location is not potentially dangerous. Long-term monitoring, including a comparison between bird mortality before and after construction, is necessary.

(iii) The sounds emitted by modern wind turbines are usually masked by other natural sounds in the area (OEERE, 2005; WRA, 2005), but there is a strong possibility that turbine-related noise (see Figure 5a) may interfere with the lives of animals (e.g. squirrels) beneath the turbines (see Table 2). In terms of assessing whether it is necessary to reduce turbine noise from the current level, it is necessary to conduct further research on the behavioural impacts of turbine noise on wildlife possessing vocalisation ability for alerting others to the presence of a predator; i.e. this subject implies how to set the permissible noise levels on the basis of wildlife conservation.

Conclusions

Wind energy is rapidly growing as a renewable source of electricity production; consequently, it can be considered that potential hazards to wildlife from wind farms are becoming more serious. It is reported that technological development has already resolved most impacts of wind power on the environment (OEERE, 2005), but this paper shows that some adverse impacts remain, and their magnitudes may increase if no measures are taken. The potential harm to wildlife should be carefully evaluated at both current and proposed wind farm sites; local administrators should ensure public access to the completed assessments. It is preferable to carry out future research rather than to criticise current impacts because further information will be useful for harmonising wind power generation with nature conservation. Ultimately, one of the keys to realising sustainable development is utilisation of renewable energy without any negative influence on the environment (Kazim, 2006).

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