Invited Paper

Wind Energy Development and Wildlife Conservation: Challenges and Opportunities

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ABSTRACT Wind energy development represents significant challenges and opportunities in contemporary wildlife management. Such challenges include the large size and extensive placement of turbines that may represent potential hazards to birds and bats. However, the associated infrastructure required to support an array of turbines—such as roads and transmission lines—represents an even larger potential threat to wildlife than the turbines themselves because such infrastructure can result in extensive habitat fragmentation and can provide avenues for invasion by exotic species. There are numerous conceptual research opportunities that pertain to issues such as identifying the best and worst placement of sites for turbines that will minimize impacts on birds and bats. Unfortunately, to date very little research of this type has appeared in the peer-reviewed scientific literature; much of it exists in the form of unpublished reports and other forms of gray literature. In this paper, we summarize what is known about the potential impacts of wind farms on wildlife and identify a 3-part hierarchical approach to use the scientific method to assess these impacts. The Lower Gulf Coast (LGC) of Texas, USA, is a region currently identified as having a potentially negative impact on migratory birds and bats, with respect to wind farm development. This area is also a region of vast importance to wildlife from the standpoint of native diversity, nature tourism, and opportunities for recreational hunting. We thus use some of the emergent issues related to wind farm development in the LGC—such as siting turbines on cropland sites as opposed to on native rangelands—to illustrate the kinds of challenges and opportunities that wildlife managers must face as we balance our demand for sustainable energy with the need to conserve and sustain bird migration routes and corridors, native vertebrates, and the habitats that support them. (JOURNAL OF WILDLIFE MANAGEMENT 71(8):2487–2498; 2007)

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"*. . . we have a serious problem: America is addicted to oil, which is often imported from unstable parts of the world. The best way to break this addiction is through technology.*"

This epigraph from the 2006 State of the Union speech by President Bush underscores our need to develop alternative and renewable sources of energy. Of the existing alternatives, wind-powered turbines that generate electricity are beginning to achieve an economy of scale that is making them ever more practical. Wind turbines generate little or no pollution and do not contribute greenhouse gasses to the environment.

Despite these positive features, constructing massive numbers of wind-powered turbines, or wind energy developments—popularly called wind farms—has the potential to impact wildlife populations, especially if their placement is done in a reckless, careless, or cavalier manner. The extent to which large numbers of huge spinning blades needed to power such turbines might impact wildlife is presently unknown and may be problematic. Additionally, the scientific literature on the effects of wind farms on wildlife populations is scant, especially with regard to bird migration corridors such as the Lower Gulf Coast (LGC). What information that does exist on this topic is dominated by gray literature, namely unpublished reports and unpublished data in the office files of various developers and consultants.

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In this paper, we summarize what is known about how wind energy developments influence wildlife populations and identify specific research opportunities and management challenges that can help mitigate the potential negative effects of this newly emerging technology. Our specific objectives are to focus on how wind energy developments influence migratory and resident birds, as well as bats and other wildlife.

We conclude by highlighting some specific issues and concerns that pertain to the LGC of Texas, USA, a region currently targeted for extensive wind farm development.

BIRDS

Collision Mortality

The primary emphasis of the majority of wind farm–wildlife research has been devoted to how wind farm development has impacted bird and, to a lesser extent, bat populations, and the primary emphasis of these studies has been to quantify collision mortality with wind turbines. Most of the research has been conducted in Europe and the United States over the past 20 years. Results from this research indicate that bird collisions range from 0 collisions/turbine/year up to >30.0 collisions/turbine/year and that this variability is due to numerous factors. Experimental designs and data collection protocols were generally inconsistent from study to study, which not only probably contributed to the observed variability between studies (e.g., Morrison

2002, Smallwood 2007) but also rendered results for the most part incomparable.

In addition to the variability associated with the lack of consistency between experimental designs, Drewitt and Langston (2006) indicated that collision risks depend on a variety of additional factors, including the layout design of the wind farm and specific characteristics of turbines, weather conditions, and topography, as well as the specific bird species and numbers of birds using the site and their behavior. For example, locating wind farms along the migratory routes or in habitats frequented by birds could result in higher bird collision rates (Orloff and Flannery 1992; Erickson et al. 2002; R. M. Montes and L. B. Jacques, Spanish Ornithological Society, unpublished report). Moreover, the specific configuration of turbines could facilitate collisions because turbines constructed linearly in long strings result in more collision mortality than turbines that are constructed in clusters. The heights, blade lengths, tip speeds, blade appearance to birds, and presence and type of lighting can also impact bird collision vulnerability with turbines. More modern turbine designs featuring taller towers and large blade lengths with slower tip speeds are thought to pose higher collision risks to birds than earlier turbine designs (Morrison 2006). Lighting on wind turbines may also influence collision risks because specific types of lighting attract nocturnal migrants. Turbine placement in relation to the topography of the wind farm site also probably influences bird collision probabilities (Hoover and Morrison 2005). Bird abundance at wind farms may also influence collision risks because collision rates at some wind farms are higher for those species that are the most abundant. Bird collision risk may also vary on a seasonal basis. Collision risks are undoubtedly higher during spring and fall because bird migration predominates during these seasons, although collisions can occur throughout the year because migratory behavior varies by geographic location, by weather, and between species (Richardson 1998). Furthermore, breeding resident bird species can collide with turbines during summer months. A number of studies have indicated that the impacts of wind farms on bird populations is generally insignificant for most species (Osborn et al. 1998; Erickson et al. 2000; R. W. Howe and W. Evans, University of Wisconsin-Green Bay, unpublished report; D. P. Young and D. Strickland, Western Ecosystems Technology, unpublished report); however, bird collision fatalities in North American wind farms constructed in bird migration routes and corridors remain a justifiable concern (Erickson et al. 2005).

Passerines and raptors.—Most of the research that has been completed in Europe and the United States indicates that passerines, particularly nocturnal migrants, suffer the most collision fatalities at wind farms regardless of what type of habitats wind farms are constructed in (Osborn et al. 2000; Mabee et al. 2006; J. Kerns and P. Kerlinger, University of Maryland, unpublished report). Indeed, Erickson et al. (2002) stated that passerines comprised 82% of all bird collision mortalities at wind farms outside of California, USA. Collision mortality estimates vary from site to site throughout the United States, but generally collision fatalities are not thought to be substantial enough to impact bird populations because few birds collide with turbines. For instance, Osborn et al (1998) reported a collision rate of <1.0 bird/turbine/year at a wind farm constructed on agricultural land and Conservation Reserve Program property in Minnesota, USA. Erickson et al. (2000) stated that 0.63 birds/turbine/year collided with wind turbines constructed on agricultural land and grasslands in Oregon, USA. Erickson et al. (2001) reviewed research results through mid-2001 from almost 20 wind farms located on either rangelands, agricultural lands, or woodlands throughout the United States and estimated a collision rate of 2.19 birds/turbine/year (range: 0–4.45). Additional results from more recent studies indicate that collision mortality remains similar to or lower than that reported by Erickson et al. (2001). For example, D. P. Young, W. P. Erickson, R. E. Good, M. D. Strickland, and G. D. Johnson (Western Ecosystems Technology, Inc., unpublished report) estimated that collision mortality was 1.5 birds/turbine/year at a wind farm located on Wyoming, USA, rangelands. DeLucas et al. (2004) found that 0.03 birds collided with turbines annually on a wind farm located in brushland in Spain. R. W. Howe, W. Evans, and A. T. Wolf (University of Wisconsin-Green Bay, unpublished report) reported that 1.29 birds/turbine/year collided with a Wisconsin, USA, wind farm located on agricultural land and woodlands. J. Kerns and P. Kerlinger (unpublished report) estimated that 4.04 birds/turbine collided with turbines between April and November at a wind farm located in woodlands in West Virginia, USA. Erickson et al. (2003) determined that 3.59 birds/turbine/year collided with turbines located on rangelands in Washington, USA.

Although collision mortality may have an insignificant impact on passerine populations, collisions with wind turbines may have an impact on raptor populations because raptors have longer life spans than passerines and consequently lower reproductive potential. Collision mortalities associated with wind turbines could be expected to have more dramatic negative effects on raptor populations because raptor populations cannot absorb mortalities on an annual basis as easily as passerine populations without declining. Justification for concern relative to the impacts wind farms have on raptor populations is warranted, especially along the LGC, because unlike the other wind farm collision studies reviewed thus far, substantial raptor fatalities have occurred on wind farms. For example, raptor fatalities resulting from collisions with turbines was a serious problem documented at the Altamont Pass Wind Resource Area (APWRA) in California (Erickson et al. 2001). Thelander and Rugge (2000) reported that raptor mortality was 0.15 birds/turbine/year at APWRA and Thelander (2004) later estimated that mortality ranged from 881 to 1,300 birds, which yields an estimated collision rate of 0.16–0.24 birds/turbine/year. Smallwood and Thelander (2005) estimated that between 570 and 835 raptors are killed annually at APWRA, yielding an estimate of 0.1062 birds/turbine/year.

Red-tailed hawks (*Buteo jamaicensis*), burrowing owls (*Athene cunicularia*), American kestrels (*Falco sparverius*), and golden eagles (*Aquila chrysaetos canadensis*) were the most common raptor fatalities documented at APWRA (Orloff and Flannery 1992, Thelander and Rugge 2000, Smallwood and Thelander 2005, Smallwood et al. 2007). Hunt et al. (1998) studied a golden eagle population in the vicinity of the APWRA from 1994 to 1997 and indicated that 23 of 179 golden eagles equipped with radiotransmitters were killed by wind turbine strikes, and Hunt et al. (1998) suggested that collision mortality could have contributed to the golden eagle population decline that occurred at APWRA during the 3-year study. Smallwood et al. (2007) found that >100 burrowing owls were killed annually at APWRA, which was about the same number of individuals nesting in the area. When compared with other large wind farms, it is clear that the APWRA supports higher resident and migratory raptor populations and experiences greater raptor fatality rates caused by collision with wind turbines. R. M. Montes and L. B. Jacques (unpublished report) also found raptor mortality (0.34 birds/turbine/yr) at a wind farm at Tarfia, Spain. In the LGC, such an impact could be magnified.

However, studies conducted at other wind farm developments indicate that raptor populations were not impacted by collisions with turbines. For example, no raptor collisions were documented at wind farms in Colorado (Kerlinger and Curry 1998, Schmidt et al. 2003), Iowa (J. W. Desmates and J. M. Trainer, Iowa State University, unpublished report), Minnesota (Osborn et al. 2000), Oregon (Erickson et al. 2000), Tennessee (C. P. Nicholson, Tennessee Valley Authority, unpublished data), or Vermont, USA (Kerlinger 2002). Furthermore, D. P. Young, W. P. Erickson, R. E. Good, M. D. Strickland, and G. D. Johnson (unpublished report) found only 2 raptor carcasses at a wind farm in Wyoming, USA, and concluded that their estimated collision rate of 0.03 birds/turbine/year was low. Similarly, Erickson et al. (2003) documented 2 raptor fatalities during a 1-year survey period at a wind farm in Washington and calculated a collision estimate of 0.065 birds/turbine/year. Moreover, Janss (1998) reported a collision rate of 0.03 raptors/turbine/year at a wind farm located in coastal hills in Spain. Similarly, Barrios and Rodriguez (2004) estimated that 0.15 griffon vultures (*Gyps fulvus*) and 0.19 common kestrels (*Falco tinniculus*) collided with turbines each year on a wind farm in Spain, and concluded that the impact on populations of each species was not significant. Additionally, Walker et al. (2005) found no evidence of golden eagle (*Aquila chrysaetos chrysaetos*) mortality as a consequence of collision with turbines at a wind farm in Scotland. It appears that raptor collision mortality can be a concern when wind turbines are constructed at inappropriate locations (e.g., migration routes), where large concentrations of raptors occur (e.g., APWRA), or where turbines are constructed in unsuitable locations within a wind farm (R. M. Montes and L. B. Jacques, unpublished report), such as on slopes of hills, draws, or ridges that are frequently used by foraging raptors (Curry and Kerlinger 1998, Barrios and Rodriguez 2004, Hoover and Morrison 2005). Where raptor habitat and behavior are considered, or specific habitat management operations are implemented to attract raptors away from wind farms (Walker et al. 2005), collision rates can evidently be reduced.

Waterbirds, wetlands, and offshore sites.—Research in Europe indicates that wind farms located offshore can also be responsible for high collision mortality for waterbirds. Collision rates within offshore wind farms are often higher than for those on terrestrial sites (Everaert and Steinen 2006; J. Pettersson, Swedish Energy Agency, unpublished report). Everaert and Steinen (2006) estimated collision rates of 19.1 birds/turbine/year, and 6.7 birds/turbine/year for terns (*Sterna* spp.), using a wind farm constructed on coastal wetlands in Belgium. J. Pettersson (unpublished report) evaluated the impact of an offshore wind farm on eiders (*Somateria* spp.) in Sweden and reported a collision rate of 11.0–14.0 birds/turbine/year. However, Guillemette and Larsen (1998) reported that an offshore wind farm in Denmark had little impact on scoter (*Melanitta* spp.) populations, and Larsen and Madsen (2000) found that pink-footed geese (*Anser brachyrhycus*) were minimally impacted by another wind farm located in coastal wetland–agricultural habitat in Denmark. Offshore wind farms have been found to divert migration routes of sea ducks from those traditionally followed, but the impacts on the populations are unclear (J. Pettersson, unpublished report). It also appears that sea ducks are able to detect the presence of wind turbines at night and during periods of poor visibility. Impacts on waterbirds over and above the presence of the turbines at offshore sites, such as the increased boat traffic to and from wind farms, has been poorly addressed.

A number of predevelopment studies in Europe suggest that wind farm development could displace migrating and breeding waterfowl and shorebirds due to disturbance associated with wind farm construction and postconstruction maintenance (Christensen et al. 2003, Kaiser et al. 2006), disruption of daily movements (Drewitt and Langston 2006), or disruption of migration activity (Drewitt and Langston 2006). At least some postconstruction studies provide evidence that support the suggestion that wind farms could create barriers to migration or alter flight paths between foraging and roosting habitats, and the additional energy expenditures required to avoid wind turbines could have cumulative negative impacts on birds (R. H. W. Langston and J. D. Pullan, Royal Society for Protection of Birds/BirdLife, unpublished report). For example, Desholm and Kahlert (2005) reported that the percentage of migrating waterfowl entering a wind farm decreased after construction. Guillemette and Larsen (1998) found that 80% fewer eiders used areas within 100 m of wind turbines compared to areas that were 300–500 m distant. Everaert (2003) also found that foraging water birds were less abundant within 15–300 m of wind turbines compared to areas beyond 300 m. Drewitt and Langston (2006) believed that the presence of offshore wind farms could discourage bird use of areas up to 800 m from a site, though they acknowledged that 600 m was generally a more widely accepted distance. However, there is evidence that at least some species will avoid wind farms at even greater distance, as I. K. Petersen, I. Clausager, and T. K. Christensen (National Environmental Research Institute-Denmark, unpublished report) indicated that a number of waterbird species displayed increased avoidance of a wind farm 2–4 km from the turbines.

Galliforms.—Although actual collisions between galliforms and turbine blades is highly unlikely, Robel (2002) and Bidwell et al. (2002*a*, *b*) believed that locating turbines on prairie landscapes used by greater prairie-chickens (*Tympanuchus cupido*) and lesser prairie-chickens (*T. pallidicinctus*) would render the developed area unsuitable for prairie-chickens because of their intolerance for human disturbance. In these cases, the infrastructure needed to support the turbines would likely have an indirect impact on prairie-chickens and perhaps other species of gallinaceous birds that inhabit the developed site.

Habitat Loss

European conservationists generally consider the habitat loss associated with wind farm developments to be a greater threat to bird populations than are collision fatalities. There is evidence that constructing wind farms renders habitat unsuitable for birds. For example, Leddy et al. (1999) found that grassland bird densities were higher on grasslands without wind turbines and on areas that were $\geq$80 m from wind turbines. They believed that the turbines themselves or something associated with the turbines were disturbing and thus displacing birds. Similarly, results from the Buffalo Ridge Resource Area in Minnesota indicated that fewer birds and fewer species used areas in the vicinity of turbines than in control areas that lacked turbines (Osborn et al. 2000). G. P. Johnson, W. P. Erickson, M. D. Strickland, M. F. Shepard, and D. A. Shepard (Western Ecosystems Technology, unpublished report) also reported from the Buffalo Ridge site that densities of 7 of 22 grassland bird species were lower in the vicinity of wind turbines but added that impacts are unlikely to effect local or regional populations. W. P. Erickson, J. Jeffery, K. Kronner, and K. Bay (Western Ecosystems Technology, unpublished report) also reported a small-scale impact of the Stateline Wind Farm in Oregon on grassland birds and indicated that the most significant portion of the impact was due to habitat loss associated with construction. R. W. Howe, W. Evans, and A. T. Wolf (unpublished report) reported that the number of bird species at a Wisconsin wind farm site was lower than at a comparable reference site.

BATS

The impact of wind farm development on bat populations has not received as much attention as it has for bird populations, and most of the research is relatively recent and was initiated because numerous bat carcasses were being discovered in wind farms during bird collision surveys. The results of the studies that have been completed indicate that the impacts of wind farm development on bat populations may be more severe than it is for birds. One of the highest fatality rates was reported by J. Kerns and P. Kerlinger (unpublished report) who estimated a collision rate of 47.53 bats/turbine between April and November on a site consisting of 44 turbines constructed in West Virginia, USA, woodland. C. P. Nicholson (unpublished data) also found a substantial number of bat fatalities on a Tennessee wind farm site where he estimated a collision rate of 28.5 bats/turbine/year. However, other studies have provided much lower fatality estimates. For example, Johnson et al. (2003) estimated that bat mortality between 1996 and 1999 ranged from 0.07 bats/turbine/year to 2.04 bats/turbine/year at a wind farm in Minnesota. Bat mortality at the same wind farm between 2001 and 2002 was estimated to range from 1.30 bats/turbine/year to 3.02 bats/turbine/year (Johnson 2004). Erickson et al. (2003) estimated that mortality at wind farm in Washington was 3.21 bats/turbine/year and during a 2-year survey at a wind farm in Oregon, W. P. Erickson, B. Gritiski, and K. Kronner (Western Ecosystems Technology, unpublished report) estimated that collision mortality averaged 1.12 bats/turbine/year. Johnson (2004) indicated that an average of 3.4 bats/turbine/year collided with turbines in the United States, though the range of collisions varied from 1.2 in the Pacific Northwest to 46.3 in the eastern United States. Recently, Kunz et al. (2007) reviewed the impacts on bats in wind energy developments and offered recommendations for sampling methods and additional research, including the use of advanced acoustic and radar techniques.

Based on studies completed thus far, it appears that collision mortality is most significant for tree-dwelling migratory species. In their review of research results, Erickson et al. (2002) also found that 90% of bat collision fatalities occurred between July and September, and migratory tree bats represented most of the fatalities. They also indicated that out of the 39 species of bats that occur in the United States, collision fatalities have been recorded for only 6 species. Hoary bats (*Lasiurus cinereus*) composed 61.7% of the carcasses identified at wind farms, followed by eastern red bats (*L. borealis*) and silver-haired bats (*Lasionycteris noctivagus*), which composed 17.2% and 7.1% of the carcasses located, respectively. The remaining carcasses identified consisted of small numbers of big brown bats (*Eptesicus fuscus*), little brown bats (*Myotis lucifugus*), and eastern pipestrelles (*Pipistrellus subflavus*). In addition to carcass survey results, Erickson et al. (2002) suggested that the random distribution of carcasses within wind farms further indicates that migratory species are more vulnerable to turbine collisions than are resident bat species because if resident bat species were colliding with turbines, carcass distribution would demonstrate defined flight patterns between roosting and foraging areas, and these patterns were not apparent. Furthermore, Johnson (2004) believed that resident bat populations that use wind farms are less vulnerable to collisions than migratory species because few bat fatalities have included resident bat populations within wind farms in Colorado, Minnesota, Wisconsin, and Wyoming.

Although the high bat collision rates that have been documented in the eastern United States justify concern about the impacts of wind farms on bat populations, G. D. Johnson, M. K. Perlik, W. P. Erickson, M. D. Strickland, D. A. Shepard, and P. Sutherland, Jr. (Western Ecosystems Technology, unpublished report) and Erickson et al. (2002) believe that the number of bat fatalities that occur at wind farms may not be sufficient to cause population declines. Like raptors, bats typically have low reproductive rates and therefore slow population growth rates, so according to Erickson (2004), high mortality rates would be expected to result in population declines. They suggest that mortality rates would begin to decrease over time as populations decline, but this was not evident during 4 years of monitoring at the Buffalo Ridge wind farm in Minnesota (Johnson et al. 2003) where migratory bat numbers may be substantial. However, in the absence of long-term research conducted at a number of wind power facilities, it would be premature and irresponsible to conclude that collision mortality at wind farms is not significant enough to cause migratory bat population declines, especially relative to bats that migrate through the LGC to Mexico and to Central and South America.

OTHER WILDLIFE

Habitat Alteration

In addition to migratory bird and bat populations, wind farm development could have negative impacts on other bird, mammal, and herpetofauna populations inhabiting wind farm development sites because these developments will alter wildlife habitat in some fashion. However, such impacts are likely less threatening than those from other methods of energy extraction, such as oil and gas exploration and production, or surface mineral mining. Impacts that would occur from wind power development would be associated with the footprint (the acreage or area impacted by construction of the wind farm) resulting from construction of turbines as well as infrastructure development, such as the construction of buildings, roads, and electrical transmission lines. Habitat disturbance associated with footprints will be a function of the size and numbers of turbines that are constructed on the development site. Typically, wind turbine footprints range from 0.08 ha (0.2 acres) to 0.20 ha (0.5 acres) and compose 2–5% of wind farm site (Fox et al. 2006). Thus, habitat disturbance from the footprint alone may not be substantial. However, turbine pads in APWRA may have created collision problems for raptors by creating habitat for small mammals, which resulted in increases in prey populations (Curry and Kerlinger 1998, Thelander 2004). Additionally, large wind power developments like the APWRA in California that consist of several thousand turbines can result in habitat disturbance from areas modified for turbine pads alone if sensitive plant communities or habitats critical to the life cycle of specific wildlife species are impacted.

Infrastructure development associated with large wind farms like APWRA could create threats to wildlife due to the construction of additional electrical transmission lines linked to existing lines as well as construction of road systems that service turbines and relay stations. R. H. W. Langston and J. D. Pullan (unpublished report) recognized that the electrical transmission lines erected in wind farms represent a significant collision and electrocution risk to birds, in addition to the collision risk posed by turbines. Erickson et al. (2001) very conservatively estimated that $\geq$174 million bird fatalities result from power line collisions in the United States every year. They indicated that ducks, geese, swans, and cranes appear to be most vulnerable to collision when power lines are located close to wetlands, whereas raptors and passerines are more vulnerable in upland habitats. Huppop (2004) also reported that rails, waders, pigeons, storks, owls, and bustards suffered high power line collision and electrocution fatality rates in Europe. Haas et al. (2005) found that power line collisions and electrocutions in Europe are major sources of mortality for pelicans, storks, upland game birds, rails, bustards, cranes, shorebirds, and owls and, in some instances, are responsible for major regional population declines. Rubolini et al. (2005) indicated that raptors, herons, and storks are particularly vulnerable to power lines in Italy, whereas passerine populations were not impacted. Ferrer et al. (1998) estimated that about 1,200 raptors/year died along 300 km of power lines in Donana National Park in Spain. They also reported that electrocution was responsible for the deaths of $\geq$50% of the banded raptors they recovered and is the primary cause of death for the endangered Spanish imperial eagle (*Aquila adalberti*). Janss and Ferrer (1998) also indicated that great bustards (*Otis tarda*) and little bustards (*O. tetrax*) suffered the highest power line collision mortality rates on their study area in Spain. Fabrizio et al. (2004) found that population density of eagle owls (*Bubo bubo*) in the Italian Alps was negatively related to electrocution from power lines.

Road networks are constructed in wind farms to service turbines and, of course, the extent of road networks depends on the size of the wind farm. Therefore, in addition to collisions with turbines and collision or electrocution associated with power lines, road networks will also likely impact wildlife populations inhabiting wind farms. Facilities consisting of several hundred or more turbines will have extensive road networks, which may negatively impact biodiversity on the wind farm site. Trombulak and Frissell (2000) reviewed the literature relevant to road effects on terrestrial and aquatic communities. Based on this literature, they concluded that the presence of roads is associated with negative effects on biotic integrity and could result in loss of biodiversity at local and regional scales. Road systems often result in habitat fragmentation (Saunders et al. 2002), thereby reducing both habitat quality and quantity, which is considered the primary threat to biodiversity on a global basis (Geneletti 2003).

Road construction and the presence of roads often reduce biodiversity by facilitating the introduction and range expansion of exotic plants. For example, Rentch et al. (2005) found that roadsides provided optimal growing sites for exotic plants that ultimately suppress native species. Furthermore, Hill et al. (2005) reported that exotic plant species richness and cover was higher in the vicinity of sealed roads, and Gelbard and Belnap (2003) found evidence that roads represented conduits for exotic plant invasions in a semiarid landscape.

In addition to facilitating exotic species introductions, roads further reduce native biodiversity by serving as barriers to dispersal for some animals, by disrupting behavior, or by increasing mortality via vehicle collisions. Increased traffic activity or noise levels associated with traffic can reduce bird densities (Reijnen et al. 1995, 1997; Brotons and Herrando 2001; St. Clair 2003; Bautista et al. 2004), as well as species diversity (Green and Baker 2002) and movement (Laurance et al. 2004) in habitat adjacent to roads. The presence of roads has also been found to affect the behavior of snakes (Shine et al. 2004). Roads can serve as barriers to the movements of small mammals (Burnett 1992, Conrey and Mills 2001) as well as those of large ungulates and carnivores (Alexander et al. 2005, Epps et al. 2005). The reduction of animal movement associated with roads also serves to genetically isolate populations. Gerlach and Musolf (2000) indicated that highways had an important effect on gene flow and genetic structuring of bank voles (*Clethrionomys glareolus*) in Germany. Moreover, Epps et al. (2005) reported that highways contributed to the rapid decline of 27 populations of desert bighorn sheep (*Ovis canadensis*) because gene flow was eliminated between populations, resulting in a rapid reduction in the genetic diversity of desert bighorn sheep populations. Lode (2000) concluded that road traffic effectively isolated the vertebrate populations he studied by influencing species demography and population exchanges. Furthermore, Forman (1998) believed that the barrier effect that subdivides populations, thereby imposing genetic consequences on these populations, is one of the most important effects roads impose on ecological communities.

Although a road system could enhance movements of certain wildlife species, such as some predators (May and Norton 1996), as well as bobwhite quail (*Colinus virginianus*; Kuvlesky 1990) and wild turkeys (*Melagris gallopavo*; W. P. Kuvlesky, Caesar Kleberg Wildlife Research Institute, unpublished data), wildlife fatalities would also increase as a result of collision with vehicles that transport wind farm personnel throughout the facility. Research in south Texas indicated that vehicle collisions are one of the primary sources of mortality for endangered ocelots (*Leopardus paradalis*; Haines et al. 2005, 2006) and that collisions with vehicles can cause mortality for bobcats (*Lynx rufus*; Cain et al. 2003). Recent declines in turtle populations in the southeastern United States have also been attributed to collision mortality from vehicles (Gibbs and Shiver 2002, Aresco 2005, Gibbs and Steen 2005), and vehicle collisions are such a significant source of mortality for desert tortoises (*Gopherus agassizii*) that populations can be reduced up to almost 1 km from roads (Boarman et al. 1997). Collisions with vehicles can also be a source of mortality for populations of snakes (Enge and Wood 2002, Andrews and Gibbons 2005), lizards (Koenig et al. 2002), small mammals (Lode 2000, Taylor and Goldingay 2003), and birds (Clevenger et al. 2003, Erritzoe et al. 2003, Erickson et al. 2005), but particularly for raptors (Newton et al. 1997, Fajardo 2001, Martinez et al. 2006) and endangered birds (Mumme et al. 2000).

WIND FARMS AND THE LGC OF TEXAS

The LGC region of Texas represents a vast area of Class 4 wind sites (5.8 m/sec at 10-m ht [23 miles/hr at 33 feet]) that contains numerous communities and their accompanying electrical transmission lines (Morrison 2006). Consequently, because Class 6 wind sites are becoming increasingly limited, newer turbine models can make more efficient use of Class 4 winds and electrical transmission lines are located close to Class 4 sites, numerous energy companies have become interested in developing wind farms in the LGC of Texas. Indeed, one company recently obtained a long-term lease on a large private ranch bordering the Laguna Madre and is currently constructing a 77,295-ha (191,000-acre) wind farm consisting of 267 turbines capable of producing 400 MW. Wind farm development on the LGC is a controversial issue because, although wind power is recognized as an alternative clean source of power and a potential source of revenue for small communities, concern exists that wind turbines may negatively impact resident and migratory bird communities that use the LGC.

The vegetation communities that compose the LGC are diverse, consisting of Gulf barrier islands, fresh- and saltwater wetlands, coastal prairie, deciduous woodlands, and mixed-brush communities (Fulbright and Bryant 2002). This vegetation community diversity is one of the reasons the south Texas region, which includes the LGC, supports 200 resident breeding bird species and an additional 200 migratory species that either winter in the region or are transients that temporarily use the diverse habitats on their way to wintering grounds in Mexico and in Central and South America (Kuvlesky et al. 2007). The extensive coastline and diverse habitats that are associated with the LGC likely contribute to the reason 3 migratory bird flyways converge north of Corpus Christi, Texas. This flyway convergence effectively funnels tens of millions of migratory birds along the LGC each year (Kuvlesky et al. 2007).

Annual Neotropical trans-Gulf bird migration is a dynamic event that varies in scope and extent each year (Barrow et al. 2005) and is profoundly influenced by weather. Russell (2005) observed migratory bird behavior on oil platforms in the Gulf of Mexico using radar and direct observations and estimated that trans-Gulf migration consisted of 316 million birds and 147 million birds during the springs of 1998 and 1999, respectively. Additionally, Russell (2005) discovered that synoptic-scale weather patterns have a significant impact on migration flight direction and landfall. His results partially supported the prevailing theory that spring trans-Gulf migration involves roughly straight-line, shortest-distance flights from the Yucatan Peninsula to the Upper Gulf Coast in the United States. However, he found that migratory flights were generally all-or-nothing events: large migratory flights occurred when winds were favorable or rarely occurred when winds were unfavorable. On days when Eastern Continental High synoptic weather patterns were prevalent over the Gulf of Mexico, large flights of migrants leaving the Yucatan Peninsula or the northern coast of the Isthmus of Tehuantepec utilized tailwinds that veered clockwise around the western Gulf, resulting in increased bird abundance on platforms in the western Gulf and landfall along the Texas coast. In contrast, bird abundance increased on platforms in the eastern Gulf and more birds made landfall along the northern Gulf Coast during days when Bermuda High synoptic weather patterns were prevalent because winds had a stronger eastern component over the northern Gulf of Mexico. Russell (2005) also found that fall migratory flights have a strong westerly component consisting of a preponderance of juvenile migrants, which he believed represented a risk-aversion strategy that minimized over-water flight because the migration routes were more circuitous. Furthermore, he suspected that many of the adults moving over the western Gulf were in poor condition when they reached the northeastern Gulf Coast and therefore stopped in select habitats along the western Gulf Coast to replenish fat stores as they proceeded south to wintering habitat. Russell's (2005) research clearly indicates that weather patterns have an impact on trans-Gulf migrant behavior and that the western Gulf coast of Texas is frequently used by millions of migratory birds.

In addition to birds, wind farms located in LGC could negatively impact both resident and migratory bat populations and, based on the results of studies we cite in this paper, wind farms could result in significant bat fatalities. Migratory bats, such as the Mexican free-tailed bat (*Tadarida brasiliensis*), and resident species, such as the southern yellow bat (*Euderma maculatum*), are present in the LGC and populations of both species are declining. Indeed the southern yellow bat is classified as a threatened species by the State of Texas. Habitat destruction, pesticide exposure, and persecution by humans represent reasons for the decline of these 2 species. Additive mortality from wind turbine collisions could therefore represent a potentially serious threat to existing populations of these 2 species.

Wind farms located in the LGC could also pose a risk to a number of federally threatened and endangered bird species because northern Aplamado falcons (*Falco femoralis*), eastern brown pelicans (*Pelecanus occidentalis*), whooping cranes (*Grus americana*), interior least tern (*Sterna antillarum athalassos*), and piping plovers (*Charadrius melodus*) either winter in the LGC or migrate through the area (Morrison 2006). Additionally, several threatened or endangered mammals also occur in LGC, including ocelot, jaguarundi (*Herpailurus yaguarundi*), Coues' rice rat (*Oryzomys couesi*), and 5 species of sea turtles (*Caretta* spp., *Chelonia* spp., *Dermochelys* spp., *Eretmochelys* spp., and *Lepidochelys* spp.) Moreover, $>$1 million raptors representing $\geq$25 species are residents, or winter, or migrate, along the lower Texas coast, and because raptors may be particularly vulnerable to collision with wind turbines, the impact of wind power developments on raptor populations is a major concern. Therefore, although no one knows how wind farms constructed on the LGC will impact wildlife populations, it is possible that the installations could have an impact particularly on some bird populations because collision mortality appears to be problematic when wind farms are located along migratory routes or where birds are otherwise abundant.

Cropland Siting Opportunities

Placing wind turbines on cropland is an overlooked aspect of the current issues related to wind farms and wildlife in the LGC of Texas. To date, all proposed locations of wind farms in the LGC have been focused on siting turbines on rangelands that are dominated by mostly native vegetation. Alternatively, we propose several arguments to locate wind farms on cropland. First, there are tens of millions of hectares of cropland in the LGC that are dryland farmed for cotton, grain sorghum, and sometimes corn. Farming these areas without irrigation is risky business that is largely sustained by crop insurance during drought years. Second, much of this cropland is well within the window of prevailing winds that can drive turbines. Wind-generated electricity represents a potentially significant drought-proof form of income for these landowners. Third, virtually all of the native vegetation has been removed from these areas, thus making them less than attractive as fallout sites for migrating birds or as any kind of habitat for galliforms. Fourth, cropland in the LGC of Texas contains an existing series of access roads and is crossed by various existing transmission grids. Fifth, these areas of cropland are dotted with various petroleum developments in the form of wells, collection and transfer stations, etc. Thus, landowners have experience and tradition in working with energy-related businesses, and this experience should easily translate to using wind-generated electrical power as a form of supplemental income.

RESEARCH NEEDS

Because the LGC represents a critical region to migratory birds and because it seems clear that wind farm developments are going to be constructed in the region, it is essential that properly designed impact research be implemented prior to construction. Despite the results of dozens of impact research projects conducted in the United States and Europe that indicate that wind farms do not represent a serious risk to most bird populations, potential risks remain enormous on the LGC so there is ample justification for concern. Because of the importance of LGC to migratory birds, an opportunity exists to determine using rigorous science how wind farm developments impact bird populations, and if research is designed properly, it will be possible to quantify and clarify impacts on resident wildlife populations, which is something that has been largely ignored by other researchers. However, in order to accomplish these objectives, rigorous experimental designs that consist of appropriate sampling protocols and data collection methodology based on sound science must be implemented.

One of the most important problems with past research efforts is that the results of most of the previously conducted studies cannot be compared because experimental designs were often unique to each study and data collection methodology varied between studies (Anderson et al. 1999, Morrison 2002, Smallwood 2007). Perhaps most importantly, however, the majority of these previous studies were not true impact studies because they focused on either pre- or postconstruction phases of development rather than developing experimental designs that incorporated pre- and postconstruction phases of data collection as well as control sites. The before-after-control-impact (BACI) experimental design therefore represents a true impact study. Our review of the literature indicated that 4 BACI studies have been completed to date (DeLucas et al. 2005, Walker et al. 2005; G. D. Johnson and W. P. Erickson, Western Ecosystems Technology, unpublished report; R. W. Howe and W. Evans, unpublished report). Pre- and postconstruction studies can provide useful information; however, results do not necessarily reflect the true impact of development on bird and bat populations, and few have demonstrated what impacts may occur for other wildlife populations that inhabit wind farm development sites.

Anderson et al. (1999) and Kunz et al. (2007) recognized these problems and highlighted recommendations from the National Wind Coordinating Committee Wildlife Work Group to correct them. They emphasized that sampling protocols and methodology employed to quantify bird and bat mortalities must be rigorous and scientifically valid. The guidelines presented in these 2 publications were developed to encourage efficient, cost-effective experimental designs that will result in comparable data and perhaps reduce the necessity of conducting future studies.

Anderson et al. (1999) identified 3 levels of surveys that should be conducted to evaluate the potential impacts of wind farms on wildlife populations that use development sites. The initial survey that should be conducted is a nonrigorous reconnaissance survey that involves a review of published literature and unpublished reports and other material relevant to the proposed site in order to determine if constructing a wind farm on the proposed site will result in impact problems. Reconnaissance surveys are useful for eliminating sites that have been determined to be unsuitable for development from further consideration. If a reconnaissance survey indicates that development can proceed, then level 1 surveys should be implemented. Level 1 surveys are scientifically rigorous and involve intensive onsite natural resource surveys that should be conducted for $\geq$1 year before a decision is made to proceed with development. During the level 1 survey period, sampling protocols quantify the presence and abundance of members of the flora and fauna communities, particularly with regard to endangered, threatened, or sensitive species. In addition, the daily and seasonal movements of wildlife as well as their use of specific habitats for foraging, breeding, and nesting are quantified, and other parameters representing population dynamics are assessed. Risk assessments are then developed for potential bird, bat, and other wildlife fatality levels that would be associated with the wind farm. If endangered, threatened, or sensitive species are discovered during level 1 surveys, it may be necessary to conduct more intensive studies prior to site development. Data from the first year of level 1 surveys can represent preconstruction or baseline data that can be compared to data collected after construction has been completed to quantify the impacts of the wind farm development on wildlife populations inhabiting the site. Obviously, data collection during the postconstruction phase would be collected using the same design protocols and sampling methodology used during the preconstruction phase. Wildlife scientists planning wind farm–wildlife impacts studies should, at the very least, consider employing BACI experimental designs because conducting only a pre- or a postconstruction study will not yield results that accurately reflect the impact that wind farms have on wildlife populations.

The third survey level that succeeds the level 1 survey are level 2 surveys, which involve more advanced experimental designs. Often, level 2 surveys will include manipulative experiments or the development of theoretical population models. Manipulative experiments could be conducted that compare fatality rates and avoidance behavior between clusters of turbines versus long strings of turbines. Similarly, other manipulative experiments should compare fatality and avoidance of various turbine designs. For example, do the more modern turbine designs that are taller and that have longer blades with slower tip speeds result in fewer collision mortalities than the older turbine designs that are shorter turbines with shorter blades and faster tip speeds? Other research questions that need to be addressed include evaluating different lighting arrangements on turbine or pattern design on blades as a deterrent to birds. Furthermore, research needs to focus on the cumulative impacts of wind farms on bird and bat populations (Exo et al. 2003, Erickson et al. 2005). This will require long-term studies as well as large-scale projects that encompass wind farms over flyways. Models should also be developed to estimate the impacts of wind farms on bird and bat populations (Morrison and Pollock 1997, West and Caldow 2006). The results of long-term research projects and manipulative experiments would prove very useful in the development of these models. Research should also address how wind farm infrastructure impacts the flora and fauna of wind farm developments, in addition to birds and bats, because few of these studies have ever been conducted.

It should be noted that at the National Wind Coordinating Collaborative Wildlife Research Meeting VI in San Antonio, Texas, species displacement by wind turbines was identified as a high research priority that has yet to be addressed (Arnold 2006). The 3 levels of impact assessment, as noted above, will be the key to addressing aspects of species displacement by turbines.

In addition to implementing phased experimental designs recommended by Anderson et al. (1999), scientists need to ensure that they are collecting data that accurately reflects bird, bat, and other wildlife utilization of development sites. For example, point counts or line transect methodology alone may provide an incomplete picture of bird utilization of wind farm sites. Research using weather radar (Gauthreaux and Belser 2003, Gauthreaux et al. 2003) and more recent studies employing portable marine radar units (Mabee et al. 2006) demonstrate that these technologies can provide valuable information about the location, height, direction, and timing of migratory bird and bat flights relative to wind farm development sites. Thermal animal detection systems have also proven useful in quantifying bird and bat behavior, flock size, and flight altitudes in response to wind turbines, and Desholm (2003) believed that employing this technology represents perhaps the best way to obtain these data at night. Employing acoustical arrays should also be considered because they may facilitate species identification of migrant flights as well as monitor collision events (Desholm et al. 2003). It may be possible to employ acoustical arrays with marine radar units or thermal animal detection systems to identify nocturnal migrant species that collide with turbines and the specific flights of these species as they pass over or through a wind farm. Kunz et al. (2007) present a review of potential sampling methods for nocturnal birds and bats.

Experimental designs should also include sampling protocols to accurately estimate scavenging rates as well as to quantify searcher efficiency (Morrison and Sinclair 1998, Morrison 2002, Erickson et al. 2005, Smallwood 2007). In addition to accounting for scavenging and searcher efficiency, the proportion of carcasses that decompose before they can be located and documented should be incorporated into experimental designs. The number of carcasses lost to scavenging and decomposition will vary according to the diversity and abundance of scavengers and the climatic conditions specific to the wind farm site. For example, one could expect high scavenging and decomposition losses in the LGC because of the diversity and abundance of potential scavengers and the hot and humid conditions that characterize the region for $\geq$8–10 months during the year.

MANAGEMENT IMPLICATIONS

There are several issues that should be considered in any type of policy development. One consideration would be to develop guidelines to assist wind developers in how best to site their projects. These guidelines should include some standard pre- and postconstruction survey methodology to allow compilation of the data collected over time. The second consideration would be a place to house the compiled data from all wind developments in each state, to have a better idea of what is going on at a state level. This would be useful in looking at wind development from a local and a multistate level. Because many wind developers consider the raw data confidential, steps should be taken to have the data analyzed by a mutually acceptable and credible third party, which could present the data at a county or ecological level, rather than at a site-by-site level. Third-party involvement would be a step toward reducing confidentiality concerns, if they exist. It could also be useful in looking at trends across the United States. The third consideration would be mechanisms in the guidelines that are incentives for the developers to avoid high-risk areas within each state and, if these high-risk areas cannot be avoided, ways to offset or mitigate the impacts of developing in high-risk areas. Part of the mitigation could include a per-megawatt payment that would go into a development fund to assist each state in conservation of high-risk areas or in additional research needs.

Hopefully, development of the guidelines would be a collaborative effort between the state and federal resource agencies, nongovernmental organizations, birding groups, and citizen groups. Consideration should also be given to developing a method to encourage wind developers to come to the state and federal agencies early in the project planning process to determine what environmental issues they will encounter in the areas in which they wish to develop. This could be a formalized review process or the information could be provided via a Web page so that developers could look at the environmental concerns and avoid confidentiality issues.

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