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Research Article

Impacts of Wind Turbines on Redheads in the Laguna Madre

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ABSTRACT Freshwater ponds adjacent to the Laguna Madre along the lower Texas coast provide an important and heavily used source of fresh water for the redhead (*Aythya americana*) throughout winter. A 267-turbine wind farm was constructed within the core wintering area of the redhead on a private ranch along the western coast of the Laguna Madre, in 2010. Our objective was to investigate the effects of this wind farm on the habitat and potential displacement of redheads and their use of coastal ponds along the lower Texas coast. We conducted weekly aerial surveys to monitor coastal pond use by wintering redheads from mid-October through mid-March during pre-construction (2000–2003) and post-construction (2012–2014) of the wind farm. Pond availability and Palmer Drought Severity Index (PDSI) within the wind farm were significantly correlated during pre-construction ($n = 16$, $R^2 = 0.53$, $P = 0.035$) and post-construction ($n = 11$, $R^2 = 0.64$, $P = 0.003$). However, the number of ponds available at each PDSI level within the wind farm decreased during post-construction (paired $t = 3.2$, $n = 5$, $P = 0.033$). The average number of redheads detected per survey on coastal ponds within the wind farm decreased by 77% from pre-construction to post-construction. Redhead abundance on ponds across the entire Laguna Madre increased by an average of 3.26 times between pre-construction and post-construction, partly due to increases in the continental redhead population. It appears that the wind farm has altered the use of coastal ponds by redheads during winter. Future wind farm placement along the lower Texas coast should consider coastal pond distribution and the dynamics of redhead use between coastal ponds and foraging areas in the Laguna Madre.

KEY WORDS coastal freshwater pond, disturbance displacement, habitat degradation, redhead, wind energy.

The lower Texas coast is the most important wintering area for the redhead (*Aythya americana*), where up to 80% of the continent's population winters (Weller 1964, Michot 2000, Woodin and Michot 2002). During winter, redheads feed primarily on shoalgrass (*Halodule wrightii*) rhizomes in the Laguna Madre, a large (~1,500 km^2), hypersaline lagoon (Cornelius 1977, Michot et al. 2008, Tunnel 2002). Because redheads ingest high concentrations of salts when foraging, they make daily flights to coastal freshwater ponds adjacent to the Laguna Madre to maintain their osmotic equilibrium (Mitchell et al. 1992, Michot et al. 2006, 2008). Thus, movements of redheads between foraging areas in the Laguna Madre and adjacent freshwater ponds are common throughout winter.

A concern among natural resource managers along the lower Texas coast has been the rapidly growing development of wind energy and its effects on wildlife such as redheads. Although there has been much political support for the development of wind energy in North America, little is known about the effects of wind energy on wildlife and their habitats. There are 3 primary ways wind farms potentially affect wildlife. The most direct effect is mortality from collisions with wind turbines and the large infrastructure of power lines (Fielding et al. 2006), with most ongoing research investigating bird and bat collisions with turbine blades (Kuvlesky et al. 2007). The estimated number of bird collisions with wind turbines varies by study and location (Smallwood 2007), and collisions have a higher probability of occurring during weather conditions that impair visibility, such as rain and fog (Osborn et al. 1998, Barrios and Rodriguez 2004, Drewitt and Langston 2006, Sovacool 2009). Research in Europe has reported that long-lived species of waterfowl (e.g., geese, swans, eiders) avoid wind turbines (Desholm and Kahlert 2005, Larsen and Guillemette 2007, Fijn et al. 2012), particularly those offshore. Less is known about the collision risk of shorter-lived species of waterfowl and in relation to wind farms located around discrete habitats on the mainland.

A second effect is through loss and degradation of habitats typically associated with the large infrastructure of roads, transmission lines, and turbines (Fielding et al. 2006, Kuvlesky et al. 2007). The terrestrial footprint of wind farms is considerable (McDonald et al. 2009). Further, the massive foundations that support a turbine, and the extensive road

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systems that allow access to each turbine often have negative effects on the local hydrology, thereby degrading wetlands in some areas and increasing erosion in others (Drewitt and Langston 2006). Additional infrastructure includes the system of transmission lines that connects wind farms to the electrical grid. Wind farms are often located in remote areas and transmission lines often run for significant distances to connect them to urban areas. Finally, wildlife can be affected by disturbance displacement in response to turbines and other infrastructure (Fielding et al. 2006). Disturbance displacement is described as wildlife avoiding previously suitable areas because of the presence of man-made structures such as wind farms (Drewitt and Langston 2006, Masden et al. 2009).

In 2010, a 267-turbine wind farm was constructed south of Baffin Bay along the lower Texas coast. This wind farm surrounds about 10% of the available coastal ponds used by redheads and has caused concern among biologists as to its potential effects on redheads, particularly because the majority of the continent's redheads winter in the region. The American Bird Conservancy (ABC) recently named this site as one of the "10 Worst-Sited Wind Energy Projects for Birds" because of its location within a "critical migratory pathway" (ABC 2016, Contreras et al. 2017). Thus, our objective was to investigate the effects of wind farms on the habitat and potential displacement of redheads and their use of coastal ponds along the lower Texas coast. We predicted that redheads would show displacement behavior from the area of the wind farm.

STUDY AREA

The lower Texas coast is one of the longest undeveloped coastlines in the United States and contains the longest undeveloped barrier island in the world, Padre Island (Fulbright and Bryant 2002). The Laguna Madre lies along the lower Texas coast and is bordered on the east by Padre Island and to the west by the mainland (Fig. 1). It is a large, shallow lagoon, covering nearly 1,500 km^2, is about 185 km in length, and averages <1 m in depth (Brown et al. 1977, Tunnel 2002). Dominant land uses in this region include cattle ranching and row crop agriculture, primarily cotton, and sorghum (Franki et al. 1965, Tunnel 2002). Common habitats of the mainland and barrier island consist of coastal prairies, fresh and saltwater wetlands, mixed-brush communities, and mesquite (*Prosopis* spp.) and live oak (*Quercus* spp.) woodlands (Fulbright and Bryant 2002). There are coastal ponds dispersed along the mainland and Padre Island, which provide critical fresh water for wintering redheads and other waterbirds (Mitchell et al. 1992, Adair et al. 1996).

The climate along the lower Texas coast is semi-arid to sub-tropical with hot, humid summers and mild winters (Franki et al. 1965, Williams et al. 1977). Average precipitation is 66 cm/year, but annual variability is high because of El Nino and La Nina effects and stochastic events, such as tropical storms and hurricanes (Franki et al. 1965, Williams et al. 1977, Kim and Montagna 2012).

Construction of a 267-turbine wind farm started in October 2008 and was completed in April 2010 on private property along the western coast of the Laguna Madre, south of Baffin Bay. The full rotor height of each wind turbine is 126 m, and the width of the rotor blades is 92 m. The wind turbines are arranged in lines from southwest to northeast to capture consistent winds coming off the Gulf of Mexico. Average distance between wetlands used by redheads and wind turbines was 484 ± 39 (SE) m and ranged from 190–1,330 m within the wind farm boundary.

METHODS

We conducted weekly aerial surveys in a 172 Cessna (Cessna, Wichita, KS, USA) to monitor coastal pond use by wintering redheads from early November through early March during 2000–2003 (prior to construction of wind farm) and 2012–2014 (post-construction of wind farm). The pilot-observer was the same during all surveys; however, the second observer changed between pre-construction and post-construction surveys but remained the same within each survey period. During all surveys, we systematically searched the coastal areas adjacent to the Laguna Madre and within 10 km of the coastline, working from the north down Padre Island and from the south up the mainland side. We reversed the route on alternative surveys to account for early versus late visits to coastal ponds. The 10-km distance is based on findings that redheads travel ≤10 km between foraging areas in the Laguna Madre and freshwater ponds (Adair et al. 1996, Ballard et al. 2010). We conducted surveys in early to mid-morning to coincide with the time when redheads actively seek out freshwater ponds (Mitchell et al. 1992). All procedures were approved by Texas A&M University-Kingsville's Animal Care and Use Committee (approval #2012-09-01).

We delineated the area of the wind farm by a line connecting the outside wind turbines in ArcGIS (Esri, Redlands, CA, USA). We identified surface water on the landscape with a surface water extraction model using LandSat imagery to investigate the effects of the wind farm on the presence of water in coastal pond basins before and after construction. Surface water was extracted from Landsat 5, Landsat 7, and Landsat 8 (USGS, Reston, VA, USA) imagery scenes taken mid-October through mid-March from 27 different dates (ranging from 1992–2014) with cloud-free scenes that covered the entire study area. We used the Palmer Drought Severity Index (PDSI; National Integrated Drought Information System, Boulder, CO, USA) to identify dates that spanned a range of conditions (wet to dry) and then searched for Landsat images for those periods to incorporate as much variation as possible into our analysis. We processed Landsat imagery in ERDAS Imagine (2011; Hexagon Geospatial, Norcross, GA, USA) using the tool Layer Stack. This tool created a single image from multiple bands (e.g., bands 1–4 and 7), which we then processed through a model we created to perform the water extraction. The model converted pixels from different band lengths in the images into numbers so that all zeroes represented water and all other integers represented surfaces

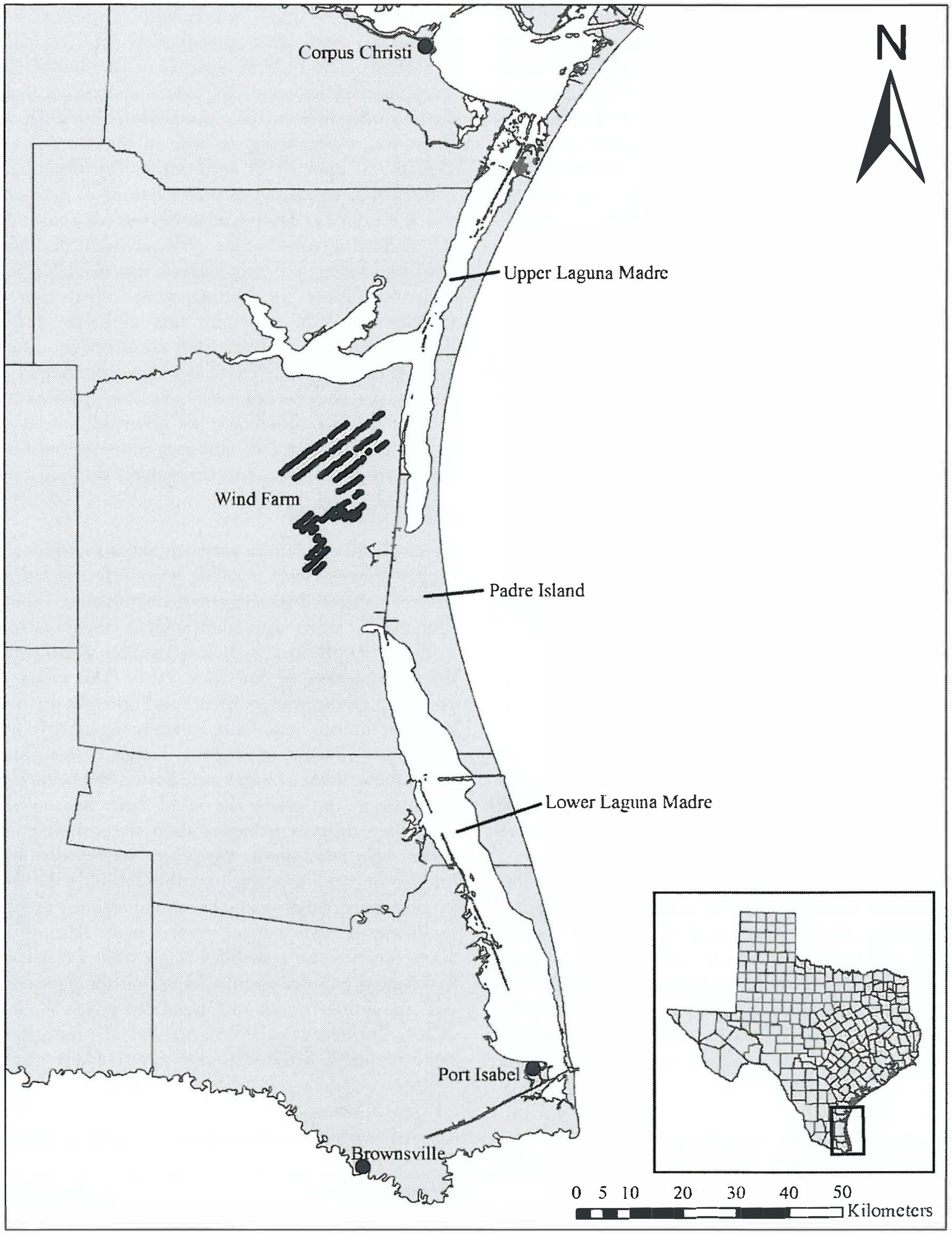

Figure 1. The lower Texas coast, USA where we conducted aerial surveys for coastal pond use by redheads during mid-October through mid-March from 2000–2003 and 2012–2014.

that were not water. We loaded scenes and manually determined the number of images each pond was inundated with water using ArcGIS.

We used the National Wetlands Inventory (NWI) data from the United States Fish and Wildlife Service (USFWS) to determine wetland type of coastal ponds used by redheads (USFWS 2013). We then intersected the NWI dataset with the water extraction images to determine the number of ponds inundated during each scene and calculated pond area. We downloaded PDSI data from 2000 to 2014 from the

National Oceanic and Atmospheric Administration (NOAA) to determine how drought conditions may affect pond availability to redheads. To determine if PDSI was an indicator of pond availability along the lower Texas coast, we ran regression analysis (SAS Institute, Inc. 2008) investigating the relationship between PDSI and number of ponds inundated. We also ran a linear regression F test to test the difference between the regression slopes for the area of coastal ponds available at different levels of PDSI during pre-construction and post-construction.

RESULTS

We flew 101 aerial surveys to monitor redhead use of coastal ponds across the 5 years of study: 69 prior to construction of the wind farm and 32 post-construction. The average number of redheads observed per survey on ponds across the entire Laguna Madre increased by 3.26 times from pre-construction ($\bar{x} = 5,811.4 \pm 969.8$) to post-construction ($\bar{x} = 18,926.6 \pm 2,322.5$). However, the average number of redheads detected per survey on coastal ponds within the wind farm decreased by 77% from pre-construction ($\bar{x} = 2,164.8 \pm 488$) to post-construction ($\bar{x} = 487.5 \pm 70.7$), suggesting a possible avoidance of coastal ponds within the wind farm area by wintering redheads (Table 1). Conditions during pre-construction ranged from very dry (PDSI < −3.5) in 2000, to average (PDSI = −0.5 to 0.7) in 2001, to dry to wet (PDSI = −2.5 to 2.3) in 2002. Conditions in 2012–2013 were very dry (PDSI < −3.5), whereas conditions in 2013–2014 approximated an average year (PDSI = −0.8 to 0.4). During 2012–2013, redheads used ponds within the wind farm on 17 surveys encompassing the entire winter period compared to just 6 surveys (65% decrease) during 2013–2014 when conditions became more wet.

Across the entire study area and every scene, PDSI was positively related to the number of ponds available during pre-construction of the wind farm ($n = 22$, $R^2 = 0.66$, $P < 0.001$) and post-construction of the wind farm ($n = 18$, $R^2 = 0.73$, $P = 0.006$), suggesting that the PDSI is a good predictor of coastal pond inundation. Similarly, within the wind farm boundaries, PDSI was positively related to the number of available ponds prior to the construction of the wind farm ($n = 16$, $R^2 = 0.53$, $P = 0.035$), and after construction ($n = 11$, $R^2 = 0.64$, $P = 0.003$). The regression slopes of the number of ponds from pre-construction to post-construction were not significantly different ($F_{1,\ 21} = 0.01$, $P = 0.972$); however, there was a significant decrease in the number of ponds available at each PDSI level within the wind farm post-construction compared to pre-construction (paired $t = 3.2$, $n = 5$, $P = 0.033$). During relatively wet conditions (PDSI > 2.5) following construction, 88% of inundated pond area available during pre-construction was available post-construction (Table 1). During years of average wetness (PDSI = 0), 57% of pond area available during pre-construction was available post-construction. During dry years (PDSI < −2.5), 7% of inundated pond area available during pre-construction was available post-construction (Table 1). The differences we observed in coastal pond availability between pre- and post-construction was greater within the wind farm than throughout the Laguna Madre.

DISCUSSION

Results from our surface water extractions and aerial surveys suggest that the wind farm has negatively affected redheads through altered hydrology and disturbance displacement. Our surface water extraction analysis provides compelling evidence that the local hydrology has been greatly affected by the construction of the wind farm. The effect is most profound during winters when conditions are dry, which are the most limiting years for redheads in regard to coastal pond availability (Ballard et al. 2010, Lange 2014). During wet years, the amount of water available on the landscape seems to mitigate the effect the wind farm has on the local hydrology because redheads seem to avoid the wetlands within the wind farm. However, during dry years, the number of ponds available to redheads within the wind farm is extremely small and the modifications to the local hydrology become a much greater issue. During dry years when coastal pond availability is low there is likely increases in foraging pressure from redheads on shoalgrass meadows near the limited number of inundated ponds (Ballard et al. 2010). The reduction in the number of coastal freshwater ponds available within the wind farm is likely attributed to

Table 1. Number of redheads observed (± SE) and area (ha) of inundated ponds during different habitat conditions during preconstruction (2000–2003) and post-construction (2012–2014) of a wind farm along the lower Texas coast, USA.

	Pre-construction	Post-construction
Mean number of redheads/survey		
Coastal ponds within Laguna Madre	5,811 ± 970	18,927 + 2,323
Coastal ponds within wind farm	2,165 ± 488	487 + 71
Area (ha) of inundated ponds within wind farm[a]		
Wet conditions (PDSI > 2.5)	576	508
Average conditions (PDSI = 0)	351	200
Dry conditions (PDSI ≤ −3.0)	187	14
Area of inundated ponds along lower Texas coast[a]		
Wet conditions (PDSI > 2.5)	5,419	5,002
Average conditions (PDSI = 0)	3,576	2,949
Dry conditions (PDSI ≤ −3.0)	1,583	954

[a] Based on regression analysis of area of pond inundation from a surface water extraction model and Palmer Drought Severity Index (PDSI) values.

the nearly 208 km of roads that have been built within the wind farm so that construction and maintenance crews can reach each wind turbine. Roads affect the hydrology of basins by inhibiting the flow of sheet water run-off (Office of Policy, Planning, and Evaluation and Apogee Research, Inc. 1997, Trombulak and Frissell 2001). The compaction of soil during road construction prevents drainage of water into basins from surface soils (Helvey and Kochenderfer 1990). Similarly, the large cement and steel foundations of nearly 270 m^3 (Martinez et al. 2009) that support each wind turbine likely influence subsurface water flows.

The wind farm is in one of the most important areas for redheads along the lower Texas coast (Lange 2014). During winter 2012–2013, drought conditions along the lower Texas coast were at their most severe and freshwater ponds were limited. However, by 2013–2014, conditions had improved and more ponds were available on the landscape. Severe drought conditions probably forced redheads to enter the wind farm in search of freshwater for drinking during 2012–2013 (Woodin 1994, Adair et al. 1996, Skoruppa and Woodin 2000), and we observed redheads using ponds that year over 7 times more often than during 2013–2014. Consistent with our hypothesis, we found decreased use during 2013–2014, which was likely attributed to more ponds being available on the landscape, enabling redheads to avoid the wind farm and use ponds in other areas without the risk of collision with wind turbines (Lange 2014). There were also more ponds that were inundated within the wind farm during 2013–2014 than 2012–2013, but redheads used other ponds on the landscape.

From 2000–2012, the now discontinued Special Winter Redhead Survey flown by the USFWS indicated, on average, that 53% of the estimated continental breeding population of redheads overwintered within the Laguna Madre, reaching over 90% in some years (USFWS 2012). From 2000–2014 the estimated continental breeding population of redheads increased 139% from 564,000 to 1.35 million (USFWS 2016). Thus, the increase in numbers of redheads observed using coastal ponds adjacent to the Laguna Madre during our surveys between pre- and post-construction is likely attributed to a combination of an increase in the continental breeding population over that time and changes in the proportion of the continental population wintering in the Laguna Madre. This also emphasizes the importance of conservation strategies directed towards coastal ponds adjacent to the Laguna Madre for providing fresh water to wintering redheads, particularly as the continental population grows and more redheads rely on this system.

High concentrations of redheads on ponds can have detrimental effects on water quality (Skoruppa and Woodin 2000). Water quality is one of the factors influencing coastal pond use by redheads wintering in the Laguna Madre (Adair et al. 1996, Skoruppa and Woodin 2000, Ballard et al. 2010). Also, disturbance displacement from the wind farm and increased use of ponds outside of the wind farm has potential to lead to heavy grazing pressure on shoalgrass meadows in these areas (Mitchell 1991, James 2006). Shoalgrass distribution has declined in the Laguna Madre since at least the 1960s, and shoalgrass now occupies 64% of its historical distribution within the lagoon (Onuf 2002). The decline in shoalgrass has been attributed to decreased light penetration from increased turbidity of the Laguna Madre from dredging and from occurrence of brown tide (Merkord 1978, Onuf 1994, 2002).

Although Lange (2014) reported that redheads marked with global positioning system-satellite transmitters made large movements along the lower Texas coast, all redheads remained >9 km from the wind farm. The average to wet conditions in 2013–2014 appeared to offer redheads options for drinking sites and allowed them to winter in other areas along the lower Texas coast away from the wind farm. This is consistent with our aerial survey data, which showed that redheads tended to stay away from the wind farm during wet years when more coastal ponds are available. Displacement of up to 800 m in response to wind farms has been recorded for various species of birds (Pettersson 2005, Drewitt and Langston 2006, Masden et al. 2009). The extent to which birds avoid wind farms is species specific and typically depends on the size of wind farm, spatial arrangement of the wind turbines, and type of movement by birds (e.g., foraging flights, migration; Langston and Pullan 2003, Fox et al. 2006). Depending on the period within the annual cycle and energy expenditure from avoiding these artificial barriers, wind farms could negatively affect carrying capacity of critically important habitats and this is particularly problematic in areas where large numbers of waterfowl congregate, such as wintering and staging areas (Langston and Pullan 2003).

Our results suggest the occurrence of direct habitat loss and disturbance displacement of redheads from the wind farm along the lower Texas coast. Although our study was directed solely toward redheads, it is likely that this wind farm has affected other species that use these wetlands or migrate along the lower Texas coast (Contreras et al. 2017). Studies in Europe investigating the effects on waterfowl by wind turbines have reported similar results, showing that turbines have likely compromised foraging opportunities for waterfowl through disturbance displacement (Larsen and Madsen 2000). Careful consideration and planning must be taken when siting and building wind farms in areas where large numbers of waterfowl and other birds congregate.

MANAGEMENT IMPLICATIONS

Our findings of a wind farm negatively affecting the hydrology of coastal ponds and causing avoidance behavior by redheads highlights the need for informed siting of wind energy in this region. Areas within 10 km from foraging areas in the Laguna Madre, and particularly those areas near coastal ponds should not be developed. The placement of wind turbines >10 km from the shoreline of the Laguna Madre would greatly decrease a wind farms disturbance displacement on wintering redheads (Ballard et al. 2010) and habitat degradation effects on coastal ponds. Although there has been recent research on offshore wind farms suggesting minimal collision risk for long-lived waterfowl species, an understanding of the susceptibility of redheads to collisions with turbines on inland sites should be conducted to gain a full understanding of total effects of wind turbines on redheads in this important wintering area.

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