



Research Article

The Effects of a Large-Scale Wind Farm on Breeding Season Survival of Female Mallards and Blue-Winged Teal in the Prairie Pothole Region

C. TANNER GUE,^{1,2} *Department of Biology, University of North Dakota, 10 Cornell Street, Grand Forks, ND 58201, USA*
JOHANN A. WALKER,³ *Great Plains Regional Office, Ducks Unlimited, 2525 River Road, Bismarck, ND 58503, USA*
KATHERINE R. MEHL,³ *Department of Biology, University of North Dakota, 10 Cornell Street, Grand Forks, ND 58201, USA*
JEFFREY S. GLEASON,⁴ *Kulm Wetland Management District, U.S. Fish and Wildlife Service, 1 First Street SW, Kulm, ND 58456, USA*
SCOTT E. STEPHENS,⁵ *Great Plains Regional Office, Ducks Unlimited, 2525 River Road, Bismarck, ND 58503, USA*
CHARLES R. LOESCH,⁶ *Habitat and Population Evaluation Team, U.S. Fish and Wildlife Service, 3425 Miriam Avenue, Bismarck, ND 58501, USA*
RONALD E. REYNOLDS,⁶ *Habitat and Population Evaluation Team, U.S. Fish and Wildlife Service, 3425 Miriam Avenue, Bismarck, ND 58501, USA*
BRETT J. GOODWIN,⁶ *Department of Biology, University of North Dakota, 10 Cornell Street, Grand Forks, ND 58201, USA*

ABSTRACT The wetlands and grasslands of the Prairie Pothole Region (PPR) make it the most productive breeding habitat for North American ducks. The growth rate of mallard (*Anas platyrhynchos*) populations is sensitive to changes in survival of adult females during the breeding season. Much of the PPR is suitable for large-scale wind-energy development and collisions of breeding females with wind turbines may be a novel source of mortality in this area. We assessed the effects of wind energy on breeding female mallard and blue-winged teal (*A. discors*) survival by monitoring 77 radio-marked mallards and 88 blue-winged teal during the 2009 and 2010 breeding seasons at the Tatanka Wind Farm (TWF) near Kulm, North Dakota. During the same period, we monitored 70 female mallards and 75 blue-winged teal at an adjacent reference site without wind turbines (REF). We used an information-theoretic approach to investigate relationships between female survival and site (TWF vs. REF), year (2009 vs. 2010), and date. Collision mortalities were rare. Only 1 radio-marked female mallard and no blue-winged teal collided with wind turbines. Most mortalities were caused by predators (78.3%; 36/46), irrespective of species and site. For mallards, the best-approximating model indicated that breeding season survival was 1) lowest when a high proportion of radio-marked females were incubating, and 2) dependent on year and site such that expected survival (\hat{S}) in 2009 was higher at TWF ($\hat{S} = 0.90$, 85% CI = 0.79–0.98) than at REF ($\hat{S} = 0.83$, 85% CI = 0.68–0.95), but expected survival in 2010 was lower at TWF ($\hat{S} = 0.62$, 85% CI = 0.46–0.79) than at REF ($\hat{S} = 0.84$, 85% CI = 0.72–0.94). For blue-winged teal, the constant model was the best-approximating model and indicated that expected female survival was 0.75 (85% CI = 0.69–0.82). The most competitive model for blue-winged teal that included the effect of wind turbines indicated that expected survival at TWF ($\hat{S} = 0.71$, 85% CI = 0.62–0.79) was lower than survival at REF ($\hat{S} = 0.81$, 85% CI = 0.73–0.89). The limited number of collisions observed for female mallards and blue-winged teal nesting at TWF suggests that wind turbines had no direct effect on female survival. Thus, conservation strategies that include protection of wetland and grassland habitat in wind-developed landscapes will most likely not cause a direct reduction in survival of breeding females due to collisions with wind turbines. © 2013 The Wildlife Society.

KEY WORDS adult survival, *Anas discors*, *Anas platyrhynchos*, blue-winged teal, breeding population, mallard, Prairie Pothole Region, radio-telemetry, wind energy, wind turbines.

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¹E-mail: tgue@ducks.org

²Present address: Great Plains Regional Office, Ducks Unlimited, 2525 River Road, Bismarck, ND 58503, USA

³Present address: Newfoundland and Labrador Department of Environment and Conservation, P.O. Box 2007, 117 Riverside Drive, Corner Brook, CA NL A2H 7S1, USA

⁴Present address: Alabama Ecological Services Field Office, U.S. Fish and Wildlife Service, 1208 Main Street, Daphne, AL 36526, USA

⁵Present address: Oak Hammock Marsh Conservation Centre, Ducks Unlimited Canada, P.O. Box 1160, Stonewall, CA MB R0C 2Z0, USA

⁶Present address: Retired, 14622, 246th Avenue Northwest, Zimmerman, MN 55436, USA

The demand for energy and growing concern about potential environmental impacts of traditional energy sources have caused increased interest in alternative energy sources (Arnett et al. 2007, Meseguer 2007). Wind energy is the fastest growing source of alternative energy, with an average annual growth rate in the United States of 39% (2005–2009; American Wind Energy Association 2010). Similar to more traditional energy development projects (coal, Anderson 1978; coal-bed natural gas, Walker et al. 2007; natural gas and oil, Gilbert and Chalfoun 2011), wind energy may also create conflicts for wildlife populations when it alters habitat in a way that reduces survival, productivity, or both (Fox et al. 2006, Johnson and St-Laurent 2011). For example, recent studies have confirmed additional mortality in populations of birds (primarily raptors and passerines) and bats due to direct collisions with wind turbines or associated infrastructure (Erickson et al. 2001, Arnett et al. 2008). However, collision risk may depend on a variety of site- and species-specific factors (Drewitt and Langston 2006). For example, collision risk may be higher at wind developments near preferred hunting habitat, as documented for common kestrels in Spain (*Falco tinnunculus*; Barrios and Rodriguez 2004), or for species that have high wing loading (Janss 2000, De Lucas et al. 2008). Given the rate at which wind energy is expanding and an incomplete understanding about the potential impacts of wind energy on wildlife, concern exists about the effect of large-scale wind-energy developments on wildlife populations (Kiesecker et al. 2011, Fargione et al. 2012).

The Prairie Pothole Region (PPR) provides critical breeding habitat for more than 50% of the continent's population of dabbling ducks (*Anas* spp.; Smith et al. 1964, Bellrose 1980, Kaminski and Weller 1992). As a result, the PPR has been identified as the highest priority for waterfowl conservation by the North American Waterfowl Management Plan (NAWMP; North American Waterfowl Management Plan Committee 2012). However, programs that conserve habitat for breeding waterfowl in the PPR were conceived in the absence of large-scale wind-energy development. Wind resources are particularly abundant in the PPR (Kiesecker et al. 2011:fig. 2, National Renewable Energy Lab 2011). This creates an apparent overlap between an area of high wind-energy potential and an area of primary conservation concern for migratory waterfowl. Although wind-energy development in the PPR is expanding, the effect of wind-energy development on waterfowl populations, particularly in North America, is poorly understood (Stewart et al. 2007, but see Loesch et al. 2013).

A primary concern regarding wind energy in the PPR is decreased survival of breeding females because of potential collisions with wind turbines. Breeding season survival of female mallards (*Anas platyrhynchos*), and presumably other upland nesting ducks, is one of the most limiting factors on population growth (Hoekman et al. 2002). Female dabbling ducks suffer greater mortality during the incubation period than any other period of their annual life cycle because of increased vulnerability to predation (Johnson and Sargeant 1977, Sargeant et al. 1984), but collision of ducks with

turbine blades or other associated infrastructure may represent a novel source of breeding season mortality.

We predicted that if breeding females are susceptible to collision with wind turbines, the probability of survival for females nesting in landscapes near wind turbines would be lower than for females nesting in similar landscapes without wind turbines. Siegfried (1972) hypothesized that male dabbling ducks may be susceptible to collisions with anthropogenic structures during pursuit flights because of a potential decrease in their awareness of such features. We predicted that female ducks may also be particularly susceptible to collision with wind turbines during pre-nesting courtship flights shortly after arrival at the breeding grounds (Titman 1983), as opposed to other periods (e.g., incubation) when females may spend more than 20 hours of a 24-hour period at nests (Afton and Paulus 1992). Further, because of increased fragmentation of grassland habitat at wind farms in the PPR (Bureau of Land Management 2005), predators might be more efficient at locating duck nests and depredating nesting females in wind-developed landscapes (Cowardin et al. 1983, Sargeant et al. 1993). To test these predictions, we used an impact-reference study design (Morrison et al. 2008). We radio-marked and monitored breeding female ducks from April to August in 2009 and 2010 at a wind development and an adjacent reference site with similar landscape characteristics but without wind turbines.

To our knowledge, this study was the first attempt to investigate potential effects of wind-energy development on the survival of breeding female ducks. The primary focus of our study was to assess the risk of collision for breeding females. Our goals were to 1) assess support for our predictions about survival of female ducks during breeding in wind-energy developments and 2) provide managers with useful information about relationships between survival probability of breeding females and wind-energy development in landscapes of the PPR with abundant grassland and wetland habitat.

STUDY AREA

In 2009 and 2010, we studied adult female mallards and blue-winged teal (*Anas discors*) at the Tatanka Wind Farm (Tatanka, Acciona Energy Company, North America; hereafter TWF) and an adjacent reference site without wind turbines (hereafter REF; Fig. 1). The wind farm was located 40 km south of Kulm, North Dakota, USA (46°56'23'N, 99°00'20'W) and extended approximately 16.5 km on the Missouri Coteau physiographic region in Dickey County, North Dakota and McPherson County, South Dakota. The reference site was located in Dickey and McIntosh counties in North Dakota. The wind farm consisted of 120 operational wind turbines located on private lands in cropland or grassland habitat. Turbine operation at TWF began in May 2008. Each turbine (model AW-77/1500) had 3 37-m blades (76-m rotor diameter) atop an 80-m tower. The turbines operated at wind speeds between 3.5 m/s and 25 m/s and were capable of producing 1.5 MW/day (Acciona North America 2011).

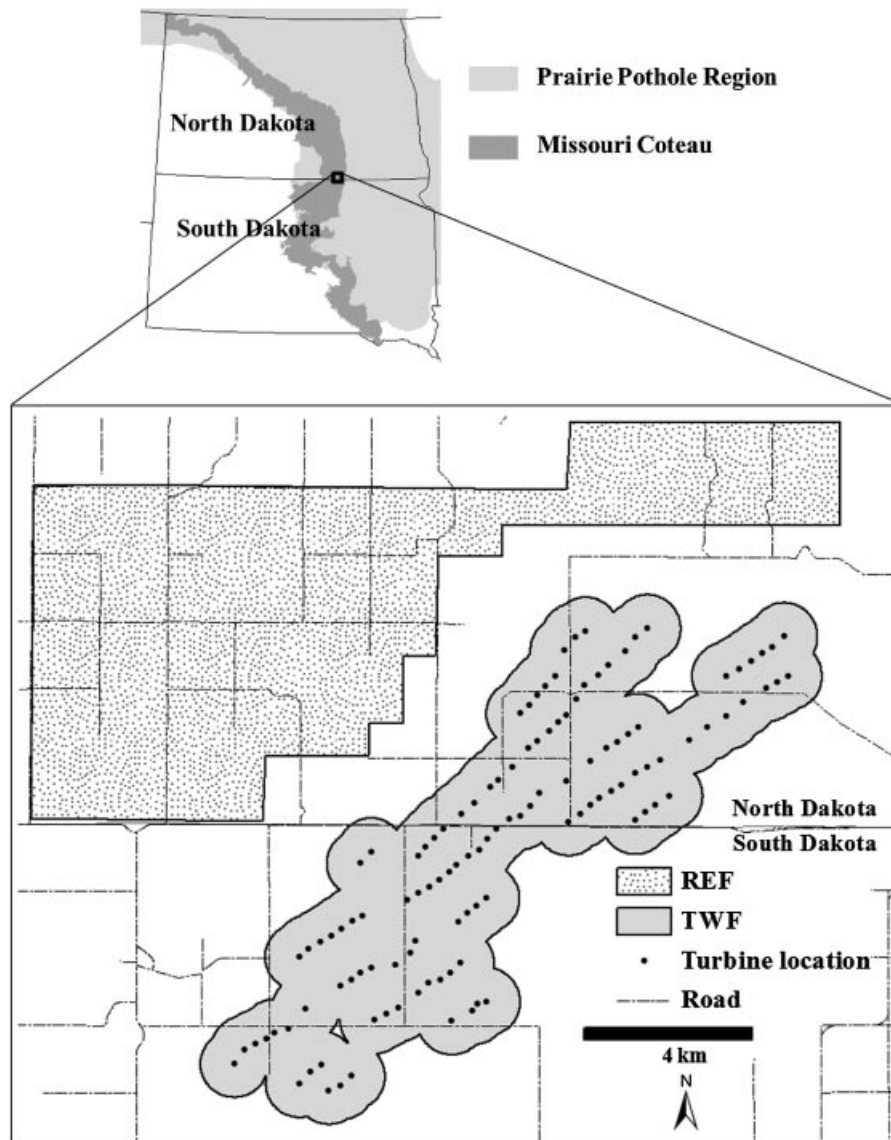


Figure 1. Location of the Tatanka Wind Farm (TWF) and the adjacent reference site (REF) on the Missouri Coteau of the Prairie Pothole Region in North and South Dakota, USA. A 0.8-km buffer around each wind turbine describes the extent of TWF (6,915 ha). We selected REF (8,768 ha) based on area and similarities in landscape characteristics with TWF.

Both sites were typical of the glaciated PPR landscape with moderately sloped topography (Bluemle 1979) and many temporary, seasonal, and semipermanent wetlands (Stewart and Kantrud 1971). Agricultural practices at both sites consisted primarily of livestock grazing and annually cultivated small grains and row crops. Habitat composition at TWF was 73.0% native grassland, 14.6% wetland, 6.6% cropland, 5.4% undisturbed grassland, 0.3% forest, and 0.1% hayland. Habitat composition at REF was 51.7% native grassland, 18.9% wetland, 17.0% undisturbed grassland, 12.1% cropland, 0.2% hayland, and 0.1% forest (U.S. Fish and Wildlife Service [USFWS] Region 6 Habitat and Population Evaluation Team, unpublished data). Wetlands were abundant at both sites (TWF: 23.4 basins/km², REF: 17.3 basins/km²). Temporary, seasonal, and semipermanent wetlands occupied 33.3%, 33.4%, and 33.3% of the wetland area at TWF, respectively, and 33.6%, 33.7%,

and 32.7% of the wetland area at REF, respectively (USFWS 2011).

The climate at TWF and REF was continental with average monthly temperature during our study ranging between 4.83° C and 21.4° C (U.S. Department of Commerce 2011a). Annual precipitation at the study site averages 49.6 cm (U.S. Department of Commerce 2002). Between June and December 2008, the study sites received 54.9 cm of precipitation (U.S. Department of Commerce 2011b). Taken together with above average precipitation in 2009 (64.5 cm) and 2010 (53.0 cm), conditions were exceptionally wet during both years of our study (U.S. Department of Commerce 2011b).

METHODS

Breeding female mallards in the PPR have home range sizes as large as 4.7 km² (Krapu et al. 1983). Blue-winged teal

have comparatively small home range sizes (0.26 km² [26 ha]; Evans and Black 1956, 0.74 km² [74 ha]; Gue 2012). However, female mallards and blue-winged teal use a small fraction of their entire home range during the egg laying and incubation period (Gilmer et al. 1975, Dwyer et al. 1979, Stewart and Titman 1980). Therefore, we assumed that if a female spent $\geq 50\%$ of the breeding season within 0.8-km of a wind turbine, it adequately represented a duck that could be influenced by the presence of wind turbines. Consequently, we described the extent of TWF as all habitats within 0.8 km of each wind turbine. We selected REF boundaries based on the land area, landscape characteristics, and wetland communities of TWF (see Loesch et al. 2013). As with TWF, we assumed that if a female spent $\geq 50\%$ of the breeding season within the boundaries of REF, it adequately represented a duck breeding in a similar landscape to TWF but without wind turbines.

Capture, Radio Attachment, and Monitoring

When mallards arrived on the study area in mid-April, we placed decoy traps in temporary, seasonal, and semipermanent wetlands where we observed territorial pairs (Sharp and Lokemoen 1987, Krapu et al. 1997). We checked decoy traps each morning and afternoon. We relocated traps frequently and distributed them throughout TWF and REF based on repeated observations of pairs on wetlands to capture a representative sample of the local mallard population. Decoy trapping continued for approximately 4 weeks in 2009 and 2010.

Beginning in early May of 2009 and 2010, we nest-searched approximately 1,000 ha at TWF and REF using an all-terrain vehicle chain-drag technique (Higgins et al. 1969, Klett et al. 1986). We conducted searches between 800 and 1400 (Gloutney et al. 1993), but we postponed or cancelled searches during periods of rainfall. We captured nesting mallards and blue-winged teal with walk-in nest traps (Dietz et al. 1994) or mist nets (Bacon and Evrard 1990) during egg-laying or early in incubation.

We marked decoy- and nest-trapped females with a standard USFWS leg band and a 9-g prong-and-suture very high frequency (VHF) transmitter equipped with a mortality sensor (Model A4430, Advanced Telemetry Systems, Isanti, MN). We attached transmitters dorsally using a subcutaneous anchor and 3 sterile monofilament polypropylene sutures (DemeTech Corporation, Miami, FL; 0 metric, 40-mm reverse cutting) following local anesthetic application (1 cc bupivacaine) as described by Pietz et al. (1995). We weighed captured females using a Pesola spring scale (± 10 g) prior to transmitter attachment to ensure that the transmitter did not exceed 3% of the bird's total body weight (Cochran 1980, Barron et al. 2010). In the event that we captured a breeding pair in a decoy trap, we secured the male in a ventilated enclosure until the procedure was complete. We released both members of the pair simultaneously. To reduce nest abandonment, we manually disoriented nest-trapped females post-procedure. Specifically, we tucked the female's head under her wing and slowly

swayed her in a horizontal figure-eight motion until the handler felt the female's muscles relax. At which point, we placed the female on her nest and quietly retreated from the nest site. This procedure generally took ≤ 1 minute. Total handling time of radio-marked females averaged 22.15 minutes (SD = 5.54 min). We recorded total handling time using a wristwatch or cellular telephone and defined it as the period beginning when the observer first contacted the bird and ending when the observer released the bird. We conducted trapping, banding, and collection under USFWS special permit (06824 and 64570) and North Dakota Game and Fish license (GNF02601675). All capture and marking procedures were sanctioned by the Institutional Animal Care and Use Committee of the University of North Dakota (Protocol no. 0907-4c).

We began monitoring radio-marked females as soon as 24 hours after radio attachment. For mallards, we included data in our analysis for the subsequent 92- and 94-day sampling period after the initiation of marking in 2009 and 2010, respectively. For blue-winged teal, we included data in our analysis for the subsequent 70- and 72-day sampling period after the initiation of marking in 2009 and 2010, respectively. We used vehicle-mounted null-peak receiving systems equipped with Location Of A Signal triangulation software (LOAS, version 4.0, Ecological Software Solutions LLC, Hegymagas, Hungary) or handheld antennas and standard triangulation techniques (White and Garrott 1990) to locate radio-marked females. We generally located females between 0700 and 2100. When a female's nest was destroyed, we later increased efforts to locate individuals between 0800 and 1400, a time when females may have been most likely to be on a new nest (Gloutney et al. 1993). We located each female within every 48-hour period between capture and termination of the sampling period unless the female died or was assumed to have left the study area. When females were missing during daily tracking, we searched via road searches and aerial telemetry flights over our study area and the surrounding area within approximately 3 km of the study area boundaries. In 2009, we searched for missing birds with 1 telemetry flight on 2 July. In 2010, we searched for missing birds with 5 telemetry flights on a tri-weekly interval. Encounter histories from females that we assumed to have either left the study area, shed their transmitter before monitoring ended, or became entangled in their transmitter were censored at the time of their last known live encounter. When radio-marked females died within 7 days of capture, we assumed that negative effects of capture and handling were a contributing factor (White and Garrott 1990:37, Cox and Afton 1998, Iverson et al. 2006), and we removed these individuals from the analysis.

Cause of Mortality

We recovered dead females as quickly as possible. Upon visual confirmation of mortality, we recorded the time, location, and cause of death. We considered carcass location (e.g., in a fox or mink den, below a raptor perch, below a wind turbine) and transmitter condition (e.g., apparent tooth or claw marks in transmitter molding, crimped antenna) when assigning the

possible cause of mortality. We took photographs and collected carcasses for further inspection. When we could not determine the cause of death in the field, we froze carcasses and submitted them to the National Wildlife Health Center (University of Wisconsin, Madison) for necropsy.

We categorized cause of death into 3 mortality factors: predation (mammal or raptor), collision (with wind turbine), and other. We identified collision mortalities based on proximity to wind turbine and carcass condition (e.g., visible appearance of trauma). We listed the cause of death as other if it was a rare occurrence for our sample, the carcass disclosed no obvious external indicators regarding the cause of death during observation in the field, or in cases where necropsy reports were inconclusive. For example, 1 female was killed by a hay swather while attending her nest. This was a rare occurrence. For another female, we could not determine the cause of death in the field, but necropsy reports suggested that the female drowned. This was also a rare occurrence. On 3 occasions, the cause of death could not be determined in the field and necropsy reports were inconclusive. One of these mortalities occurred 40 m from a wind turbine, but no evidence of trauma was visible. We categorized all 3 of these mortalities as other.

We were initially concerned that any females that struck turbines may be scavenged by predators, causing us to misclassify the mortality factor (Smallwood et al. 2010). During 2009, we used a transmitter equipped with a precise event mortality sensor that allowed us to determine the time of death to nearest 30 minutes (Advanced Telemetry Systems). In 2010, we used a simple tilt switch mortality sensor that did not record time since death. We determined the median retrieval time in 2010 using the interval between the last live encounter and the day of carcass discovery.

Statistical Analyses

We used an information-theoretic approach (Burnham and Anderson 2002) to assess the relative support for potential relationships between survival probability of breeding females and site, year, and date. We created a set of candidate models that described the potential effect of wind turbines on adult female survival given variation between years and within each breeding season. Every female in the analysis was described by 2 binary variables: site (TWF or REF) to account for the presence or absence of wind turbines, and year (2009 or 2010) to account for annual variation in female survival (Nichols et al. 1982, Blohm et al. 1987, Johnson et al. 1992).

To test our prediction that females may be susceptible to collision prior to incubation, an ideal covariate would have described each radio-marked female as either pre-incubating, incubating, or post-incubating. Similar to Devries et al. (2003) and Hoekman et al. (2006), we initially classified the behavioral phase of each female based on within-season nesting effort of all monitored female mallards and blue-winged teal. However, we detected either very few or no mortalities for some groups of females. For example, we did not observe any mallard mortalities during the generalized pre-nesting phase at TWF in 2009 (see Gue 2012).

Therefore, we used date of the season as a continuous variable to account for potential within-season trends in daily survival rate (DSR) associated with different phases in the breeding cycle. Our model set included models with date, as well as models including both date and date², which allowed daily survival to follow a curvilinear pattern. As a baseline, we predicted a concave-up curvilinear relationship between DSR, date, and date² given that female ducks are more susceptible to predation during incubation (Johnson and Sargeant 1977, Sargeant et al. 1984, Arnold et al. 2012). We predicted that if mortalities increased because of collision with wind turbines during the pre-nesting period, we would observe a positive linear relationship between DSR and date or, possibly, a concave-down curvilinear relationship between DSR, date, and date².

We used Program MARK (White and Burnham 1999) to evaluate support for our predictions and constant survival independent of variables (*S*). We chose the most parsimonious model(s) using Akaike's Information Criterion adjusted for sample size (AIC_c; Burnham and Anderson 2002). Because encounter histories were of unequal length (i.e., ragged telemetry), we used the nest survival data format and nest survival module in Program MARK (Dinsmore et al. 2002) to compare survival of females at TWF and REF. This method, unlike the known-fate method, enabled us to include data of radio-marked females with uneven intervals between resightings. We reported survival estimates using 85% confidence intervals because these intervals are more appropriate for AIC-based model selection than 95% confidence intervals (Arnold 2010).

The models of DSR required that the data met the following 4 assumptions: 1) female fates were known, 2) investigator activity did not influence female fate, 3) female fates were not correlated, and 4) survival among females was not heterogeneous (Dinsmore et al. 2002, Williams et al. 2002). To avoid confusion of movement and mortality, we specifically targeted females missing from daily tracking with road searches and telemetry flights, and we right-censored capture histories of females that left the study area. To reduce potential effects of investigator disturbance on female survival, we 1) flushed radio-marked females as infrequently as possible and 2) spent as little time at radio-marked females' nests as possible.

An unbiased test and associated adjustment factor for correlation of fates and heterogeneity of survival is not available for nest survival models in Program MARK (Dinsmore et al. 2002, Rotella et al. 2007). Nevertheless, little evidence exists for correlation and heterogeneity of fates in large samples of radio-marked mallards, and previous researchers have used unadjusted estimates and model selection criteria for inference in studies of survival of radio-marked females (Devries et al. 2003, Brasher et al. 2006, Bond et al. 2009). We adopted this approach to the analysis of our smaller dataset.

RESULTS

During our 2-year study, we marked 81 and 85 female mallards at REF and TWF, respectively. We censored 11

and 8 female mallards at REF and TWF, respectively, because they were either monitored ≤ 1 week ($n = 16$), their transmitter failed ($n = 1$), or their transmitter emitted a mortality signal on private land that we could not gain access to ($n = 2$). Thus, we analyzed 3,555 exposure days for 70 females at REF and 3,693 exposure days for 77 female mallards at TWF (see Table S1, available online at www.onlinelibrary.wiley.com). Approximately, half (75/147) of the female mallards included in the survival analysis were decoy-trapped prior to nesting. In comparison, we captured all blue-winged teal females at the nest. We marked 79 and 94 female blue-winged teal at REF and TWF, respectively. We censored 4 blue-winged teal at REF and 6 blue-winged teal at TWF because they were monitored ≤ 1 week. Thus, we analyzed 2,651.5 exposure days for 75 females at REF and 3,130.5 exposure days for 88 females at TWF (see Table S1, available online at www.onlinelibrary.wiley.com). Of the 310 female mallards and blue-winged teal included in analyses, we monitored 128 for the duration of the study period, right censored 136, and recorded 46 mortalities (Table 1). We right censored data from females that we assumed to have either left the study area ($n = 94$), shed their transmitter before monitoring ended ($n = 36$), or became entangled in their transmitter ($n = 6$).

Cause of Mortality

Median retrieval time of all dead birds and shed transmitters in 2009 and 2010 was 49 hours ($n = 35$; range = 8–128 hr) and 48 hours ($n = 47$; range = 24–505 hr), respectively. Median retrieval time of all carcasses and shed transmitters in both years at REF was 48 hours ($n = 32$; range = 8–216 hr). We recovered carcasses and shed transmitters in both years at TWF similarly with the exception of 1 female; median retrieval time was 48 hours ($n = 50$; range = 8–505 hr).

Table 1. Number of female mortalities by species (MALL, mallard; BWTE, blue-winged teal), site (Tatanka Wind Farm [TWF] or reference [REF]), year (2009 or 2010), and mortality factor. Mortalities caused by raptors or mammals are included as predator mortalities. We categorized mortalities in which the cause of death was rare or could not be determined in the field and necropsy reports were inconclusive as other mortalities.

	Collision	Predator	Other	Total
2009				
REF				
MALL	0	2	1	3
BWTE	0	3	0	3
TWF				
MALL	1 ^a	1	0	2
BWTE	0	8	0	8
2010				
REF				
MALL	0	3	2	5
BWTE	0	5	0	5
TWF				
MALL	1	7	5	13
BWTE	0	7	0	7
Total	2	36	8	46

^a Mortality could not confidently be attributed to wind turbines. Other obstructions occurred in the immediate area of her carcass (e.g., barbed-wire fence, power line).

Although we detected few mallard mortalities at REF and TWF in 2009, predation was the most common cause of mortality for mallards at both sites in 2009 and 2010 (TWF: 8/15, REF: 5/8; Table 1). We detected similar numbers of blue-winged teal mortalities at both sites in 2009 and 2010. Predation was the only cause of mortality for blue-winged teal at both sites (TWF: 15/15, REF: 8/8; Table 1). Among all recorded mortalities across species, predation accounted for 78.3% ($n = 36/46$) of deaths. We observed 8 mallard mortalities in which we either could not determine the cause of death in the field, necropsy reports were inconclusive, or the cause of death was rare for our sample (e.g., 1 nesting female was killed by a hay swather and another may have drowned). On 3 occasions at TWF, the cause of death could not be determined in the field and necropsy reports were inconclusive. Although 1 of these 3 mortalities occurred 40 m from a wind turbine, there was no evidence of trauma in all cases. These carcass characteristics were inconsistent with obvious external trauma that we observed for an individual female that collided with a wind turbine.

Wind turbine collision contributed to 1 of 15 mallard deaths at TWF (Table 1). We observed 1 additional mallard collision mortality at TWF, but multiple vertical obstructions in the immediate area confounded the cause of mortality (e.g., wind turbine, barbed-wire fence, power line). We observed no blue-winged teal collision-related mortalities (Table 1).

Survival Rates

We observed support that female mallard DSR varied within the season, as the 3 most competitive models included a quadratic time trend (Table 2). We accrued evidence that mallard DSR varied by year, and we observed some evidence that DSR varied by site. Our best-approximating model indicated that mallard DSR varied by each of these factors with an interaction between site and year (Table 2). Nonetheless, we found some model selection uncertainty and the weight of evidence in support (w_i) of the best-

Table 2. Model selection results from analysis investigating female mallard daily survival rate (DSR) at the Tatanka Wind Farm (TWF) and adjacent reference site (REF) in the Prairie Pothole Region of North and South Dakota, USA. We modeled DSR as a function of year (2009 and 2010), site (TWF and REF), and time (date) within the breeding season. We modeled quadratic time trends (date + date²) to investigate predictions about survival during 3 behavioral periods (pre-incubation, incubation, post-incubation) of female mallards. We selected the best model using Akaike's Information Criterion corrected for sample size (AIC_c). We report model weights (w_i), the number of parameters (K), and deviance for each DSR model.

DSR model	ΔAIC_c	w_i	K	Deviance
Site \times year + date + date ²	0.00	0.33	6	252.44
Year + date + date ²	0.28	0.29	4	256.73
Site + date + date ²	1.65	0.15	4	258.10
Site \times year	3.38	0.06	4	259.82
Site + year	3.80	0.05	3	262.24
Year	4.01	0.05	2	264.46
Site \times year + date	4.80	0.03	5	259.24
Constant	5.30	0.02	1	267.75
Site	5.40	0.02	2	265.84

approximating model was 0.33. According to this model, survival varied by time such that the lowest DSR occurred during the middle of the season, which generally corresponded to the highest proportion of females incubating at both sites in 2009 and 2010 (Fig. 2). The estimated 93-day survival probability of radio-marked female mallards for this model at REF was 0.83 (85% CI = 0.68–0.95) and 0.84 (85% CI = 0.72–0.94) in 2009 and 2010, respectively. According to this model, the 93-day survival probability at TWF was high in 2009 ($\hat{S} = 0.90$, 85% CI = 0.79–0.98), but low in 2010 ($\hat{S} = 0.62$, 95% CI = 0.46–0.79).

We observed similar levels of uncertainty in our model set for blue-winged teal and we did not observe as much support for within-season variation in survival for this species. Female blue-winged teal DSR was best described by a constant model, but we found some support for a relationship between DSR and site and year (Table 3). According to the constant model, the estimated 71-day survival probability of blue-winged teal was 0.75 (85% CI = 0.69–0.82). Extrapolated to 93 days for comparison with female mallard breeding season survival estimates, female blue-winged teal survival according to the constant model was 0.69 (85% CI = 0.61–0.77). According to the second best model, which included only the effect of site and held 0.19% of the model weight, 71-day female survival was 0.81 (85% CI = 0.73–0.89) at REF and 0.71 (85% CI = 0.62–0.79) at TWF. Estimated

93-day survival according to this model was 0.76 (85% CI = 0.66–0.86) and 0.64 (85% CI = 0.54–0.73) at REF and TWF, respectively.

DISCUSSION

The motivation for our research was the concern that wind turbines may directly reduce survival probability of breeding females through collision with wind turbines. Collisions at TWF were uncommon. With the exception of high rates of avian collision at the Altamont Pass Wind Resource Area in California (Smallwood and Thelander 2008), other research suggests that avian collision mortality may be minor compared to other potential effects of wind farms (Leddy et al. 1999, Erickson et al. 2001, Arnett et al. 2007, Manville 2009, Loesch et al. 2013). Similarly, we observed no evidence that wind turbines at TWF directly reduced survival of breeding female mallards and blue-winged teal.

The use of telemetry allowed us to intensively study females throughout the breeding season and our capturing and monitoring techniques did not likely cause us to underestimate the number of collision mortalities. Although we nest-trapped approximately half of all mallards ($n = 75$ of 147) and all blue-winged teal ($n = 163$), 68.0% (51/75) and 59.5% (97/163) of nest-trapped mallards and blue-winged teal, respectively, failed at nesting. Of these failed nesters, we

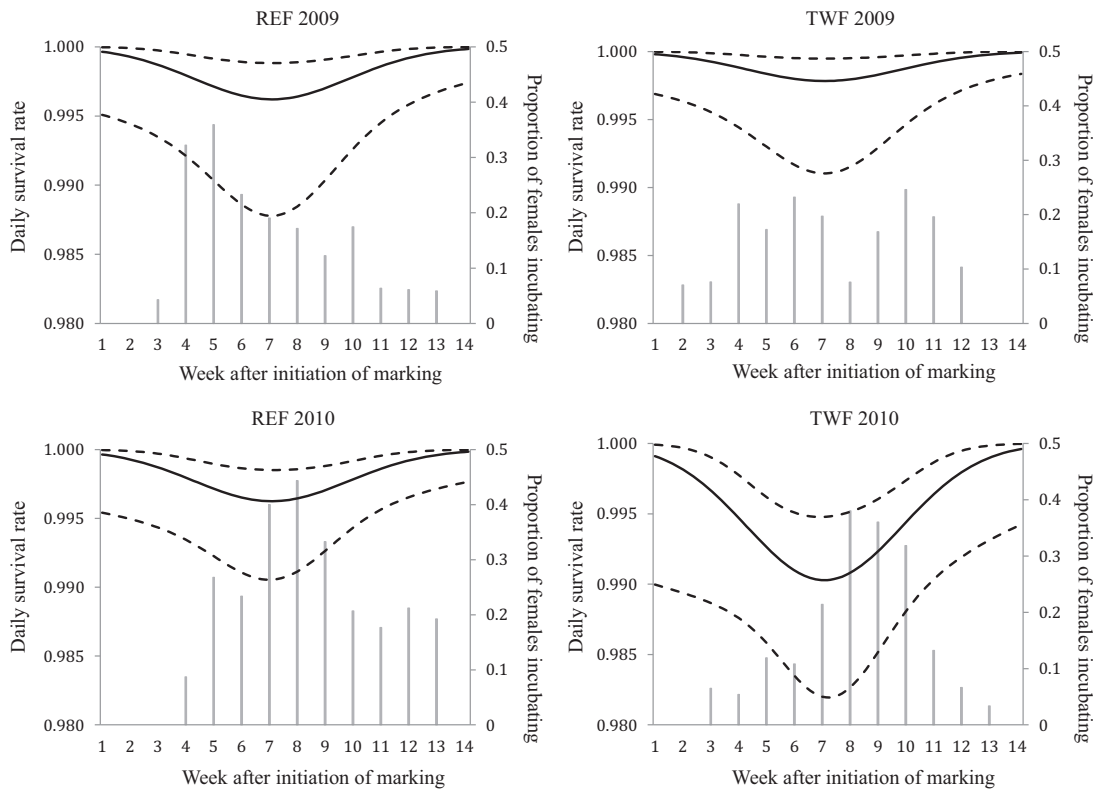


Figure 2. The relationship between within-season time trends as a quadratic ($\text{date} + \text{date}^2$) and daily survival rate (DSR; black line, primary y-axis) of female mallards at Tatanka Wind Farm (TWF) and the adjacent reference site (REF) in the Prairie Pothole Region of North and South Dakota, USA in 2009 and 2010. The estimates are predicted by the model: $\text{DSR} = \text{site} \times \text{year} + \text{date} + \text{date}^2$. Dashed lines are 85% confidence limits. We include proportion of radio-marked females known to be incubating (gray bars, secondary y-axis) for each week of the 14-week study period (mid-Apr–mid-Jul) following the initiation of marking.

Table 3. Model selection results from analysis investigating female blue-winged teal daily survival rate (DSR) at the Tatanka Wind Farm (TWF) and adjacent reference site (REF) in the Prairie Pothole Region of North and South Dakota, USA. We modeled DSR as a function of year (2009 and 2010), site (TWF and REF), and time (date) within the breeding season. We modeled quadratic time trends (date + date²) to investigate predictions about survival during 3 behavioral periods (pre-incubation, incubation, post-incubation) of female blue-winged teal. We selected the best model using Akaike's Information Criterion corrected for sample size (AIC_c). We report model weights (w_i), the number of parameters (K), and deviance for each DSR model.

DSR model	ΔAIC_c	w_i	K	Deviance
Constant	0.00	0.29	1	267.23
Site	0.84	0.19	2	266.07
Year	1.18	0.16	2	266.41
Site + date + date ²	2.23	0.10	4	263.46
Site + year	2.23	0.10	3	265.46
Year + date + date ²	2.35	0.09	4	263.57
Site \times year	4.21	0.04	4	265.44
Site \times year + date + date ²	5.37	0.02	6	262.59
Site \times year + date	5.89	0.02	5	265.11

confirmed that 43.1% (22/51) of mallards and 38.1% (37/97) of blue-winged teal re-nested. Thus, we monitored a sample of females attending nests and females involved in courtship behavior throughout the breeding season. In addition, we located 95.7% (44/46) of all dead radio-marked females within 7 days of their last known live encounter. Scavenging predators in the PPR did not likely remove carcasses from beneath wind turbines within this time frame (see Johnson et al. 2002), which otherwise may have caused us to misclassify the cause of death. However, local landscape characteristics may influence collision risk (Drewitt and Langston 2006, De Lucas et al. 2008). High wetland densities at TWF taken together with habitat conditions during our study may have influenced the number of collisions. Wetlands at TWF and REF were >100% full for most of the spring during both years of our study. Wetland density and area are the primary habitat factors explaining female mallard distribution (Dwyer et al. 1979, Krapu et al. 1997). Waterfowl pair densities are positively related to wetland densities (Johnson and Grier 1988, Viljugrein et al. 2005) and breeding mallards establish smaller breeding territories when pair density is high (Titman 1983). Thus, females breeding at TWF may have encountered fewer turbines during our study than expected in years of average or below average precipitation.

Previous research suggests that collision risk may vary by species (Drewitt and Langston 2006). Species-specific collision risk is likely the result of an interaction between flight behavior and body size (Barrios and Rodriguez 2004, De Lucas et al. 2008). Blue-winged teal may be less susceptible to collisions than mallards because blue-winged teal have smaller home ranges (Dzubin 1955, Evans and Black 1956) and may spend less time in the rotor swept zone while flying among wetland and grassland nesting areas (Stewart 1977). This hypothesis is weakly supported by the fact that we observed no blue-winged teal collisions at TWF. Alternatively, we may not have observed any blue-winged teal collisions because we captured them while they had

active nests. However, 63.6% (56/88) of nest-trapped blue-winged teal at TWF in both years failed at nesting, and although we certainly missed some nests (see McPherson et al. 2003), we confirmed that 41.1% (23/56) of those failed nesters initiated at least 1 more nest. Re-nesting female blue-winged teal re-engaged in courtship and pre-nesting behavior, which we hypothesized to be a period when females were most vulnerable to collisions with wind turbines.

Breeding season survival of female blue-winged teal in our study was similar to that reported by other researchers. For example, Garrettson and Rohwer (1998) reported survival of backpack harness and surgical implant radio-marked blue-winged teal during the 90-day breeding season in the Canadian prairie-parklands to be 60.6 (95% CI = $\pm 28.4\%$) and 72.7 (95% CI = $\pm 27.7\%$), respectively. Their estimates bound the extrapolated survival probability (i.e., DSR⁹³) estimated from the best-approximating blue-winged teal model in our study ($\hat{S}_{(t)} = 0.69$, 85% CI = 0.61–0.77). With the exception of comparatively low breeding season survival of mallards in 2010 at TWF, our mallard survival estimates were generally high, particularly at TWF in 2009. Nonetheless, our estimates were within the range of estimates reported previously. Brasher et al. (2006) estimated 90-day breeding season female mallard survival in the Canadian prairie-parklands to be 0.78 (SE = 0.025). Devries et al. (2003) observed a range of 90-day mallard breeding season survival estimates at 19 different sites in Canada's PPR between 0.62 (SE = 0.028) and 0.84 (SE = 0.018).

We suspected that survival estimates of mallards and blue-winged teal at both sites may have been inflated in 2009 because the probability of incorrectly assuming emigration might have been higher during that year. For example, we detected no mortalities during 1 telemetry flight in 2009 and 3 mallard mortalities during 5 telemetry flights in 2010. Interestingly, these mallard mortalities occurred at TWF. However, mallard survival estimates after censoring these 3 individuals were largely unaffected ($\hat{S}_{TWF\ 2009} = 0.90$, 85% CI = 0.79–0.98), $\hat{S}_{REF\ 2009} = 0.83$, 85% CI = 0.68–0.95), $\hat{S}_{TWF\ 2010} = 0.63$, 85% CI = 0.46–0.80), $\hat{S}_{REF\ 2010} = 0.83$, 85% CI = 0.71–0.94).

Several investigations have reported that survival of female ducks during the breeding season is lowest when females are nesting and are vulnerable to predators (Devries et al. 2003, Richkus et al. 2005, Arnold et al. 2012). Consistent with these findings, survival of female mallards at TWF and REF was lowest when a high proportion of radio-marked females were incubating nests (Fig. 2). Although we accrued only limited support for site-level variation in survival for blue-winged teal, we suspect that, at both sites, most mortalities of blue-winged teal occurred while females were incubating nests.

Given that most mortality appeared to be the result of depredation at REF and TWF, differences in survival between sites for both species may reflect site-specific differences in predator foraging efficiency. Estimated permanent disturbance of habitat at TWF from wind

turbine pads and access roads was 60.9 ac (M. Erickson, USFWS, personal communication), and disturbance of waterfowl nesting habitat may create a favorable scenario for mammalian predators (Johnson and Sargeant 1977, Clark and Nudds 1991). High predation of nesting females in altered landscapes may specifically result from preference of edge habitat as travel corridors by predators (Bider 1968, Larivière and Messier 2000, Phillips et al. 2003), changes in prey density (Larivière and Messier 1998), or decreased nesting cover (Duebbert 1969, Hines and Mitchell 1983, Guyn and Clark 1997). Schmitz and Clark (1999) attributed a negative relationship between survival probabilities of female ring-necked pheasants (*Phasianus colchicus*) and edge habitat density to any 1 or a combination of these factors. Although REF had less native and undisturbed grassland habitat (68.7%) than TWF (78.4%), wind turbine access roads and pads may have indirectly reduced female survival probability at TWF as well.

Changes in local predator community composition or predator abundance may also explain differences in survival between TWF and REF. Raptors are responsible for considerable female mortality in the PPR (Sargeant et al. 1993, Richkus et al. 2005). Disturbance at wind-developed landscapes may increase the abundance of raptor prey species (Morrison and Davis 1996, Thelander et al. 2003) and because TWF began operation in 2008, this may have been a mechanism of temporal differences in raptor abundances at TWF as well. Although we observed raptors foraging at TWF and REF in both years of our study, we have no evidence of a systematic difference in predator communities between sites or years. Long-term studies may be required to elucidate indirect effects of wind development infrastructure on breeding season survival of upland-nesting ducks.

Breeding season survival of female mallards, and presumably other upland-nesting ducks, varies spatially and temporally throughout their breeding ranges (Johnson et al. 1992, Devries et al. 2003). The spatial and temporal extent of our study needs to be considered when evaluating the compatibility of waterfowl conservation strategies and wind energy in the PPR. Nonetheless, breeding females occupying wetland and grassland habitat at TWF during our study rarely collided with wind turbines. Our study also raised some questions about the breeding ecology of upland-nesting ducks at wind-developed landscapes in the PPR. For example, what are the effects of wind turbines on the local composition and abundance of duck predator communities? Is the potential for collision mortality consistent among landscapes with different habitat composition, such as in areas with lower wetland densities or in years of below average precipitation? Answers to these questions would be useful to waterfowl managers given continued wind-energy development in the PPR.

MANAGEMENT IMPLICATIONS

Our results suggest that direct mortality of breeding female mallards and blue-winged teal due to collisions with wind turbines at TWF is probably of limited concern. Consistent

with previous research, predation was the most influential mortality factor for female ducks during the breeding season at REF and TWF (Sargeant et al. 1984, Cowardin et al. 1985). Thus, conservation strategies that include protection of wetland and grassland habitat in wind-developed landscapes (see Kiesecker et al. 2011, Obermeyer et al. 2011, Fargione et al. 2012) will most likely not cause a direct reduction in survival of breeding females due to collisions with wind turbines.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web-site.

Table S1. Number of females and exposure days (in parentheses) included in the survival analysis by species (MALL, mallard; BWTE, blue-winged teal), site (Tatanka Wind Farm [TWF] or reference [REF]), and year (2009 or 2010).