Effectiveness of Changing Wind Turbine Cut-in Speed to Reduce Bat Fatalities at Wind Facilities

Final Report

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This study is dedicated in memory of Andy Linehan, who left us far too soon.

bats and wind energy cooperative

EXECUTIVE SUMMARY

We implemented an experiment testing the effectiveness of changing turbine cut-in speed on reducing bat fatality at wind turbines at the Casselman Wind Project in Somerset County, Pennsylvania in 2008 and 2009. Our objectives were to 1) determine the difference in bat fatalities at turbines with different cut-in-speeds relative to fully operational turbines, and 2) determine the economic costs of the experiment and estimated costs for the entire project area under different curtailment prescriptions and timeframes.

Twelve of the 23 turbines at the study site were randomly selected for the experiment and we employed three treatments at each turbine: 1) fully operational, 2) cut-in speed at 5.0 m/s (C5 turbines), and 3) cut-in speed at 6.5 m/s (C6 turbines), with four replicates on each night of the experiment. We used a completely randomized design and treatments were randomly assigned to turbines each night of the experiment, with the night when treatments were applied as the experimental unit. We re-randomized these treatments during the second year of the study. We conducted daily searches at the 12 turbines from 27 July to 9 October 2008, and 26 July to 8 October 2009. During this same period, we also conducted daily searches at 10 different turbines that were part of a complementary study to determine if bat activity data collected prior to construction with acoustic detectors can be used to predict post-construction fatalities, and to meet permitting requirements of the Pennsylvania Game Commission's (PGC) voluntary agreement for wind energy (herein referred to as "PGC" turbines). These 10 turbines formed an alternative 'control' to the curtailed turbines. We performed two different analyses to evaluate the effectiveness of changing turbine cut-in speed to reduce bat fatalities; for one we used 12 turbines to determine differences in fatality between curtailment levels and for another we used 22 turbines to determine differences in fatalities between curtailment and fully operational turbines. The experimental unit in the first analysis was the turbine-night and turbines were considered a random blocking factor within which all treatments were applied. In our first analysis, the total number of fatalities estimated to have been killed the previous night, herein referred to as "fresh" fatalities, in each treatment at each turbine was modeled as a Poisson random variable with an offset of the number of days a treatment occurred within a turbine (due to the slight imbalance of the design). For our second analysis, the turbine was the experimental unit, with 12 turbines receiving the curtailment treatment, 10 the control (fully operational at all times). We used all carcasses found at a turbine to estimate the total number of bat fatalities that occurred at each turbine between 27 July to 9 October 2008 and 26 July to 8 October 2009 and compared fatalities using one-way ANOVA.

In 2008, we found a total of 32 fresh bat fatalities at the 12 treatment turbines. At least one fresh fatality was found at each turbine, and 10 of the 12 turbines had at least 1 fatality during a fully operational night, indicating that fatalities did not occur disproportionately at only some turbines, but were well distributed among all turbines. There was strong evidence that the estimated number of fatalities differed among turbine treatments ($F_{2,33} = 7.36$, $p = 0.004$). There was no difference between the number of fatalities for C5 and C6 turbines ($\chi_1^2 = 0.68$, $p = 0.41$). Total fatalities at fully operational turbines were estimated to be 5.4 times greater on average than at curtailed turbines (C5 and C6 combined; $\chi_1^2 = 14.11$, $p = 0.0005$, 95% CI: 2.08, 14.11); in other words, 82% (95% CI: 52–93%) of all fatalities at curtailment turbines likely occurred when the turbines were fully operational. Estimated total bat fatalities per turbine (i.e., all

carcasses found and corrected for field bias) were 1.48–5.09 times greater (mean = 2.57) at PGC turbines relative to curtailed turbines, further supporting the contention that reducing operational hours during low wind periods reduces bat fatalities.

In 2009, we found a total of 39 fresh bat fatalities at the 12 treatment turbines. Similar to 2008, we found at least one fresh fatality at each turbine, and 11 of the 12 turbines had at least 1 fatality during a fully operational night, indicating that fatalities did not occur disproportionately at only some turbines and were well distributed among all turbines. We found strong evidence that the estimated number of fatalities over 25 nights differed among turbine treatments in 2009 ($F_{2,33} = 6.94$, $p = 0.005$). There was no difference between the number of fatalities for C5 and C6 turbines ($\chi_1^2 = 0.24$, $p = 0.616$). Total fatalities at fully operational turbines were estimated to be 3.6 times greater on average than at curtailed turbines (C5 and C6 combined; $\chi_1^2 = 12.93$, $p = 0.0003$, 95% CI: 1.79, 7.26); in other words, 72% (95% CI: 44–86%) fewer fatalities occurred when the turbines were curtailed than when the turbines were fully operational. Estimated total bat fatalities per turbine (i.e., all carcasses found and corrected for field bias) were 1.23–2.58 times greater (mean = 1.80) at PGC turbines relative to curtailed turbines, again providing further support for the contention that reducing operational hours during low wind periods reduces bat fatalities. Our comparisons between PGC and curtailed turbines in both years of the study are conservative estimates of the difference because treatment turbines were fully operational one-third of the time during the study.

The lost power output resulting from the experiment amounted to approximately 2% of total project output during the 75-day study period for the 12 turbines. Hypothetically, if the experimental changes in cut-in speed had been applied to all 23 turbines at the Casselman site for the study period (0.5 hour before sunset to 0.5 hour after sunrise for the 75 days we studied), the 5.0 m/s curtailment used would have resulted in lost output equaling 3% of output during the study period and only 0.3 % of total annual output. If the 6.5 m/s curtailment were applied to all 23 turbines during the study period, the lost output would have amounted to 11% of total output for the period and 1% of total annual output. In addition to the lost power revenues, the company also incurred costs for staff time to set up the processes and controls and to implement the curtailment from the company’s offsite 24-hour operations center.

Our study demonstrated nightly reductions in bat fatality ranging from 44–93% with marginal annual power loss. Given the magnitude and extent of bat fatalities worldwide, the conservation implications of our findings are critically important. While more studies are needed to test changes in turbine cut-in speed among different sizes and types of turbines, wind regimes, and habitat conditions, we believe changing cut-in speeds to the levels we tested offers an effective mitigation strategy for reducing bat fatalities at wind facilities.

INTRODUCTION

Although wind-generated electricity is renewable and generally considered environmentally clean, fatalities of bats and birds have been recorded at wind facilities worldwide (Erickson et al. 2002, Durr and Bach 2004, Kunz et al. 2007, Arnett et al. 2008, Baerwald 2008). Bat fatalities at wind energy facilities generally received little attention in North America until 2003 when 1,400–4,000 bats were estimated to have been killed at the Mountaineer Wind Energy Center in West Virginia (Kerns and Kerlinger 2004). High bat fatalities continued at the Mountaineer facility in 2004 (Arnett 2005) and large kills also have been reported at facilities in Pennsylvania (Arnett 2005) and Tennessee (Fiedler 2004, Fiedler et al. 2007). These fatalities raise concerns about potential impacts on bat populations at a time when many species of bats are known or suspected to be in decline (Racey and Entwistle 2003, Winhold et al. 2008) and extensive planning and development of both onshore and offshore wind energy development is increasing worldwide (EIA 2008, Arnett et al. 2007a, Kunz et al. 2007).

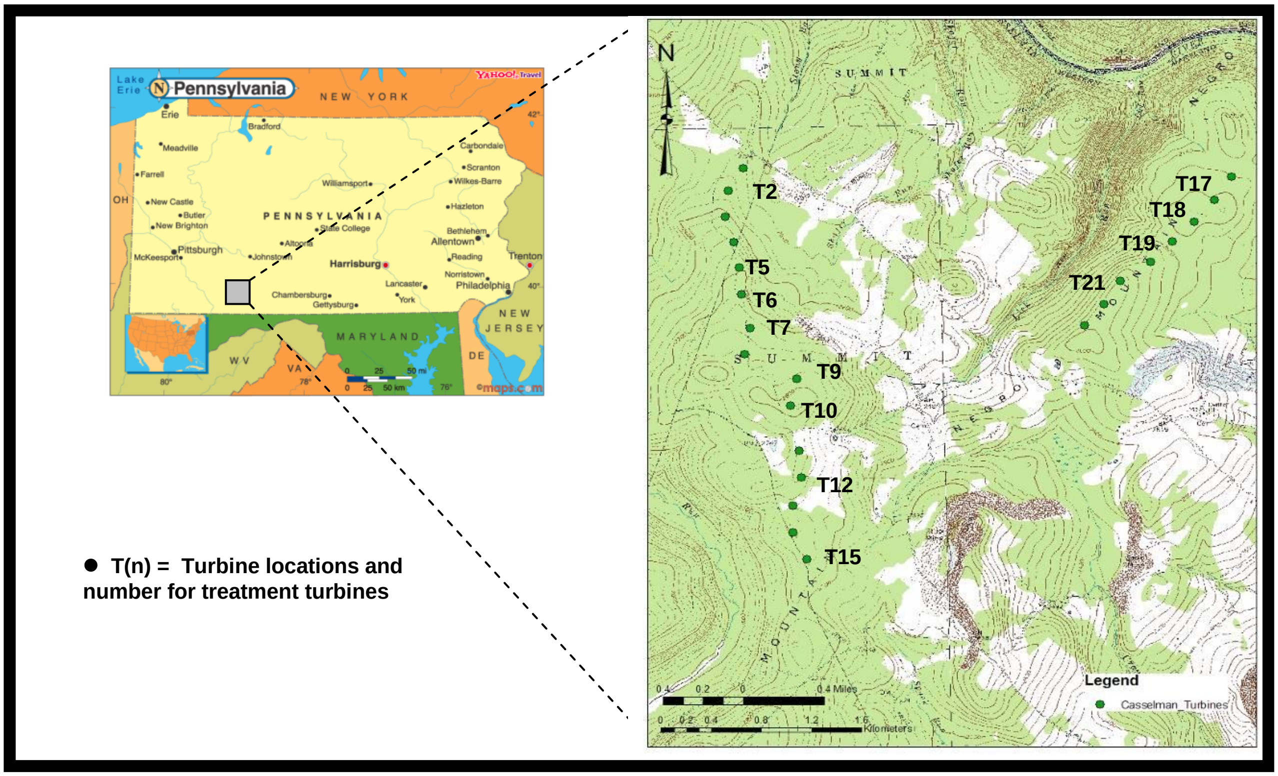
Data previously collected at operating wind energy facilities indicate that a substantial portion of the bat fatalities occurs during relatively low-wind conditions over a relatively short period of time during the summer-fall bat migration period (Arnett et al. 2008). Curtailment of turbine operations under these conditions and during this period of time has been proposed as a possible means of reducing impacts to bats (Kunz et al. 2007, Arnett et al. 2008). Indeed, recent results from studies in Canada (Baerwald et al. 2009) and in Germany (O. Behr, University of Erlangen, unpublished data) indicate that changing turbine “cut-in speed” (i.e., wind speed at which wind-generated electricity enters the power grid) from the manufactured speed (usually 3.5–4.0 m/s for modern turbines) to 5.5 m/s resulted in at least a 50% reduction in bat fatalities compared to normally operating turbines. Altering turbine operations even on a partial, limited-term basis potentially poses operational and financial difficulties for project operators, but this mitigation may ultimately prove sufficiently feasible and effective at reducing impacts to bats at minimal costs to companies that operate wind energy facilities with relatively high incidence of mortality.

We implemented an experiment testing the effectiveness of operational curtailment on reducing bat fatality at wind turbines. Our objectives were to: 1) determine the difference in bat fatality at turbines with different changes in the cut-in-speed relative to fully operational turbines, and 2) determine the economic costs of the experiment and estimated costs for the entire project area under different curtailment prescriptions and timeframes. Our first year of research demonstrated a 52–93% reduction in bat kills at curtailed turbines (Arnett et al. 2009). This report presents our experimental design, methods, and results from 2 years of research findings.

STUDY AREA

The Casselman Wind Project is located near the town of Rockwood in Somerset County, Pennsylvania (Figure 1). The facility lies within the Appalachian mixed mesophytic forests ecoregion that encompasses the moist broadleaf forests that cover the plateaus and rolling hills west of the Appalachian Mountains (Brown and Brown 1972, Strausbaugh and Core 1978). Turbines at

Figure 1. Location of the Casselman Wind Project study area in Somerset County in south-central Pennsylvania, and locations of 23 turbines at the facility. Curtailment treatment turbines have numbers next to them.



the Casselman facility are GE SLE 1.5 MW turbines with a 77 m rotor diameter, 4,657 m^2 rotor-swept area, 80 m hub height, variable rotor speeds from 12–20 RPMs, and cut-in speed of 3.5 m/s (http://www.gepower.com/prod_serv/products/wind_turbines/en/downloads/ge_15_brochure.pdf). There are two "strings" of turbines at the Casselman site. The western string has 15 turbines and is mostly forested (herein referred to as the "forested ridge"; Figure 1). Eleven of the 15 turbines in this string occur in relatively dense, second-growth deciduous hardwood forest with a canopy height generally ranging from 15–20 m; 3 of the 15 turbines in this string occur in open hay pasture near second-growth forest and one occurs in a stand of young (<10 years old) regenerating forest. The eastern string has 8 turbines (herein referred to as "mine ridge"; Figure 1). All turbines in this string occur in open grassland reclaimed after strip mining for coal.

EXPERIMENTAL DESIGN and HYPOTHESES

Twelve turbines were used for the operational curtailment experiment and we employed three turbine treatments: 1) fully operational, 2) cut-in speed at 5.0 m/s, and 3) cut-in speed at 6.5 m/s, with four replicates of each treatment on each night of the experiment. We used a randomized block design (Hurlbert 1984) wherein treatments were randomly assigned to turbines each night of the experiment, with the night when treatments were applied as the experimental unit. Treatments were re-randomized during the second year of the study. Randomization was constrained so that on each night, each treatment was assigned to 4 turbines and over the course of 15 nights, each treatment occurred 5 times at each turbine, in random order. Randomization was further constrained so that each of the three treatments was assigned to at least one turbine on the mine side of the site. Each treatment was assigned to each turbine for 25 nights.

On any given night, there was little variation in the wind speed among turbines (M. Huso, unpublished data), so we assumed that wind speeds were the same at all turbines each night. The GE 1.5 MW turbines used in this experiment generally do not rotate at low wind speeds and "feather" when winds are <3.5 m/s (i.e., turbine blades are pitched parallel with the wind and free-wheel at very low rotation rates). Thus, the actual application of the curtailment treatment was dependent on the ambient wind speed on each night. There were 4 possible levels of ambient wind speed: <3.5 m/s, 3.5–5.0 m/s, 5.0–6.5 m/s, >6.5 m/s. Table 1 presents conditions of turbines under each of these treatments and wind speeds. When wind speeds were <3.5 or >6.5 m/s, all turbines were in the same operational condition and no curtailment treatments were in effect for those times; only when wind speeds were between 3.5 and 6.5 m/s were any treatments actually effective. When wind speeds were low, bat activity was expected to be high (Table 2; e.g., Arnett et al. 2006, 2007b), and when winds were <3.5 m/s none of the turbines were expected to rotate, so we expected no fatalities during these periods at any of the treated turbines because all turbines were feathered below the cut-in speed (Table 2). When wind speeds were >6.5 m/s and all turbines were rotating, bat activity was expected to be low (e.g., Arnett et al. 2006, 2007b) so we expected few fatalities during these nights as well, and hypothesized there would be no differences among treatments (Table 2). When wind speeds were 3.5–5.0 m/s, bat activity was expected to be moderate to high and turbines with two different feathering treatments were not rotating, so we expected no fatalities at these turbines, but potentially high fatalities at the unfeathered, fully operational turbines under these wind conditions. Finally, when wind speeds were 5–6.5 m/s, we expected bat activity to be moderate to low, turbines assigned the 6.5 m/s treatment were not rotating, and we expected no fatalities at these turbines and moderate to low fatalities at the unfeathered turbines. However, wind speed varied throughout the night, changing the effective treatment application throughout the night. In addition, fatalities were only observed at the end of the night and it was impossible to determine when and under exactly what conditions of wind speed that a fatality occurred. Our design actively accounted for this effect by maintaining balance (4 replicates of each treatment on each night), and reassigning treatment to turbines each night. Also, the measure of fatality for a treatment was the sum of all fatalities found at a given turbine following a particular treatment assignment, thereby evenly distributing the effect of varying wind speed within a night and among nights across all turbines and treatments in the study.

FIELD METHODS

Delineation of Carcass Search Plots and Habitat Mapping

We attempted to delineate a rectangular plot that was 126 m east-west by 120 m north-south (60 m radius from the turbine mast in any direction; 15,120 m^2 total area) centered on each turbine sampled; this area represents the maximum possible search area for this study (see Figure 2 for an

Table 1. Possible turbine conditions ("feathered" or "rotating") under different treatments and wind conditions at the Casselman Wind Project in Somerset County, Pennsylvania. Under the treatment condition when wind is <3.5 m/s, we expected all turbines to be feathered with no rotation.

Treatment	**Wind Speed (m/s)**			
	< 3.5	**3.5–5.0**	**5.1–6.5**	**> 6.5**
5.0 m/s	Feathered/ No rotation	Feathered/ No rotation	No feathering/ Full rotation	No feathering/ Full rotation
6.5 m/s	Feathered/ No rotation	Feathered/ No rotation	Feathered/ No rotation	No feathering/ Full rotation
Fully Operational	Feathered/ No rotation	No feathering/ Full rotation	No feathering/ Full rotation	No feathering/ Full rotation

Table 2. Predicted bat activity levels under different treatments and wind conditions (based on analyses in Arnett et al. 2006, 2007b) and predicted fatality levels at the Casselman Wind Project in Somerset County, Pennsylvania.

Treatment		**Wind Speed (m/s)**			
		< 3.5	**3.5–5.0**	**5.1–6.5**	**> 6.5**
5.0 m/s	Activity	High	Moderate	Moderate	Low
	Fatality	None	None	Moderate	Low
6.5 m/s	Activity	High	Moderate	Moderate	Low
	Fatality	None	None	None	Low
Fully Operational					
	Activity	High	Moderate	Moderate	Low
	Fatality	None	High	Moderate	Low

example). Transects were set 6 m apart within each plot and observers searched 3 m on each side of the transect line; thus, the maximum plot in the east-west direction could be up to 126 m wide. However, dense vegetation and the area cleared of forest at this facility was highly varied and, thus, we eliminated unsearchable habitat (e.g., forest, tall and dense grassland) and usually did not search the entire possible maximum area. We used a global positioning system (GPS) to map the actual area searched at each turbine (see Figure 2 for an example, and Appendix 1 for plot maps). The density-weighted proportion of area searched was used to standardize results and adjust fatality estimates (see methods below). The number of transect lines and length of each line was recorded for each plot and habitat in each plot mapped with a GPS unit. We recorded the percent ground cover, height of ground cover (low [<10 cm], medium [11–50 cm], high [>50 cm]), type of habitat (vegetation, brush pile, boulder, etc), and the presence of extreme slope and collapsed these habitat characteristics into visibility classes that reflect their combined influence on carcass detectability (Table 3; following PGC 2007).

Fatality Searches

We conducted daily searches at 12 of the 23 turbines (2, 5, 6, 7, 9, 10, 12, 15, 17, 18, 19, 21; Figure 1) from 27 July to 9 October 2008 and from 26 July to 8 October 2009. During these same periods, we also conducted daily searches at 10 different turbines (1, 3, 4, 8, 11, 13, 14, 16, 20, 23; Figure 1) as part of a different study effort to determine if activity data collected prior to construction with acoustic detectors can predict post-construction fatalities (Arnett et al. 2006, 2009), and to meet requirements of the Pennsylvania Game Commission's (PGC) voluntary agreement for wind energy (PGC 2007). These 10 turbines, herein referred to as "PGC" turbines, were selected because they had multiple years of acoustic data previously collected from 2005–2007 to be correlated with turbine-specific fatality data in the future (Arnett et al. 2006). We then randomly selected the 12 turbines listed above (of the remaining 13 turbines) for the curtailment study; no searches were conducted at turbine 22.

Each searcher completed 5 or 6 turbine plots each day during the study. Searchers walked at a rate of approximately 10–20 m/min. along each transect searching out to 3 m on each side for fatalities. Searches were abandoned only if severe or otherwise unsafe weather (e.g., heavy rain, lightning) conditions were present and searches were resumed that day if weather conditions permitted. Searches commenced at sunrise and all turbines were searched within 8 hr after sunrise. We recorded date, start time, end time, observer, and weather data for each search at turbines. When a dead bat or bird was found, the searcher placed a flag near the carcass and continued the search. After searching the entire plot, the searcher returned to each carcass and recorded information on date, time found, species, sex and age (where possible), observer name, identification number of carcass, turbine number, perpendicular distance from the transect line to the carcass, distance from turbine, azimuth from turbine, habitat surrounding carcass, condition of carcass (entire, partial, scavenged), and estimated time of death (e.g., ≤1 day, 2 days, etc.). The field crew leader (M. Schirmacher) confirmed all species identifications at the end of each day. Disposable nitrile surgical gloves were used to handle all carcasses to reduce possible human scent bias for carcasses later used in scavenger removal trials. Carcasses were placed in a plastic bag and labeled. Fresh carcasses, those determined to have been killed the night immediately before a

Figure 2. Sample carcass search plot at a wind turbine depicting the maximum plot size of 126 m east-west and 120 m north-south, 6 m wide transect lines (searched 3 m on each side), unsearchable area (black), and area encompassed by easy (white), moderate (light tan), difficult (dark tan), and very difficult (brown) visibility habitat.

Table 3. Habitat visibility classes used during this study (following PGC 2007). Data for Classes 3 and 4 were combined during our final analyses.

% Vegetative Cover	Vegetation Height	Visibility Class
≥90% bare ground	≤15 cm tall	Class 1 (Easy)
≥25% bare ground	≤15 cm tall	Class 2 (Moderate)
≤25% bare ground	≤25% > 30 cm tall	Class 3 (Difficult)
Little or no bare ground	≥25% > 30 cm tall	Class 4 (Very Difficult)

search, were redistributed at random points on the same day for searcher efficiency and scavenging trials. Following PGC's protocol, all downed bats were euthanized, even if no physical injury was observed, following acceptable methods suggested by the American Society for Mammalogists (Gannon et al. 2007); because sedation or anesthesia were not used in our study, we employed cervical dislocation.

Field Bias Trials

Searcher efficiency and removal of carcasses by scavengers was quantified to adjust the estimate of total bat fatalities for detection bias. We conducted bias trials throughout the entire study period and searchers were never aware which turbines were used or the number of carcasses placed beneath those turbines during trials. Prior to the study's inception, we generated a list of random turbine numbers and random azimuths and distances (m) from turbines for placement of each bat used in bias trials.

We used only fresh killed bats for searcher efficiency and carcass removal trials during this study. At the end of each day's search, the field crew leader gathered all bats and then redistributed only fresh bats at predetermined random points within any given turbine's searchable area. Data recorded for each trial carcass prior to placement included date of placement, species, turbine number, distance and direction from turbine, and visibility class surrounding the carcass. We attempted to distribute trial bats equally among the different visibility classes throughout the study period, and succeeded in distributing roughly one-third of all trial bats in each visibility class (easy, moderate, and difficult [difficult and very difficult were combined]). We attempted to avoid "over-seeding" any one turbine with carcasses by placing no more than 4 carcasses at any one time at a given turbine.

Because we used fresh bats for searcher efficiency trials and carcass removal trials simultaneously, we did not mark bats with tape or some other previously used methods (see Kerns et al. 2005) that could impart human or other scents on trial bat carcasses. Rather, we removed an upper canine tooth from each trial bat so as to distinguish them from other fatalities landing nearby or if scavengers pulled the trial bat away from its original random location. Each trial bat was left in place and checked daily by the field crew leader or a searcher not involved with the bias trials; thus, trial bats were available and could be found by searchers on consecutive days during daily searches unless they were previously removed by a scavenger. We recorded the day that each bat was found by a searcher, at which time the carcass remained in the scavenger removal trial. However, if a carcass was removed by a scavenger before detection by a searcher it was removed from the searcher efficiency trial and used only in the removal data set. When a bat carcass was found, the searcher inspected the canine teeth to determine if a bias trial carcass had been found. If so, the searcher contacted the field crew leader and the bat was left in place for the carcass removal trial. Carcasses were left in place until removed by a scavenger or they decomposed to a point beyond recognition, at which time the number of days after placement was recorded.

ANALYTICAL METHODS

Comparison of Treatments

The experimental unit in our first analysis was the turbine-night and turbines were considered a random blocking factor. The total number of fatalities estimated to have been killed the previous night, herein referred to as “fresh” fatalities, in each treatment at each turbine was modeled as a Poisson random variable with an offset of the number of days a treatment occurred within a turbine (due to the slight imbalance of the design). These data were fit to a Generalized Linear Mixed Model using PROC GLIMMIX in SAS v9.1 (SAS Institute 2007) with the turbine as the blocking factor. The block effect was found to be negligible and results were almost identical when the data were fit to a simple log-linear model. We did not include year in the model and analyzed each year separately.

Comparison of PGC and Curtailment Turbine Bat Fatalities

For our second analysis, the turbine was the experimental unit, with 12 turbines receiving the curtailment treatment, 10 the control (fully operational at all times; “PGC” turbines). We used all carcasses found at a turbine to estimate the total number of bat fatalities that occurred at each turbine between 27 July and 9 October 2008 and 26 July and 8 October 2009. We compared fatalities at PGC with curtailment turbines using one-way analysis of variance with each turbine as the experimental unit and $\log_e$ (estimated total fatalities) as the response (SAS Institute 2007).

Carcass persistence/removal. Estimates of the probability that a carcass was not removed in the interval between searches were used to adjust carcass counts for removal bias. Removal includes removal by predation, scavenging, wind or water, or decomposition beyond recognition. In most fatality monitoring efforts, it is assumed that carcass removal occurs at a constant rate that is not dependent on the time since death; this simplifying assumption allows us to estimate fatality when search intervals exceed one day. The length of time a carcass remains on the study area before it is removed is typically modeled as an exponentially distributed random variable. The probability that a carcass is not removed during an interval of length I can be approximated as the average probability of persisting given its death might have occurred at any time during the interval:

$$\hat{r}_{jk} = \hat{\bar{t}}_{jk} * (1 - \exp(-I_{ij} / \hat{\bar{t}}_{jk})) / I_{ij}$$

$\hat{r}_{jk}$ is the estimated probability that a carcass in the k^{th} visibility class that died during the interval preceding the j^{th} search will not be removed by scavengers;

$\hat{\bar{t}}_{jk}$ is the estimated average persistence time of a carcass in the k^{th} visibility class that died during the interval preceding the j^{th} search;

I_{ij} is the length of the effective interval preceding the j^{th} search at the i^{th} turbine;

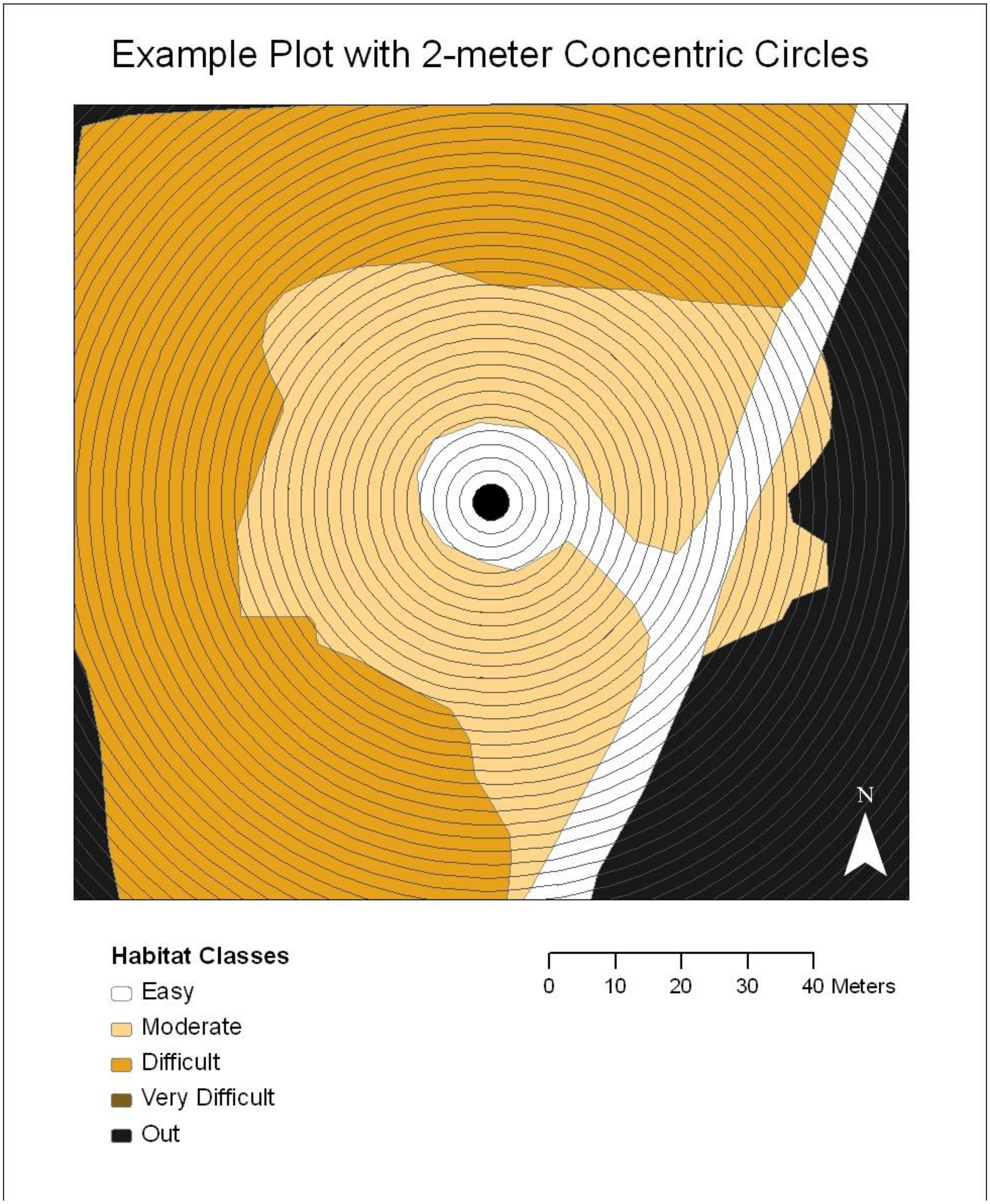
NOTE: k^{th} visibility class can be expanded to any combination of factors that have been modeled as affecting a carcass's persistence time or probability of detection, e.g. size, season, etc.

Data from 114 bat carcasses used in removal trials in 2008 and 131 bat carcasses in 2009 were fit to an interval-censored parametric failure time model, with carcass persistence time modeled as a function of visibility class. We used an alpha of 0.15 to determine if there was a statistically significant effect among visibility classes. We used a liberal alpha value to minimize Type II errors and consequently model searcher efficiency and average carcass persistence time with the greatest sensitivity to potentially influential factors

Searcher efficiency. Estimates of the probability that a carcass will be detected by an observer during a search (searcher efficiency) were used to adjust carcass counts for observer bias. Failure of an observer to detect a carcass on a search plot may be due to its size, color, or time since death, as well as conditions in its immediate vicinity (e.g., vegetation density, shade). In most fatality monitoring efforts, because we cannot measure time since death, it is assumed that a carcass' observability was constant over the period of the search interval. In this study, searches were conducted daily and carcass persistence times were long, giving a substantial opportunity for a searcher to detect a carcass that was missed on a previous search. Carcasses used in searcher efficiency trials were placed on search plots and monitored for 20 days. The day on which the carcass was either observed or removed by a scavenger was noted. After accounting for trial bats that had been removed by scavengers before the searches took place, 70 bats in 2008 and 98 in 2009 were either seen or persisted beyond 7 days and were included in estimates of searcher efficiency rates. We fit these searcher efficiency data to a logistic regression model with odds of observing a carcass throughout the study period, given that it persisted, modeled as a function of visibility class. We used an alpha of 0.15 to determine if there was a statistically significant effect among visibility classes.

Density of carcasses and proportion of area surveyed. The density of bat carcasses was modeled as a function of distance from the turbine. Because searcher efficiency was similar in

Figure 3. Hypothetical carcass search plot for a wind turbine illustrating 2 m rings extending from the turbine edge out to the theoretical maximum plot distance and the depicted “easy” searchable area (shaded area within line drawing) of the plot, used to develop weights for adjusting fatalities.



easy and moderate visibility areas, fresh bat carcasses from both visibility classes were used for this analysis and data from all turbines were used, yielding a total of 144 bat carcasses from 2008 and 66 carcasses from 2009. We assumed that the carcass persistence time would be equal for all carcasses within this class and would not change as a function of distance from the turbine. Carcasses were "binned" into 2 m rings (Figure 3) extending from the turbine edge out to the theoretical maximum plot distance. We determined the total area among all search plots that was in the searchable area (m^2) and calculated carcass density (number of carcasses/m^2) in each ring. These data were modeled as a conditional cubic polynomial. Because the resulting model did not differ statistically between years of the study, and the 2008 model was based on a sample more than twice as large as 2009, we used the same density weight function for calculating estimates for both years of the study:

If distance $\leq$81m, then density = exp (-2.8573 + 0.0849*dist – 0.0028* $dist^2$ + 0.00001858*$dist^3$) -0.01; otherwise, density = 0.00137*exp (-0.05*(distance-81))

The actual area surveyed within a plot differed among turbines and ranged from 41–96% of the delineated theoretical maximum search plot. Density of carcasses is known to diminish with increasing distance from the turbine (e.g., Kerns et al. 2005), so a simple adjustment to fatality based on area surveyed would likely lead to overestimates, because unsearched areas tend to be farthest from turbines. The calculated function (see above) relating density to distance from a turbine was used to weight each square meter in the plot. The density-weighted fraction of each plot that was actually searched was used as an area adjustment to per-turbine fatality estimates rather than using a simple proportion; the weighted density area of plots averaged 83% (range: 61–99.6%). The per turbine fatality adjusted for weighted density area of the plots did not account for the small fraction of the carcasses found to occur beyond the limits of the designated search areas. Over the entire site, we estimated that 5.28% of carcasses occurred in areas outside of search plot areas surrounding each turbine and per turbine as well as total fatality estimates were adjusted accordingly.

Fatality estimates. We adjusted the number of bat and bird fatalities found by searchers by estimates of searcher efficiency and of the proportion of carcasses expected to persist unscavenged during each interval using the following equation:

$$\hat{f}_{ijk} = \frac{c_{ijk}}{\hat{a}_i * \hat{p}_{jk} * \hat{r}_{jk} * \hat{e}_{jk}}$$

where:

$\hat{f}_{ijk}$ is the estimated fatality in the k^{th} visibility class that occurred at the i^{th} turbine during the j^{th} search;

c_{ijk} is the observed number of carcasses in the k^{th} visibility class at the i^{th} turbine during the j^{th} search;

$\hat{a}_i$ is the density-weighted proportion of the area of the i^{th} turbine that was searched;

$\hat{p}_{jk}$ is the estimated probability that a carcass in the k^{th} visibility class that is on the ground during the j^{th} search will actually be seen by the observer;

$\hat{r}_j$ is the probability than an individual bird or bat that died during the interval preceding the j^{th} search will not be removed by scavengers; and

$\hat{e}_{jk}$ is the effective interval adjustment (i.e., the ratio of the length of time before 99% of carcasses can be expected to be removed to the search interval) associated with a carcass in the k^{th} visibility class that died during the interval preceding the j^{th} search.

The value for $\hat{p}_{jk}$ was estimated through searcher efficiency trials with estimates given above; $\hat{r}_j$ is a function of the average carcass persistence rate and the length of the interval preceding the j^{th} search; and $\hat{r}_j$, $\hat{e}_j$ and $\hat{p}_{jk}$ are assumed not to differ among turbines, but differ with search interval (j) and visibility class (k).

The estimated annual per turbine fatality was calculated for PGC and curtailed turbines using an estimator newly derived by M. Huso, Oregon State University (Huso 2010; herein referred to as the MH estimator). The equation for the MH estimator in this study is:

$$\hat{f} = \frac{\sum_{i=1}^{10}\sum_{j=1}^{n_i}\sum_{k=1}^{3}\hat{f}_{ijk}}{10}$$

where n_i is the number of searches carried out at turbine i ($i = 1\ldots, 10$), and $\hat{f}_{ijk}$ is defined above. The per turbine estimate and confidence limits were multiplied by 23 (the total number of turbines) and divided by 0.947 to adjust for actual density-weighted area searched to give total annual fatality estimates (Cochran 1977). This estimate assumes that no fatalities occurred during the winter, i.e. prior to April and after November. No closed form solution is yet available for the variance of this estimator, so 95% confidence intervals of this estimate were calculated by bootstrapping (Manly 1997). Searcher efficiency was estimated from a bootstrap sample (with replacement) of searcher efficiency data, carcass persistence estimated from a bootstrap sample of carcass persistence data, and these values were applied to the carcass data from a bootstrap sample of turbines to estimate average fatality per turbine. This process was repeated 1000 times. The 2.5th and 97.5th quantiles from the 1,000 bootstrapped estimates formed the 95% confidence limits of the estimated fatality.

RESULTS

Comparison of Treatments

In 2008, we found a total of 32 fresh bat fatalities at the 12 curtailment study turbines between 27 July and 9 October 2008. At least one fresh fatality was found at each turbine, and 10 of the 12 turbines had at least 1 fatality during a fully operational night, indicating that fatalities did not occur disproportionately at only some turbines, but were well distributed among all turbines (Figure 4). We found 3 fresh fatalities at turbines that were curtailed when wind speeds were <5.0 m/s (C5) the preceding night, 6 at turbines curtailed when wind speeds were <6.5 m/s (C6), and 23 at turbines that were fully operational. The estimated average number of bat fatalities per turbine over 25 nights was 0.27 (95% CI: 0.07, 1.05) for those with a 5.0 m/s cut-in speed, 0.53 (95% CI: 0.20, 1.42) for those with a 6.5 m/s cut-in speed, and 2.04 (95% CI: 1.19, 3.51) for fully operational turbines (Figure 5). There was strong evidence that the estimated number of fatalities over 25 nights differed among turbine treatments ($F_{2,33} = 7.36$, $p = 0.004$). There was no difference between the number of fatalities for C5 and C6 turbines ($\chi_1^2 = 0.68$, $p = 0.41$). Total fatalities at fully operational turbines were estimated to be 5.4 times greater on average than at curtailed turbines (C5 and C6 combined; $\chi_1^2 = 14.11$, $p = 0.0005$, 95% CI: 2.08, 14.11); in other words, 82% (95% CI: 52–93%) fewer fatalities occurred when turbines were curtailed than when the turbines were fully operational.

In 2009, we found 39 fresh bat fatalities at the 12 treatment turbines. Similar to 2008, we found at least one fresh fatality at each turbine, and 11 of the 12 turbines had at least 1 fatality during a fully operational night, indicating that fatalities did not occur disproportionately at only some turbines and were well distributed among all turbines (Figure 6). We found 8 fresh fatalities at turbines that were curtailed when wind speeds were <5.0 m/s (C5) the preceding night, 6 at turbines curtailed when wind speeds were <6.5 m/s (C6), and 25 at turbines that were fully operational. The estimated average number of bat fatalities per turbine over 25 nights was 2.29 (95% CI: 1.46, 3.58) for fully operational turbines, 0.73 (95% CI: 0.34, 1.56) for those with a 5.0 m/s cut-in speed, and 0.55 (95% CI: 0.23, 1.31) for those with a 6.5 m/s cut-in speed (Figure 5). We again found strong evidence that the estimated number of fatalities over 25 nights differed among turbine treatments in 2009 ($F_{2,33} = 6.94$, $p = 0.005$). There was no difference between the number of fatalities for C5 and C6 turbines ($\chi_1^2 = 0.24$, $p = 0.616$). Total fatalities at fully operational turbines were estimated to be 3.6 times greater on average than at curtailed turbines (C5 and C6 combined; $\chi_1^2 = 12.93$, $p = 0.0003$, 95% CI: 1.79, 7.26); in other words, 72% (95% CI: 44–86%) fewer fatalities occurred when turbines were curtailed than when the turbines were fully operational.

Comparison of PGC and Curtailment Turbine Bat Fatalities

The average temperature (Figure 7), average wind speed (Figure 8), and percent of night when wind speed was <6.5 m/s (Figure 9) were similar between the PGC and curtailed turbines, suggesting no inherent environmental differences between the two groups of turbines that might have influenced our comparison of bat fatalities. However, while the average proportion of density weighted area in the easy visibility class was not significantly different between the two

Figure 4. Number of fresh bat fatalities (n = 32 total) found at each turbine for each of three operational treatments (cut-in speed changed to 5.0 m/s [C5], cut-in at 6.5 m/s [C6], and fully operational [F]) for 12 turbines at the Casselman Wind Project in Somerset County, Pennsylvania, 27 July to 9 October 2008.

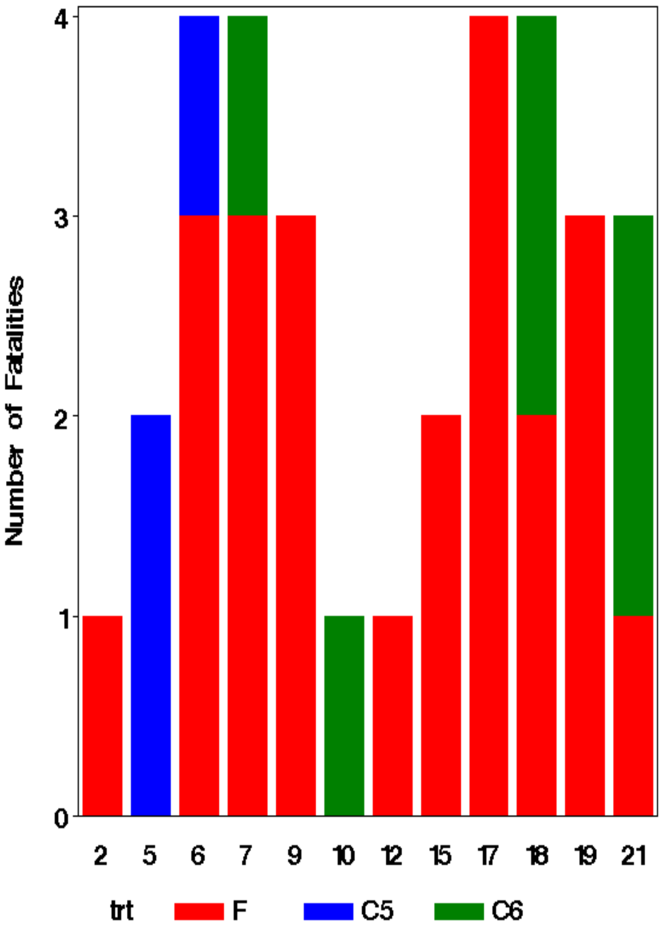
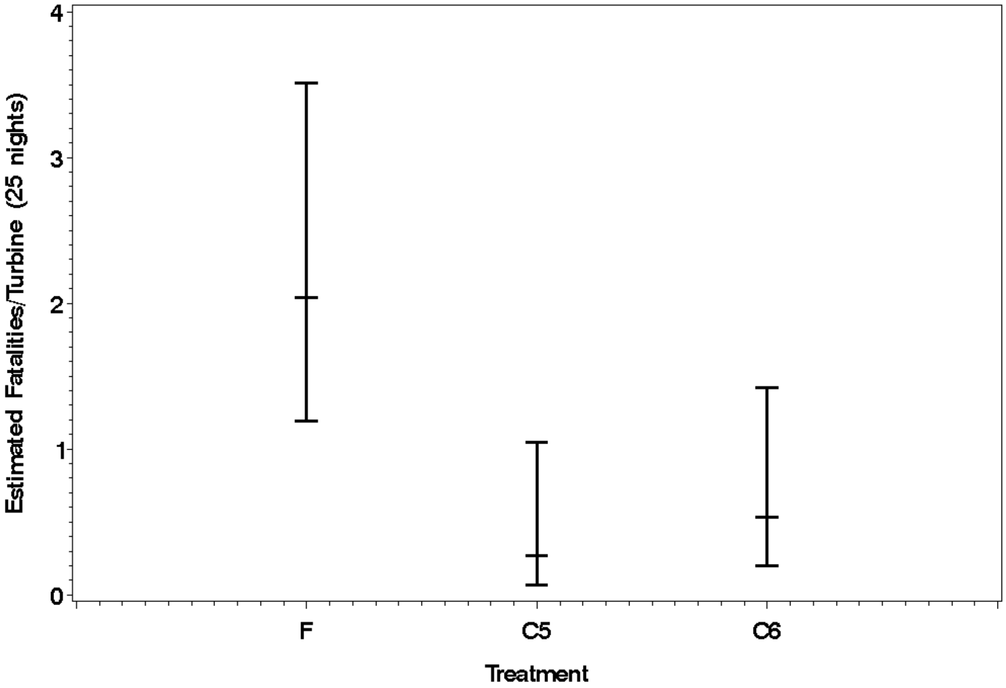


Figure 5. Estimated number of fresh bat fatalities per turbine, and 95% confidence intervals, over 25 nights for each of three treatments (cut-in speed changed to 5.0 m/s, cut-in at 6.5 m/s, and fully operational [none]) for 12 turbines at the Casselman Wind Project in Somerset County, Pennsylvania, 27 July to 9 October 2008 (a) and 26 July to 8 October 2009 (b).

a)



b)

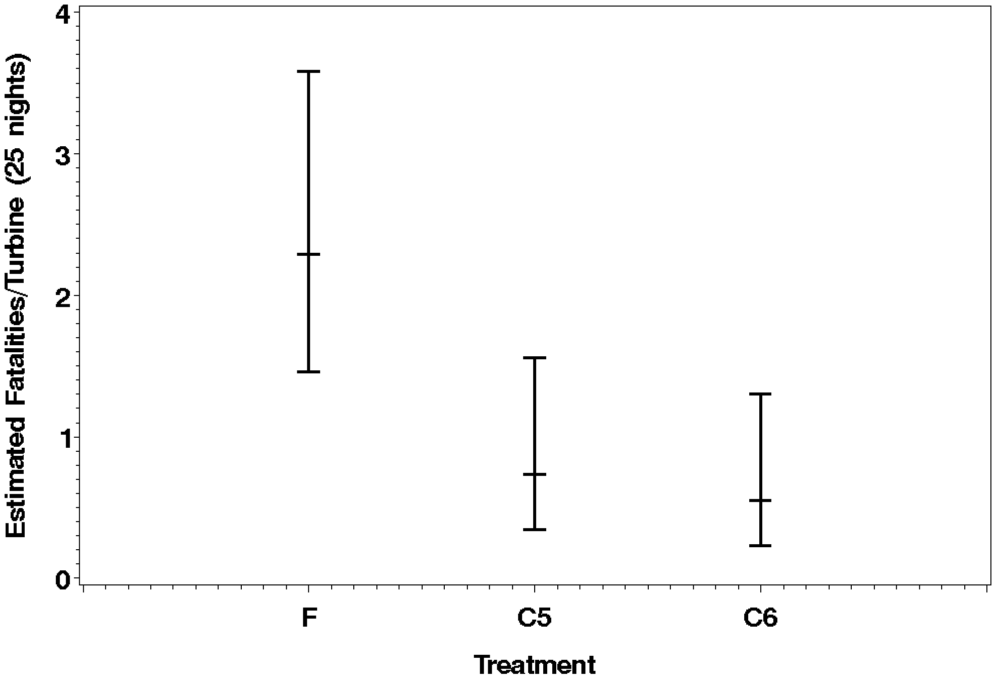


Figure 6. Number of fresh bat fatalities (n = 39 total) found at each turbine for each of three operational treatments (cut-in speed changed to 5.0 m/s [C5], cut-in at 6.5 m/s [C6], and fully operational [F]) for 12 turbines at the Casselman Wind Project in Somerset County, Pennsylvania, 26 July to 8 October 2009.

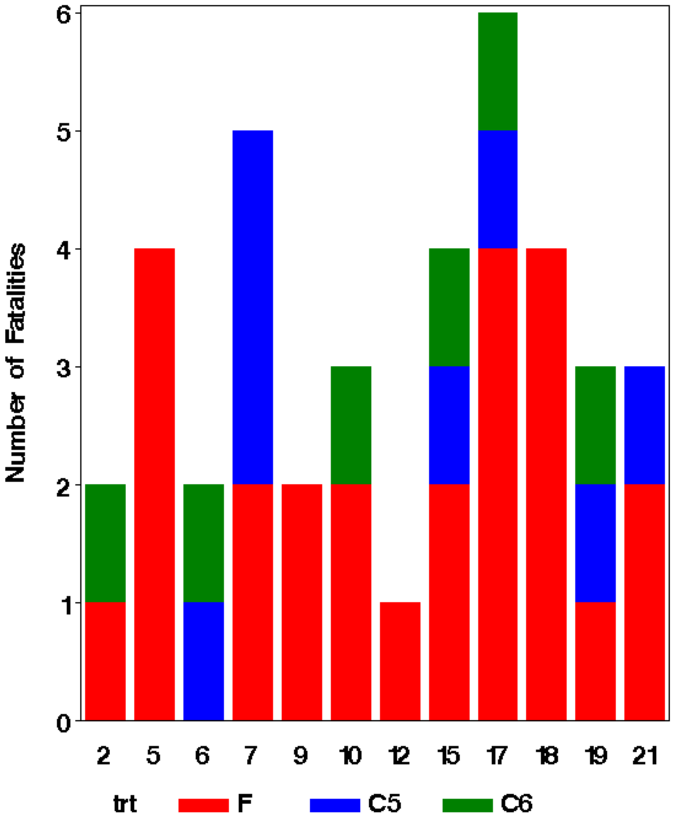
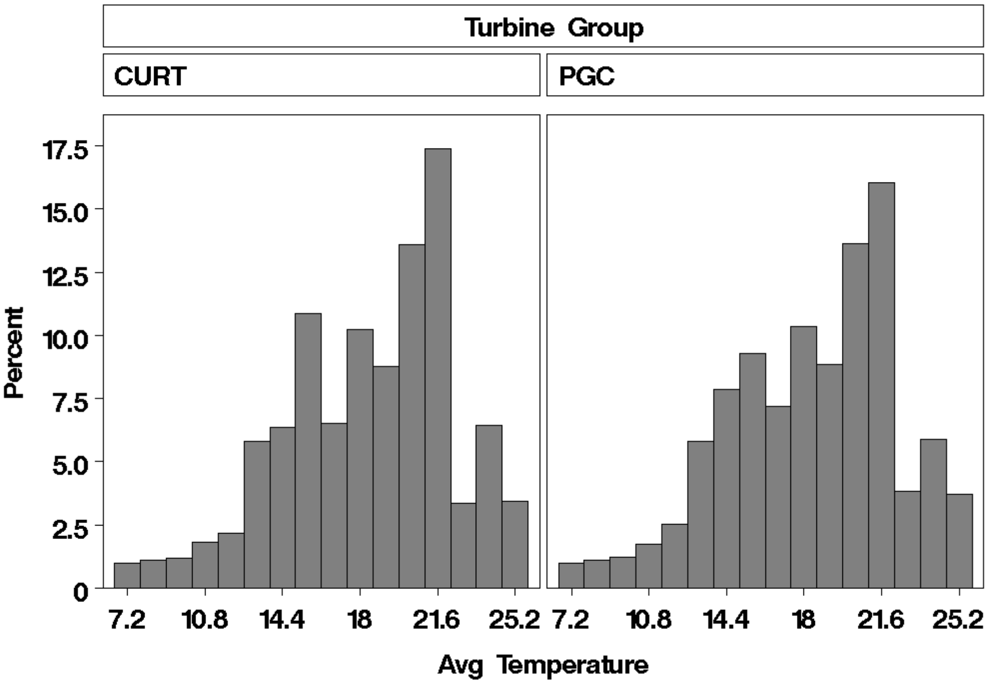


Figure 7. Histograms of the percent of survey nights and average temperature (C) for 10 turbines surveyed as part of the Pennsylvania Game Commission cooperative agreement (PGC; n = 10) and experimentally curtailed turbines (CURT; n = 12) from 27 July to 9 October 2008 (a) and 26 July to 8 October 2009 (b) at the Casselman Wind Project facility in Somerset County, Pennsylvania.

a)



b)

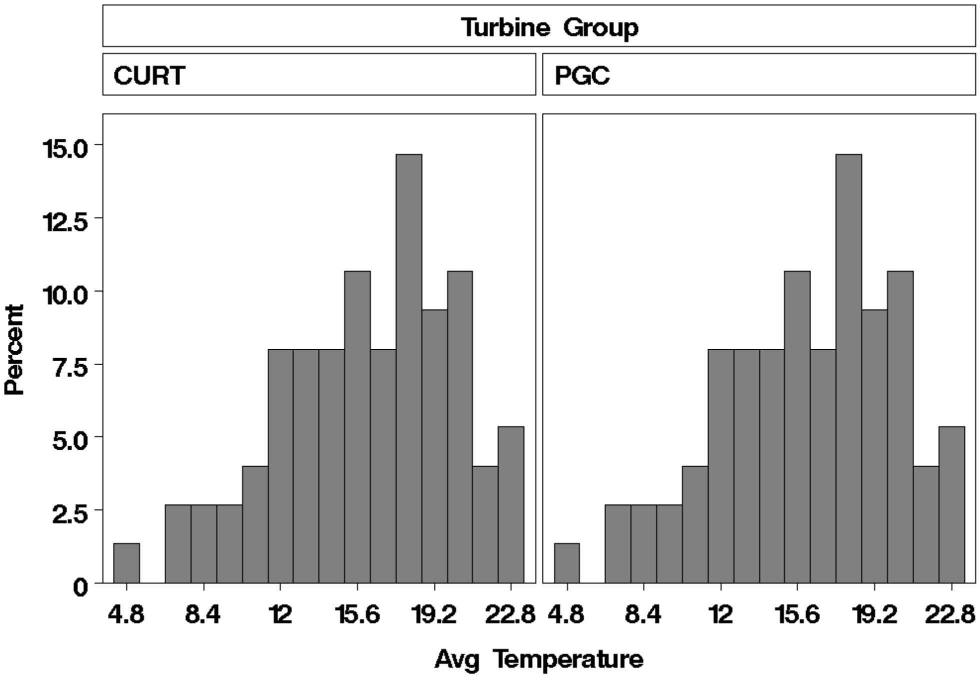
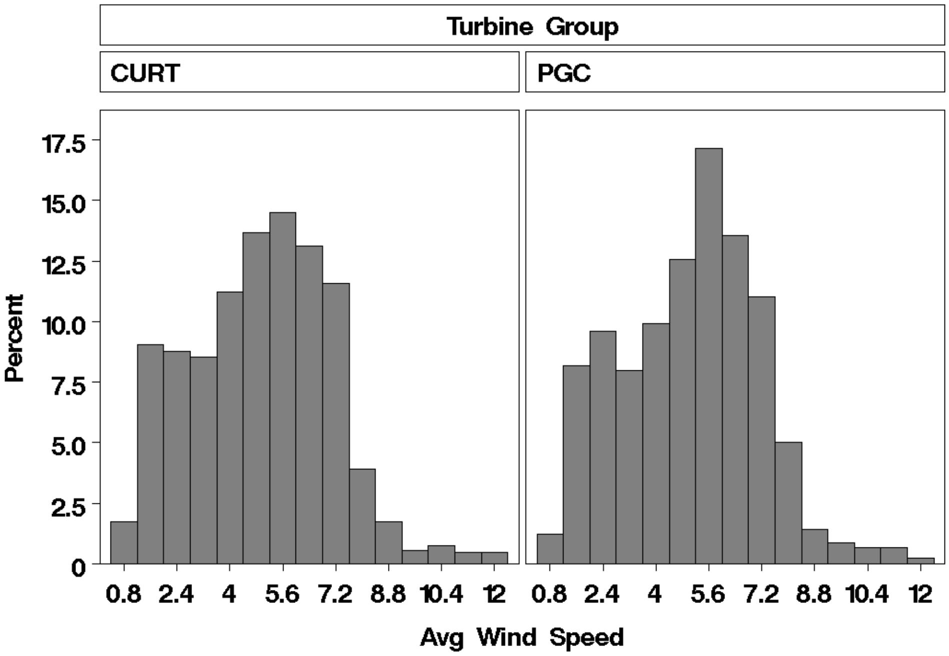


Figure 8. Histograms of the percent of survey nights and average wind speed (m/s) for 10 turbines surveyed as part of the Pennsylvania Game Commission cooperative agreement (PGC; n = 10) and experimentally curtailed turbines (CURT; n = 12) from 27 July to 9 October 2008 (a) and 26 July to 8 October 2009 (b) at the Casselman Wind Project facility in Somerset County, Pennsylvania.

a)



b)

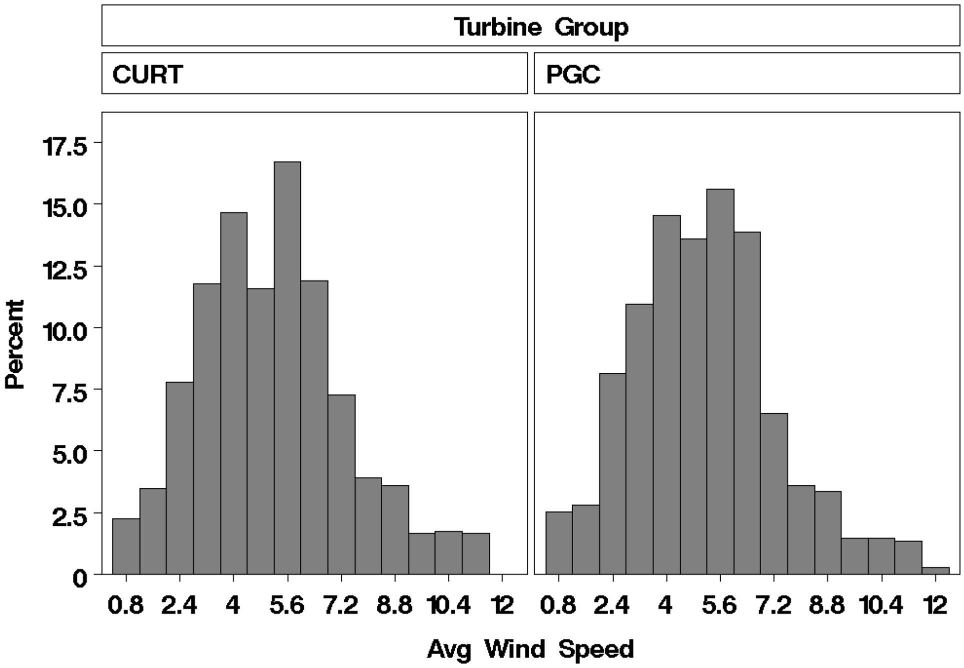
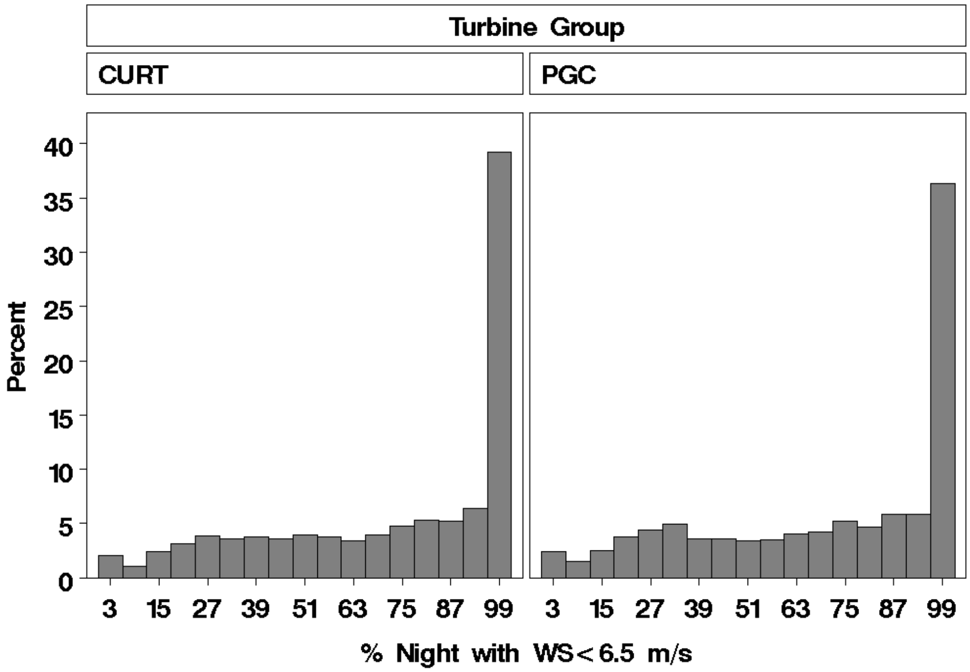


Figure 9. Histograms of the percent of survey nights and percent of night when wind speed was < 6.5 m/s for 10 turbines surveyed as part of the Pennsylvania Game Commission cooperative agreement (PGC; n = 10) and experimentally curtailed turbines (CURT; n = 12) from 27 July to 9 October 2008 (a) and 26 July to 8 October 2009 (b) at the Casselman Wind Project facility in Somerset County, Pennsylvania.

a)



b)

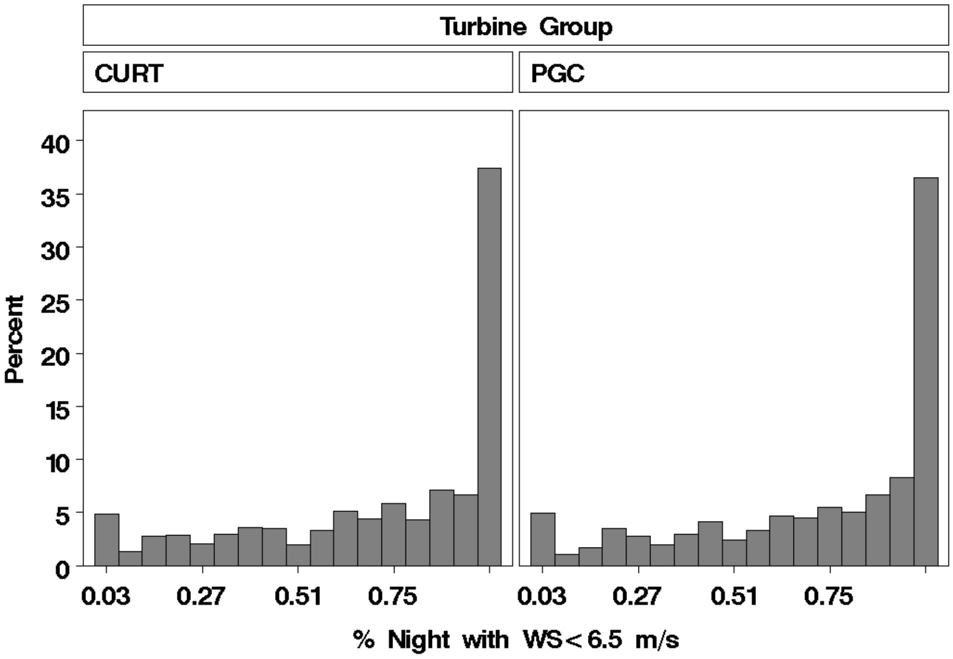
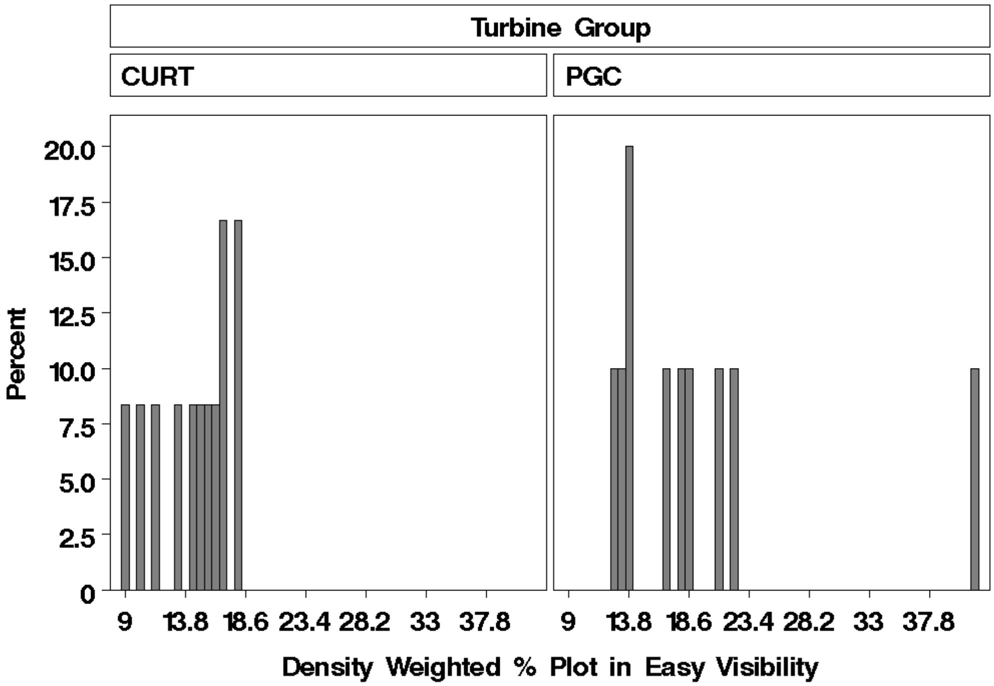
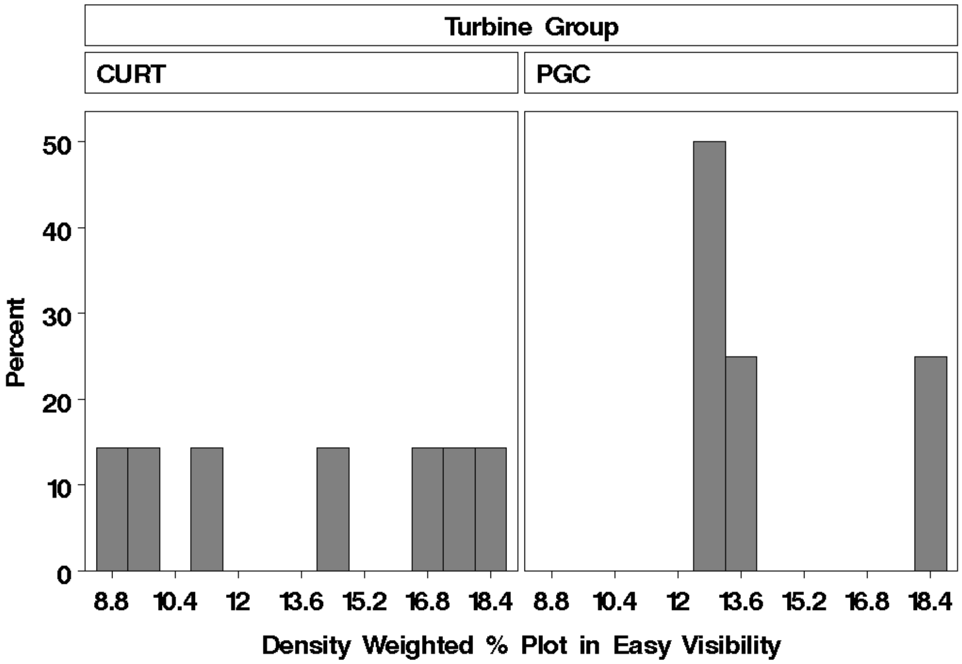


Figure 10. Histograms of the density weighted percent of plots in easy visibility habitat for 10 turbines surveyed as part of the Pennsylvania Game Commission cooperative agreement (PGC; n = 10) and experimentally curtailed turbines (CURT; n = 12) from 27 July to 9 October 2008 (a) and 26 July to 8 October 2009 (b) at the Casselman Wind Project facility in Somerset County, Pennsylvania.

a)



b)



turbine groups (Satterthwaite t-test with unequal variances, $t_{10.9} = -1.64$, p = 0.129), one PGC turbine had about 40% in the easy class when all others in the PGC and the curtailment group were ~20% or less (Figure 10). This turbine (PGC #20) could bias fatality numbers for the PGC group because carcasses at this turbine would be easier to find than at other turbines. When this turbine was omitted from the analysis, the average percent of the density weighted area in the easy visibility class was 16.7% (95% CI: 13.9, 19.5) for PGC turbines and 14.5% (95% CI: 12.5, 16.4) for curtailed turbines. Without turbine 20, there was no evidence that the average fraction of the density weighted area actually searched differed between the two groups ($t_{19} = 0.48$, p = 0.640).

Field Bias Trials. Data from 70 searcher efficiency trials for randomly placed carcasses were fit to a logistic regression model and searcher efficiency differed significantly among the visibility classes ($\chi^2_2 = 25.8$, p = 0.0001). All 30 carcasses in the 'easy' class that persisted long enough to be observed were found by searchers, while 17 of the 24 carcasses in the 'moderate' class that persisted long enough to be observed were found. Only 2 of 16 carcasses that persisted more than 1 week in the 'difficult' class were found. Data from 114 scavenger removal trials for carcasses were fit to an interval-censored parametric failure time model. Using alpha = 0.15, average carcass persistence time was not found to differ among visibility classes ($\chi^2_2 = 1.778$, *p* = 0.411). Average persistence time was estimated to be 28.19 (95% CI: 16.87, 50.15) days.

Fatality Estimates. The estimated number of bat fatalities per turbine from 27 July through 9 October 2008 was 24.2 (95% CI: 12.4, 58.2) for the PGC turbines and 9.4 (95% CI: 5.1, 24.7) for the curtailed turbines (Table 4). Estimated bat fatalities per turbines were 1.48–5.09 times greater (mean = 2.57) at PGC turbines relative to curtailed turbines in 2008. From 26 July through 8 October 2009, the estimated number of bat fatalities per turbine was 17.4 (95% CI: 11.8, 27.8) for the PGC turbines and 9.9 (95% CI: 6.9, 15.7) for the curtailed turbines (Table 4). Estimated total bat fatalities per turbine were 1.23–2.58 times greater (mean = 1.80) at PGC turbines relative to curtailed turbines in 2009. This analysis provides additional support for our contention that reducing operational hours during low wind periods reduces bat fatalities, but represents a conservative estimate of the actual difference because treatment turbines were fully operational one-third of the time during the study.

Financial Costs of Curtailment

At the end of the experiment, Iberdrola Renewables evaluated how much power loss had occurred by comparing daily output of the curtailed turbines with the output of turbines that were not curtailed. The lost power output resulting from the experiment amounted to approximately 2% of total project output during the 75-day study period for the 12 turbines. Hypothetically, if the experiment had been applied to all 23 turbines at the Casselman site for the study period (½ hour before sunset to ½ hour after sunrise for the 75 days we studied), the 5.0 m/s curtailment used would have resulted in lost output equaling 3% of output during the period and only 0.3 % of total annual output. If the 6.5 m/s curtailment were applied to all 23 turbines during the study period, the lost output would have amounted to 11% of total output for the study period and 1% of total annual output. In addition to the lost power revenues, the company also incurred costs for staff time to set up the processes and controls and to implement the curtailment from the company's offsite 24-hour operations center based in Portland, Oregon.

Table 4. Estimated fatalities (mean and 95% confidence intervals [CI]) per turbine and for the site total, adjusted for searcher efficiency, carcass removal, and area, for PGC (fully operational) and curtailed (CURT; curtailed one-third of study period) from 27 July through 9 October 2008 and 26 July through 8 October 2009 at the Casselman Wind Project in Somerset County, Pennsylvania. We also present the estimated ratio of per turbine fatality at PGC versus Curtailment turbines for the same period.

		2008			**2009**		
	N turbines	**Mean**	**Lower 95% CL**	**Upper 95% CL**	**Mean**	**Lower 95% CL**	**Upper 95% CL**
Per Turbine							
CURT	12	9.4	5.1	24.7	9.9	6.9	15.7
PGC	10	24.2	12.4	58.2	17.4	11.8	27.8
Site total							
CURT	23	216.2	116.9	567.9	229.9	159.6	360.1
PGC	23	555.7	285.8	1338.7	400.6	271.0	639.0
Ratio of PGC:CURT		2.57	1.48	5.09	1.80	1.23	2.58

DISCUSSION

Our findings were consistent with our predictions that bat fatalities would be significantly reduced by changing turbine cut-in speed and reducing the operational hours during low wind periods, and corroborate the only other studies of operational curtailment (Baerwald et al. 2009, O. Behr, University of Erlangen, unpublished data). All three studies of operational curtailment conducted to date indicate that bat fatalities can be reduced by at least 50%.

In the first analysis, our study design differed from other studies in part because we were able to change treatments easily on each night of the study from a centralized, off-site command center, thus allowing the night to be the experimental unit in our analysis. Because we used the turbine as a blocking factor, any differences in searchable area among turbines were contained in the blocking factor. The almost even distribution of fatalities among turbines indicates that there was no strong distinction in fatality among turbines, so detected effects can be reasonably attributed to the treatments. This design is powerful, but also dependent on the correct determination of fresh carcasses and assumes field classifications are accurate. We do not believe that our misclassification rate was a factor, nor do we have reason to believe that the probability of misclassifying a carcass as fresh is in any way associated with the treatment. Thus, we assume that any error in our classification of fresh bats was equal among turbines and treatments and that it did not greatly influence the results of this study. Our second analysis demonstrated that estimated fatalities were higher at PGC compared to curtailed turbines and further supports our contention that reducing operational hours during low wind periods reduces bat fatalities. These fatality differences likely represent a conservative estimate of the effect of curtailment because the curtailed turbines were fully operational 1/3 of the time during the study.

Higher bat activity (e.g., Arnett et al. 2006, 2007b, Redell et al. 2006, Reynolds 2006, Weller 2007) and fatalities (Arnett et al. 2008) have been consistently related to periods of low wind speed and weather conditions typical of the passage of storm fronts. The casual mechanism underlying this relationship remains unclear, but perhaps migration is less efficient for bats in high wind speeds and thus migratory movement by these species is reduced (Baerwald et al. 2009). Cryan and Brown (2007) reported that fall arrivals of hoary bats on Southeast Farallon Island were related to periods of low wind speed, dark phases of the moon, and low barometric pressure, supporting the view that migration events may be predictable. Low barometric pressure can coincide with passage of cold fronts that may be exploited by migrating birds and bats (Cryan and Brown 2007). Erickson and West (2002) reported that regional climate patterns as well as local weather conditions can be analyzed to predict foraging and migratory activity of bats. On a local scale, strong winds can influence abundance and activity of insects, which in turn influence bat activity. Bats are known to reduce their foraging activity during periods of rain, low temperatures, and strong winds (Erkert 1982, Erickson et al. 2002). Episodic hatches of insects that are likely associated with favorable weather and flight conditions may periodically increase local bat activity (Erickson and West 2002). More studies incorporating daily fatality searches are needed so that patterns such as those described above can be determined at multiple sites across regions. These data will be critical for developing robust predictive models of environmental conditions preceding fatality events, and for predicting when operational curtailment will be most effective to reduce bat fatalities.

Numerous factors influence power loss and, thus, financial costs of changing cut-in speed of wind turbines to reduce bat fatalities. These include, but are not limited to, the type and size of wind turbines and computer hardware used, market or contract prices of power, power purchase agreements and associated fines for violating delivery of power, and variation in temporal consistency, speed and duration of wind across different sites. Wind speeds in the Mid-Atlantic Highlands region are typically lowest in late summer and early fall (S. McDonald, Iberdrola Renewables, unpublished data). Power loss during our experiment was considerably different from that reported by Baerwald et al. (2009) primarily because we curtailed turbines only at night when bats are flying and because of different market pricing for electricity between the two study sites. Technological limitations of the Vestas V80 turbines studied by Baerwald et al. (2009) forced them to change the cut-in speed for the entire duration of the study, 24 hours a day. Baerwald et al. (2009) noted that if the operational parameters could have been changed only when bats were active at night, then costs would have been even less for their study. The loss in power production resulting from our experimental treatments was surprisingly low when considering the full annual productivity lost, but power loss was 3 times higher for the 6.5 m/s change in cut-in speed compared to the 5.0 m/s treatment. This reflects the cubic effect of wind speed and power produced (Albadi and El-Saadany 2009). Our analysis was not able to detect any significant difference in fatalities between these two changes in cut-in speed during either year of the study. Further research at other sites is needed to determine whether lower changes in cut-in speed can provide similar biological effects to higher cut-in speeds but with less financial cost. Unfortunately, our understanding of biological impacts is hindered by a lack of knowledge of bat populations (O'Shea et al. 2003) and the impacts of wind energy relative to other sources of mortality. Until populations and associated impacts are quantified, it will be difficult to determine if a 50% reduction in bat fatalities from changing turbine cut-in speed over time is adequate to mitigate impacts or whether it simply delays inevitable population-level impacts. We believe that gathering information on populations is important and fundamental to truly evaluating biological impacts, but these data are not expected to be available for most species of bats in the near future and we contend that wind operators should implement curtailment at sites where bat fatalities are high and warrant mitigation even in the absence of population data.

Our study is the first U.S.-based experiment of changing cut-in speed to reduce bat fatalities, and only the third we are aware of anywhere in the world. We demonstrated reductions in average nightly bat fatality ranging from 44 to 93% with marginal annual power loss; Baerwald et al. (2009) demonstrated a 58% reduction in fatalities at curtailed turbines and a third study conducted in Germany demonstrated a 50% reduction in fatalities from curtailed turbines (O. Behr, University of Erlangen, unpublished data). Given the magnitude and extent of bat fatalities worldwide, the conservation implications of our findings and those of Baerwald et al. (2009) are critically important. More research is needed to test changes in turbine cut-in speed among different sizes and types of turbines, wind regimes, and habitat conditions. Nevertheless, we believe changing cut-in speeds to the levels we tested offers an effective mitigation strategy for reducing bat fatalities at wind facilities.

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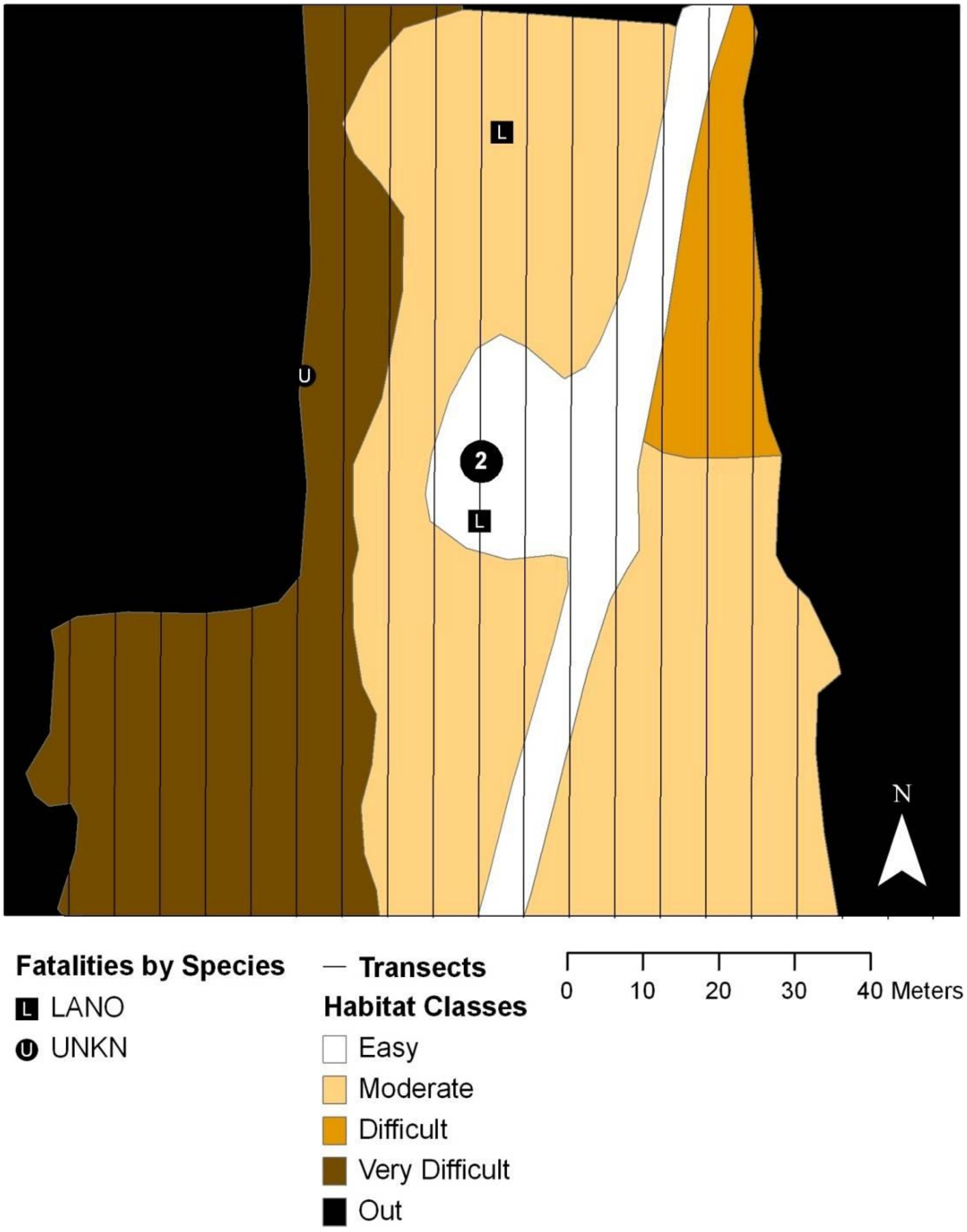
APPENDIX 1
(Turbine Plot Maps)

Table A-1. Species list and 4-letter codes for bats fatalities depicted on maps.

Species	**4-Letter Code**
Big brown bat	EPFU
Eastern red bat	LABO
Hoary bat	LACI
Little brown bat	MYLU
Seminole bat	LASE
Silver-haired bat	LANO
Tri-colored bat	PESU
Unknown bat	UNKN
Unknown myotis	MY- -

2008

Turbine 2



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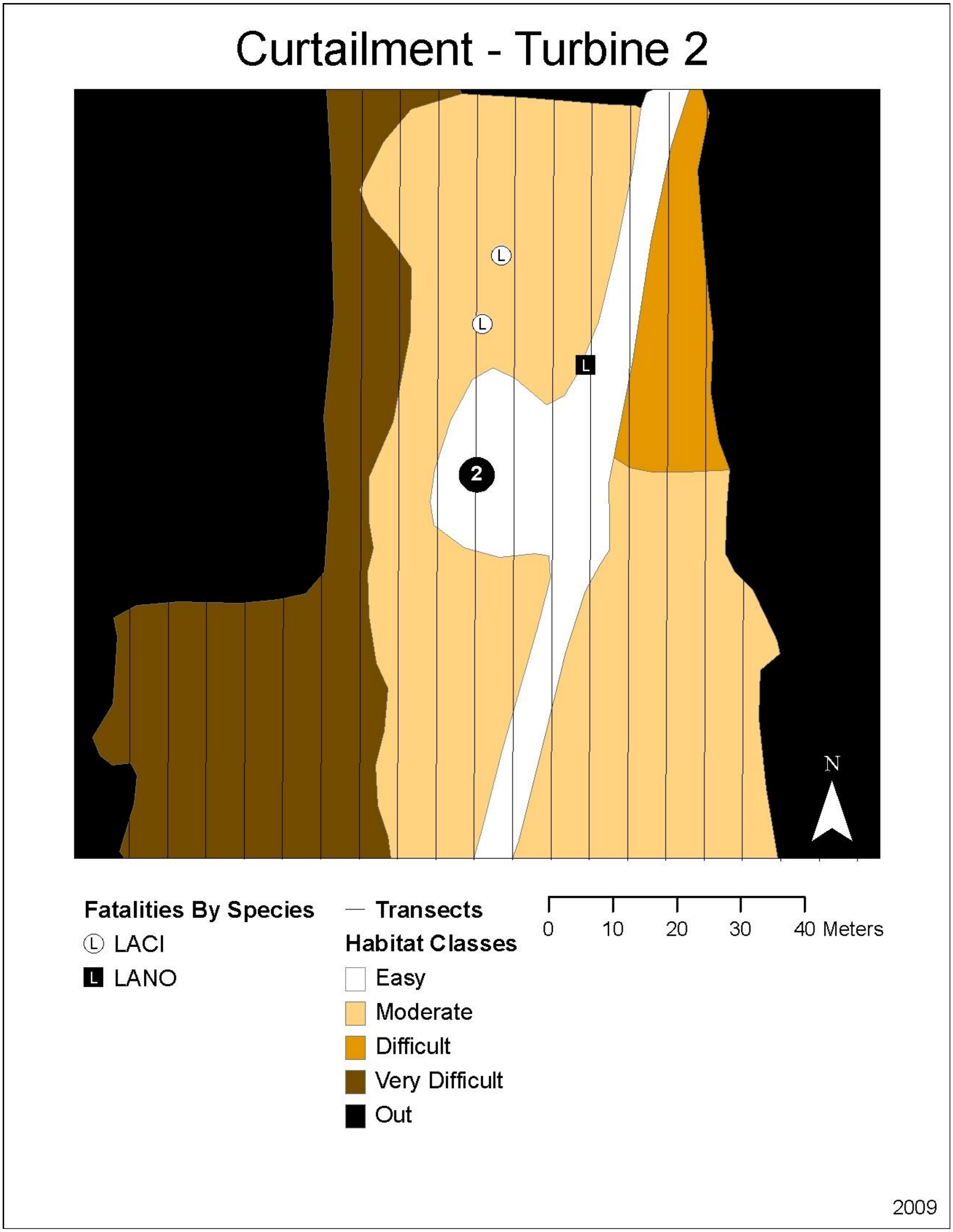

Curtailment - Turbine 2

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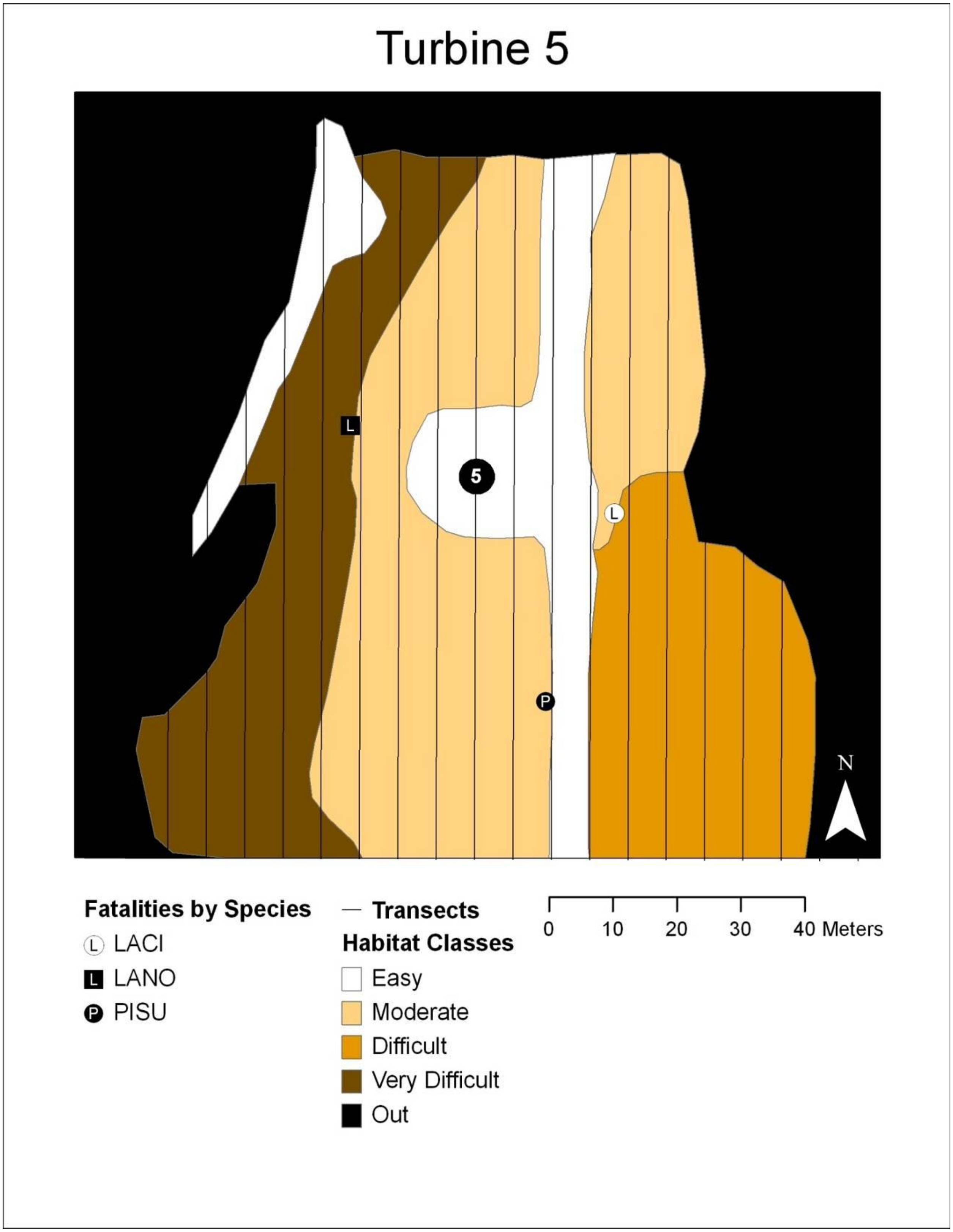
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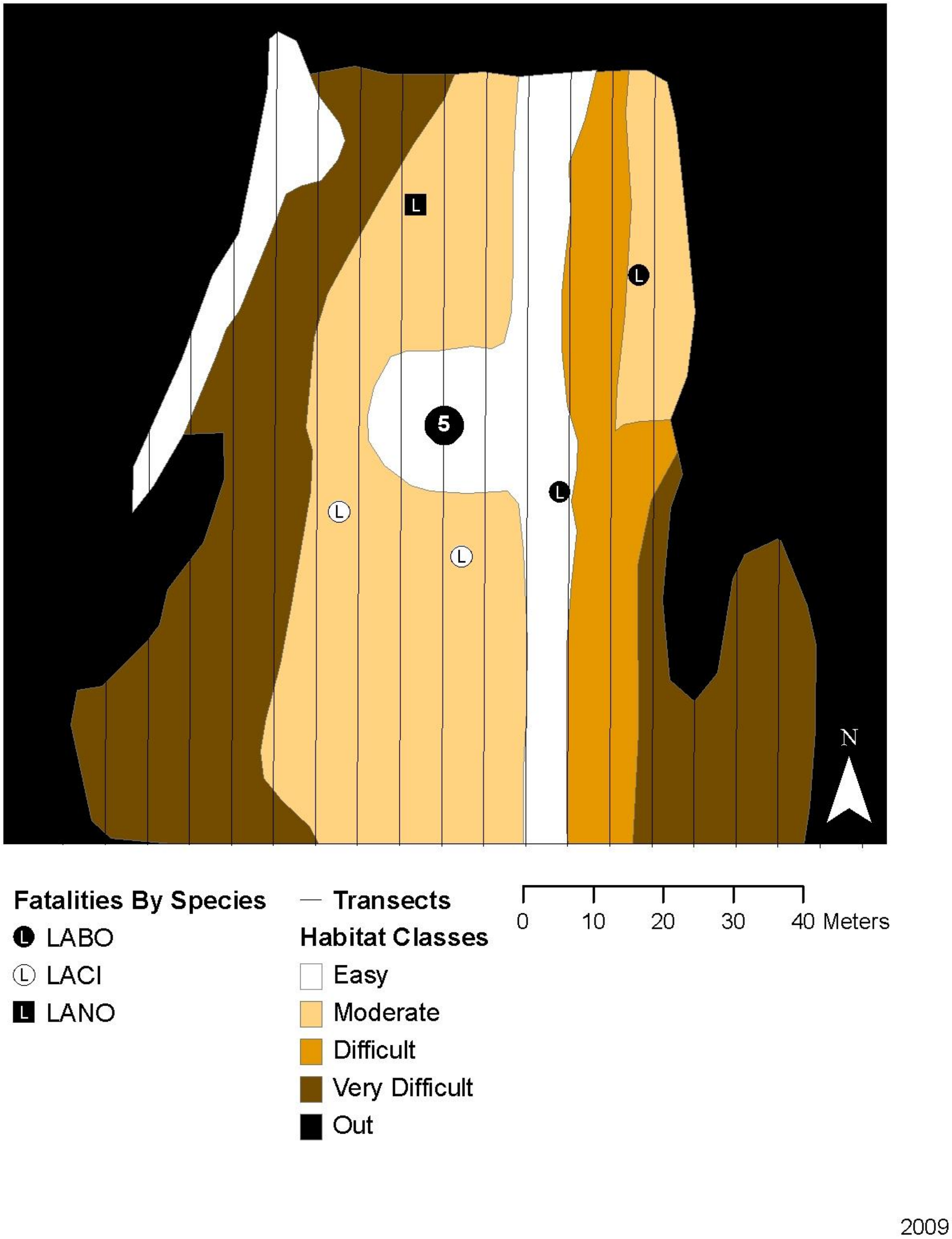

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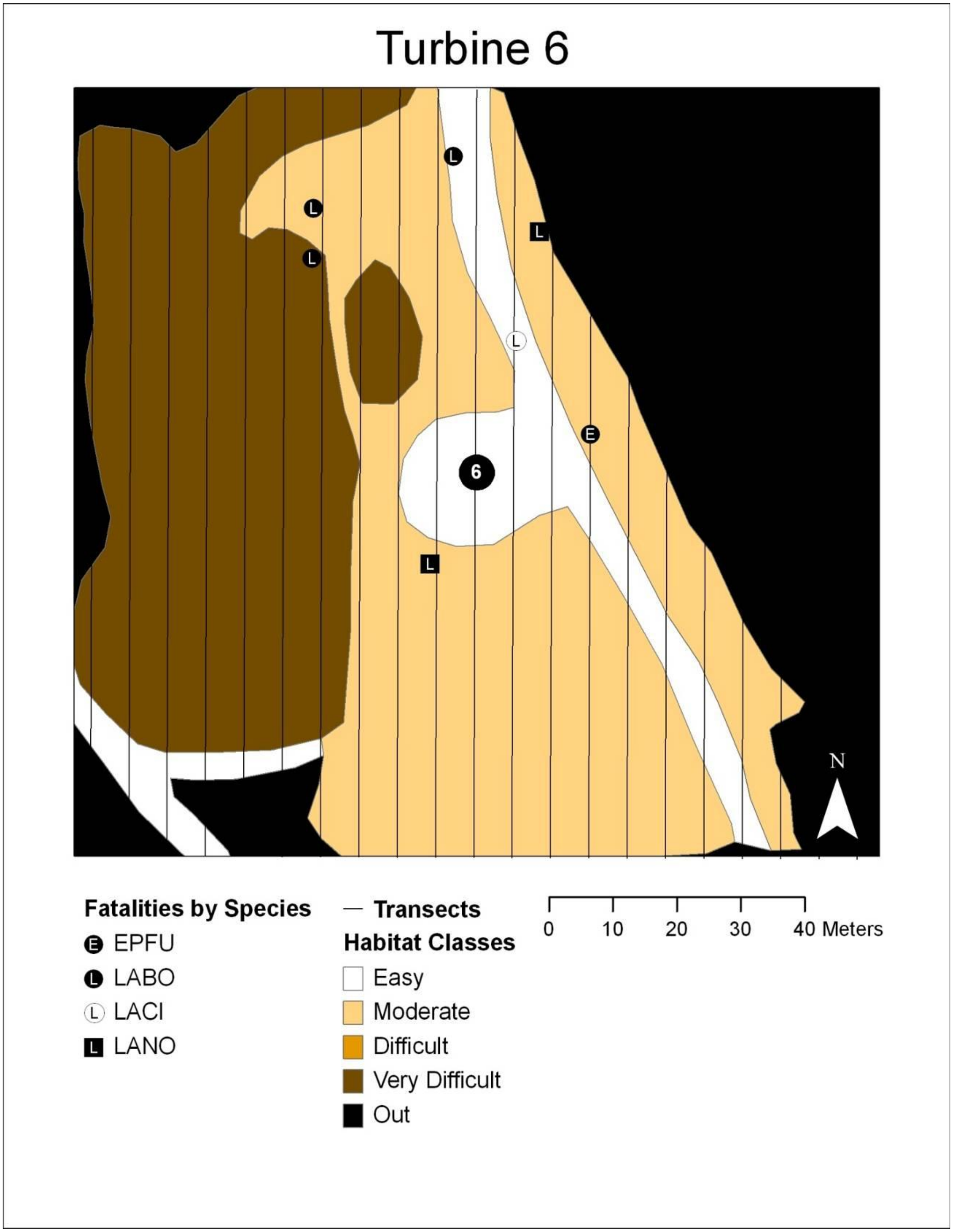

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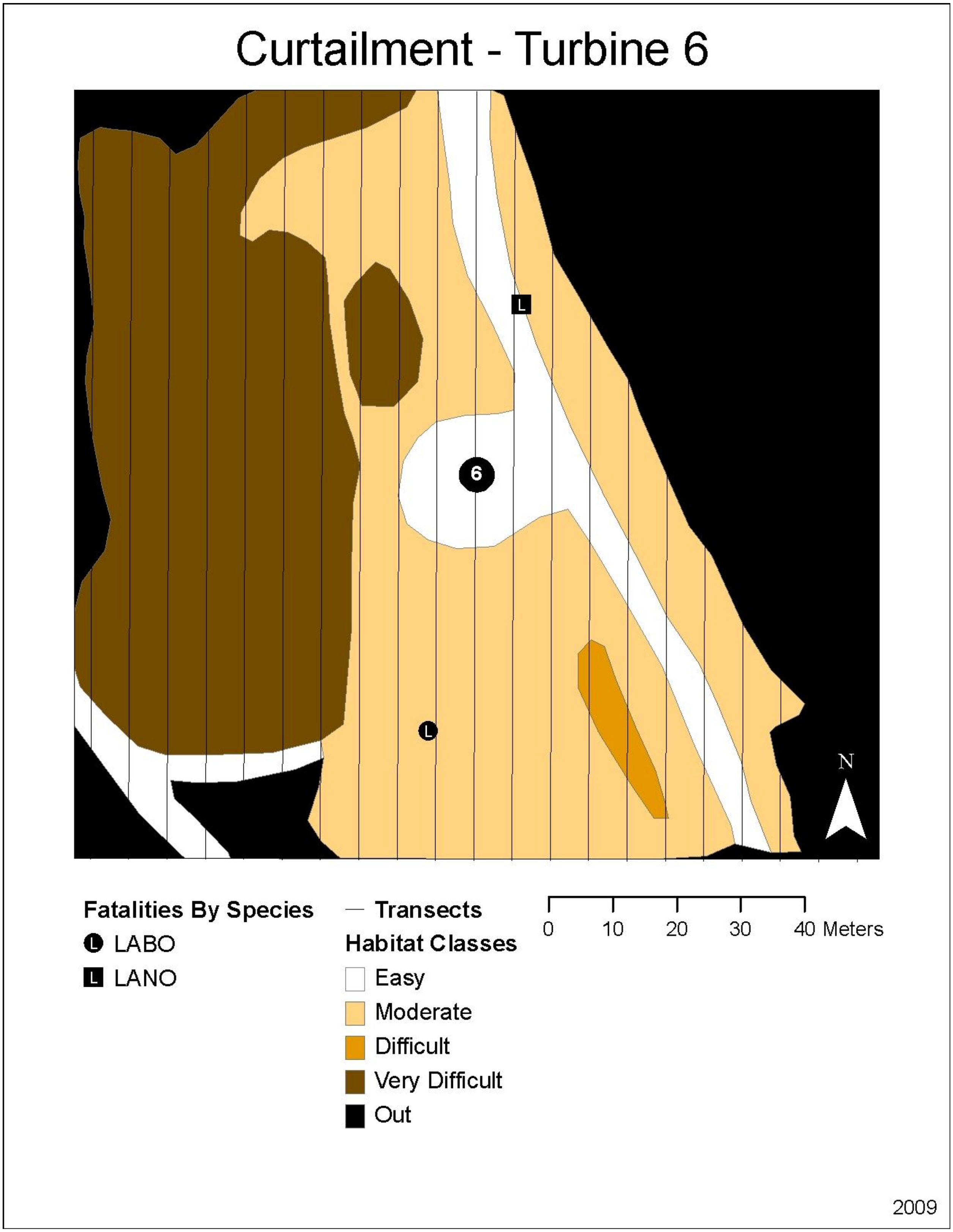
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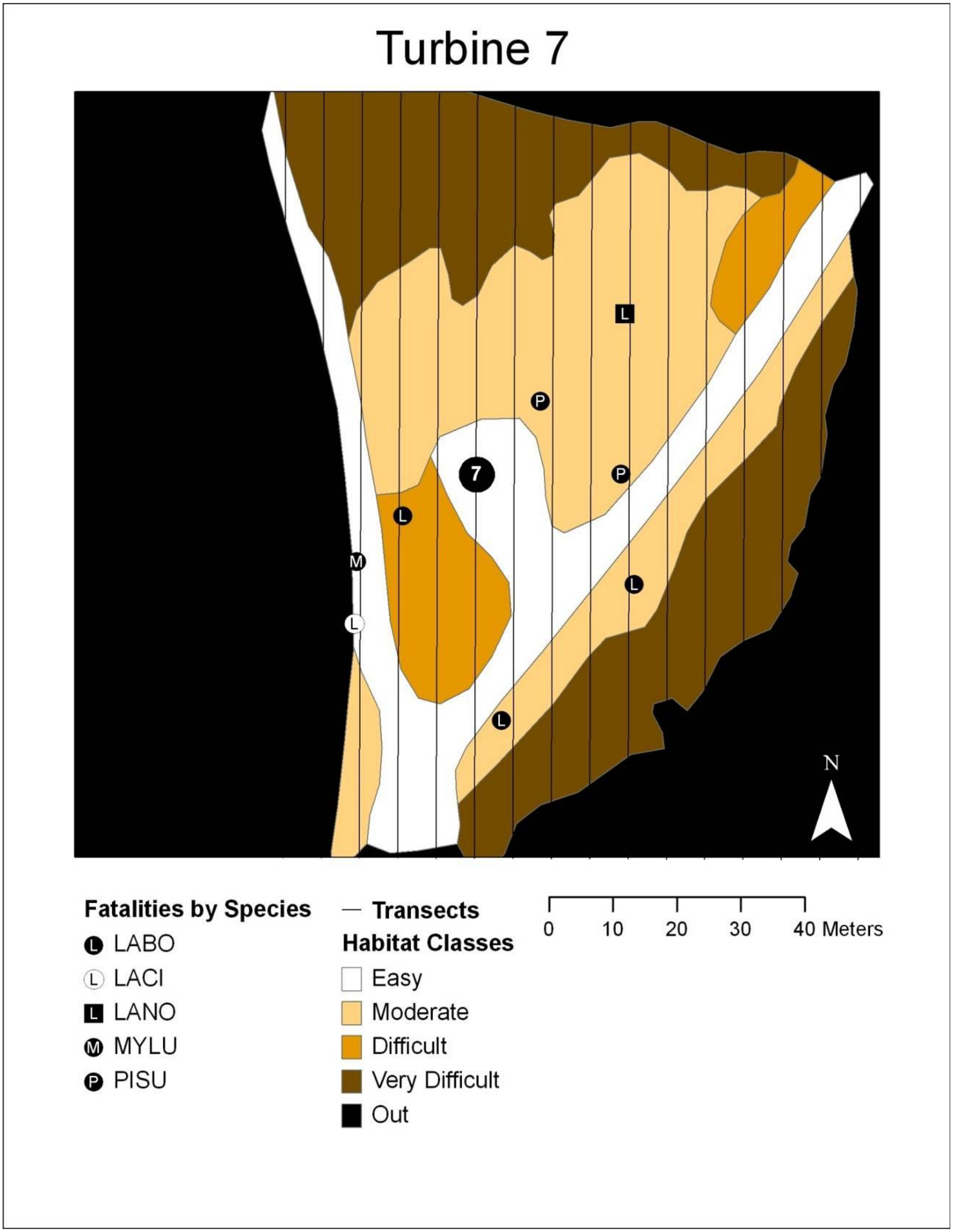
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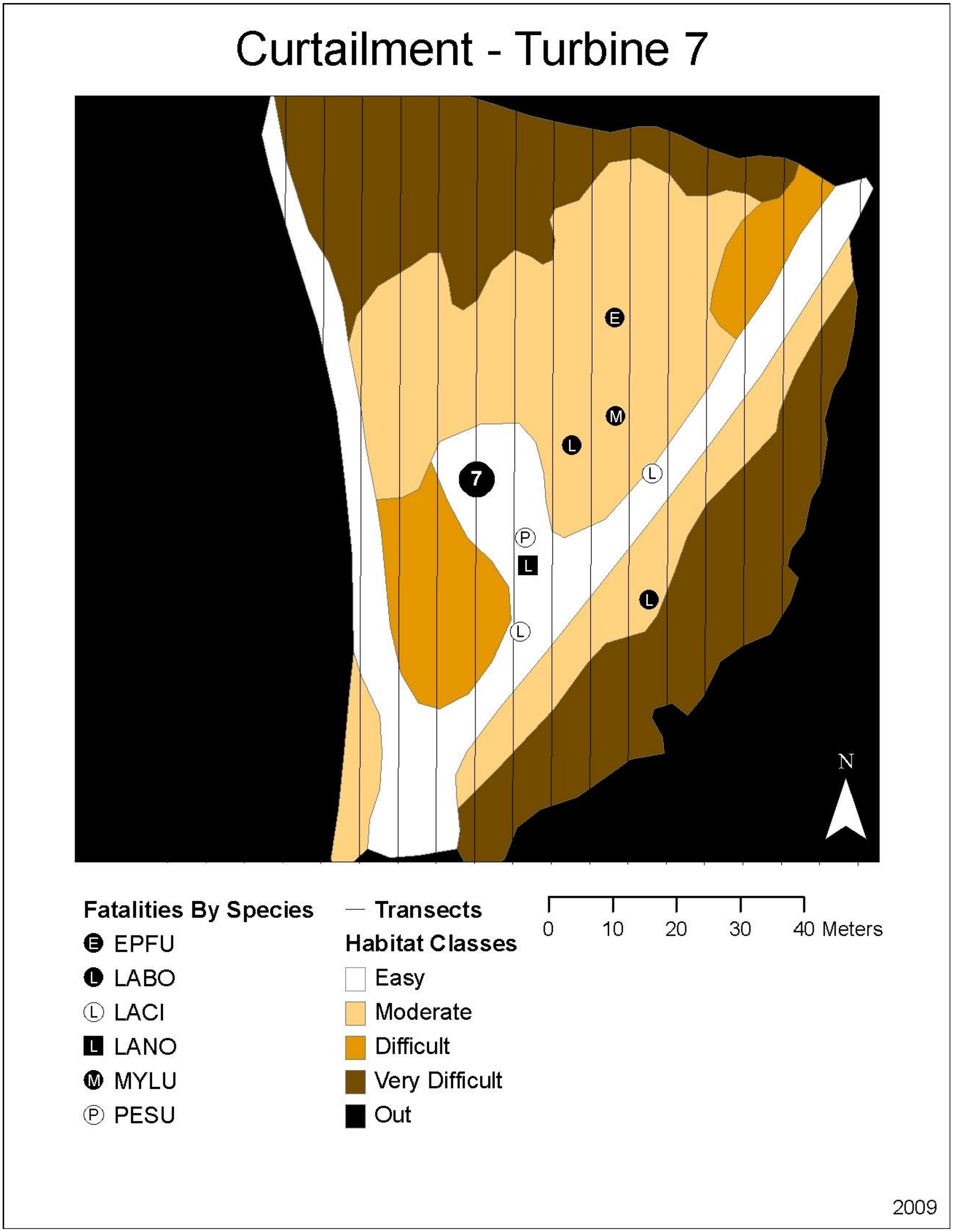
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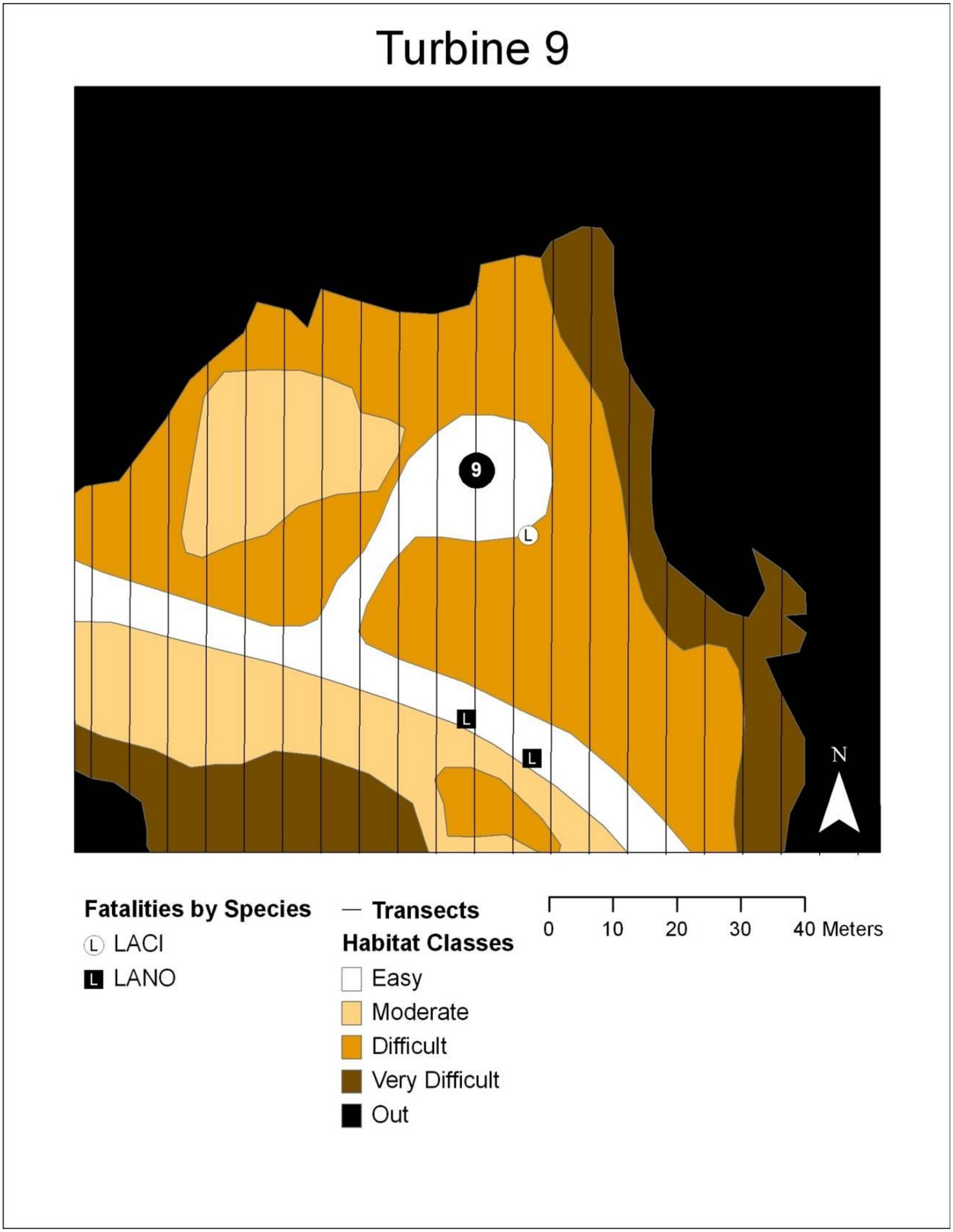
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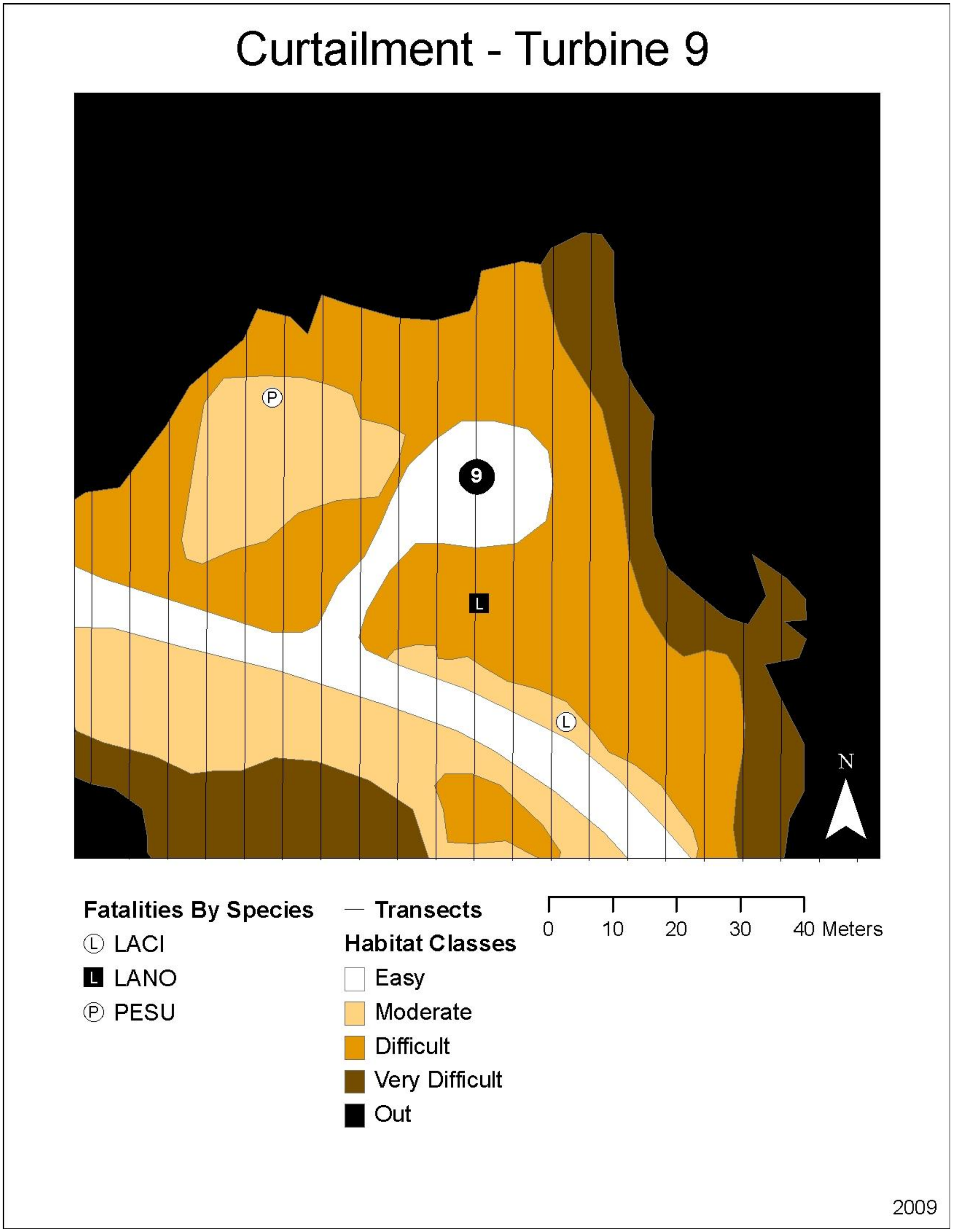

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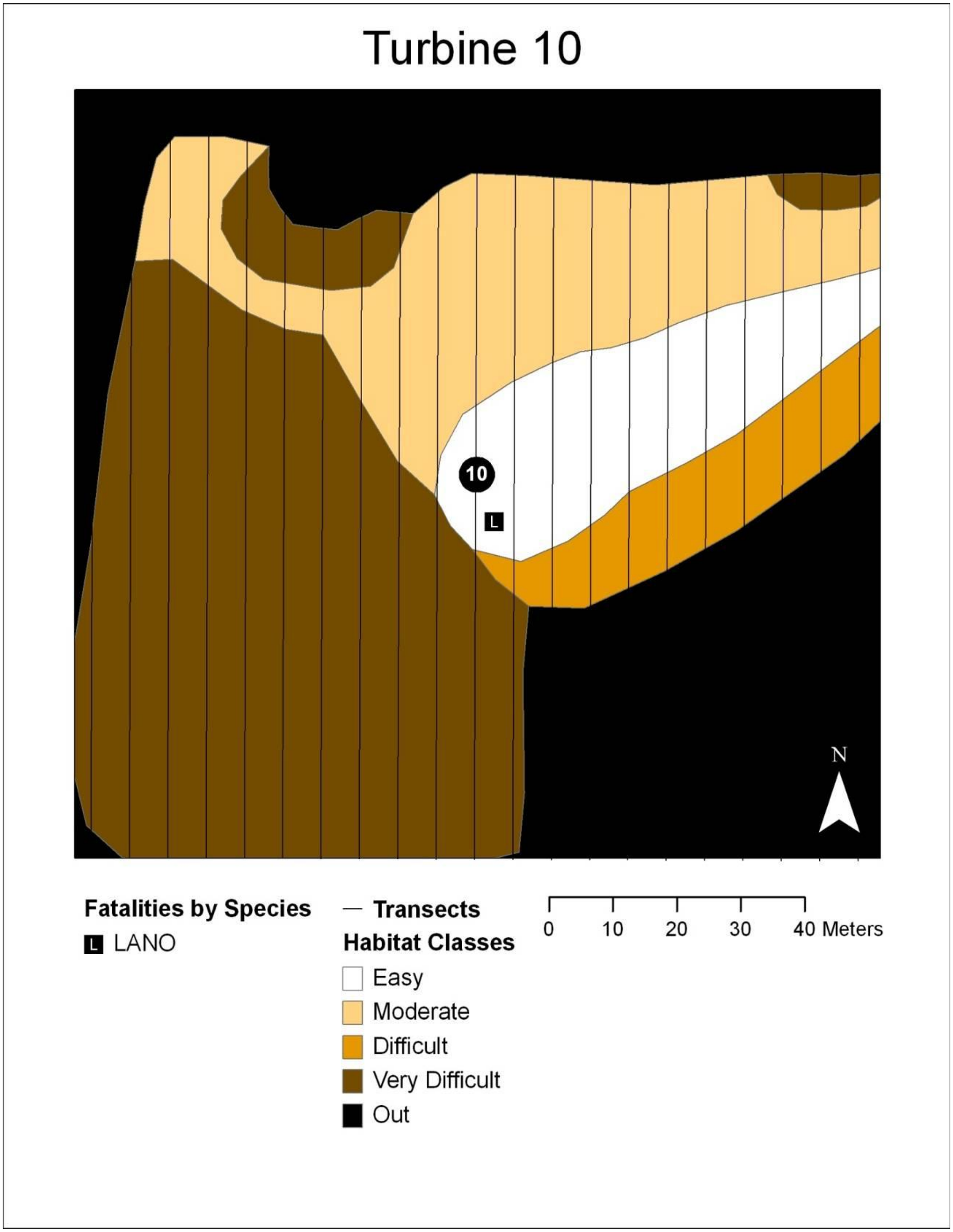
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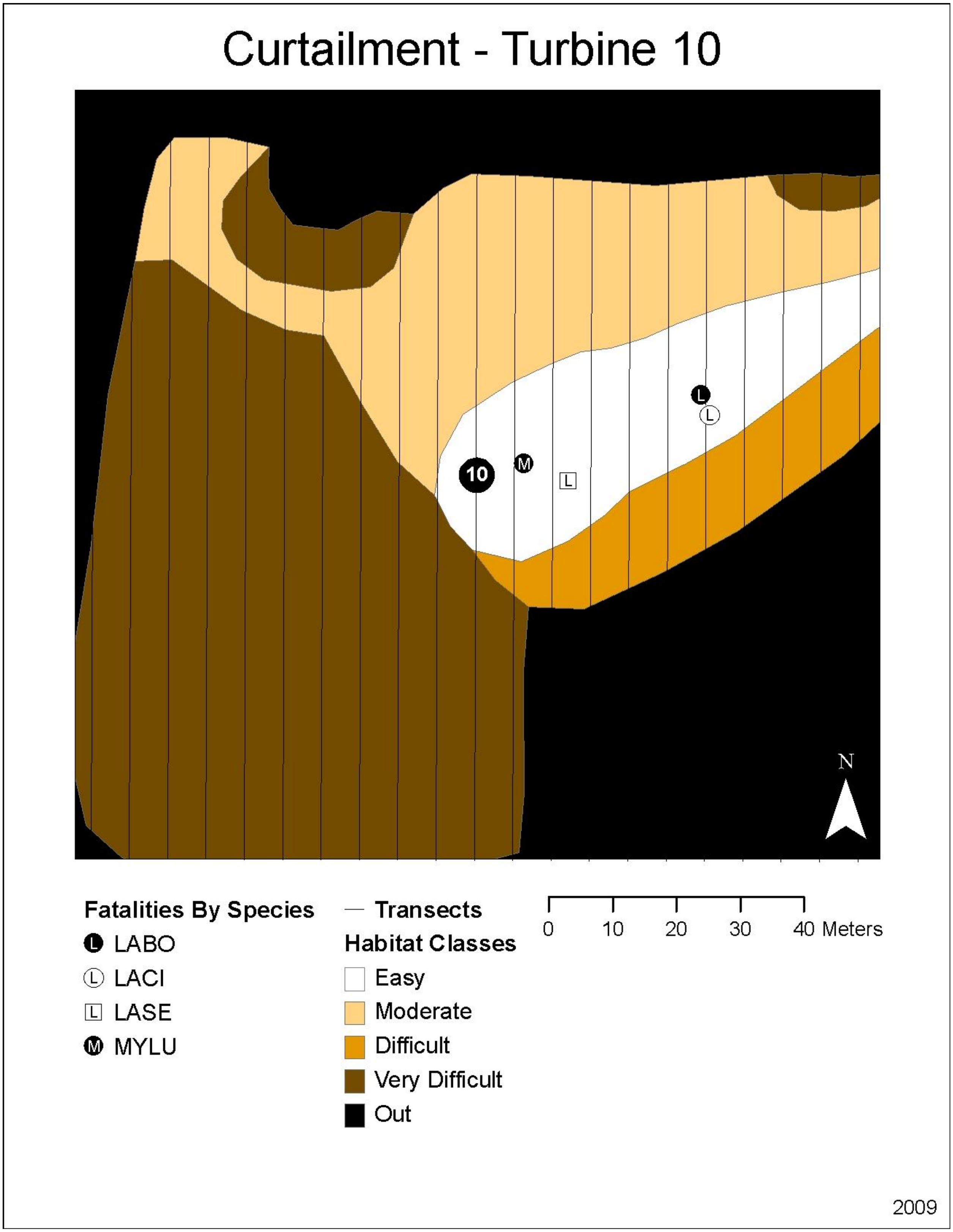
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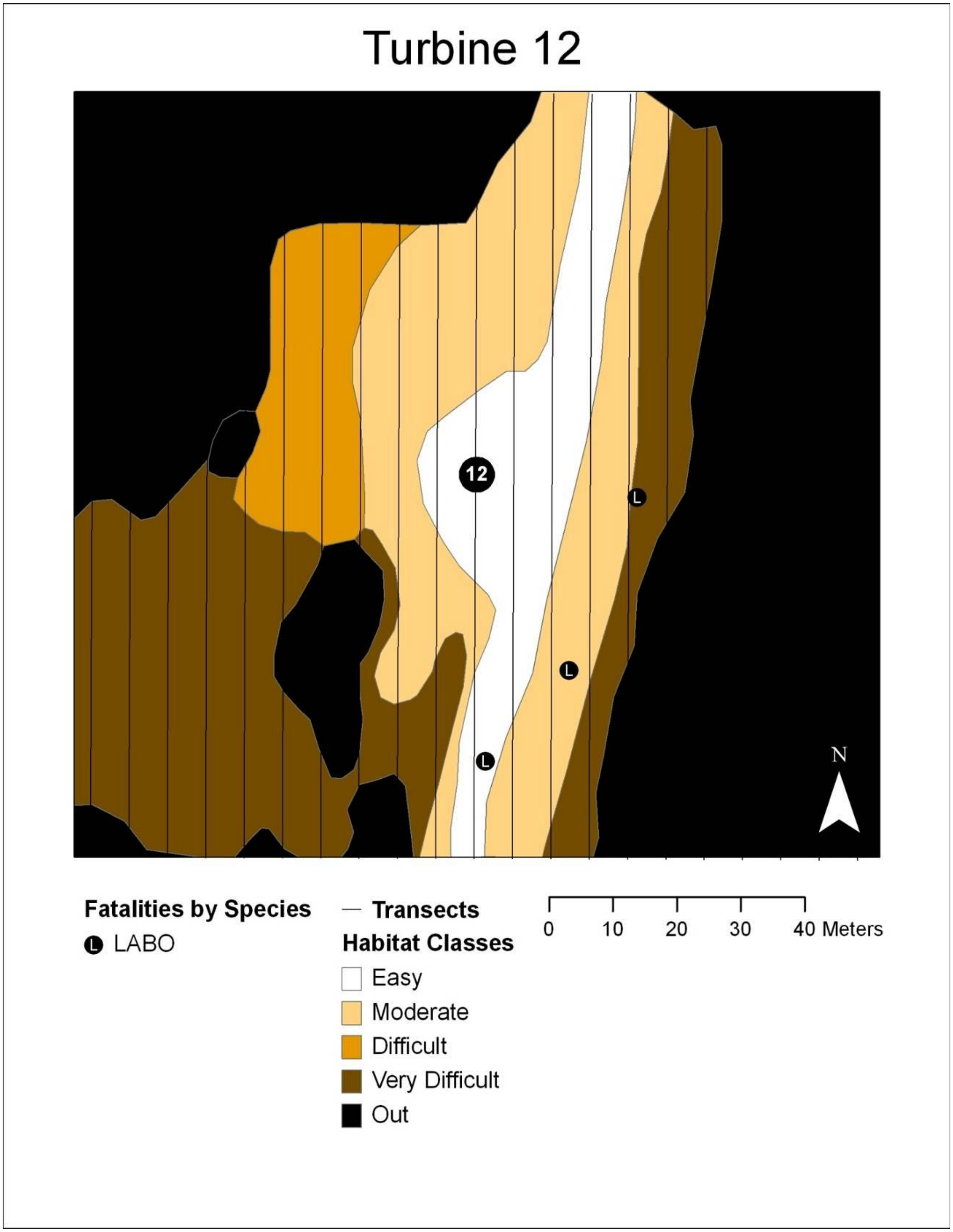
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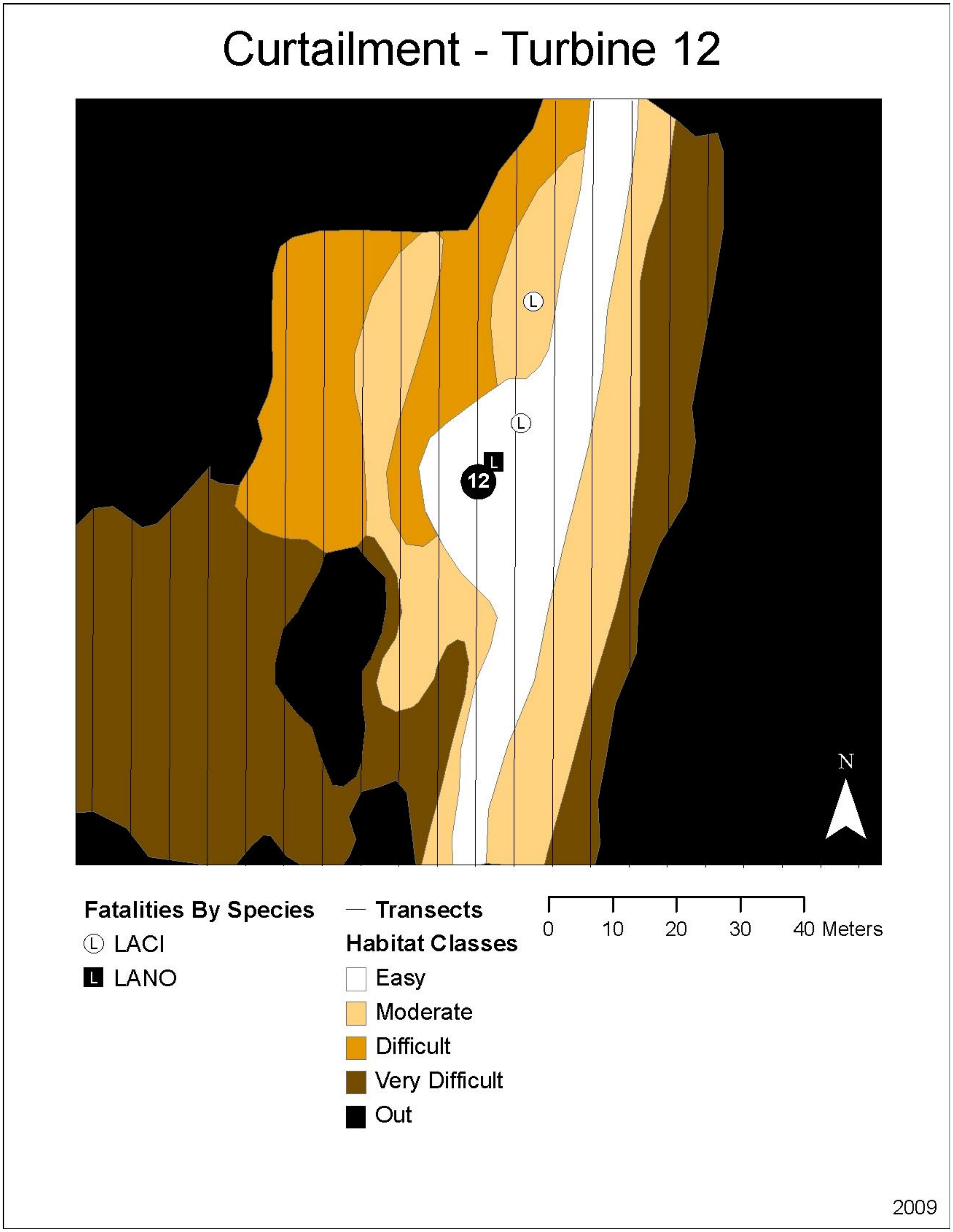
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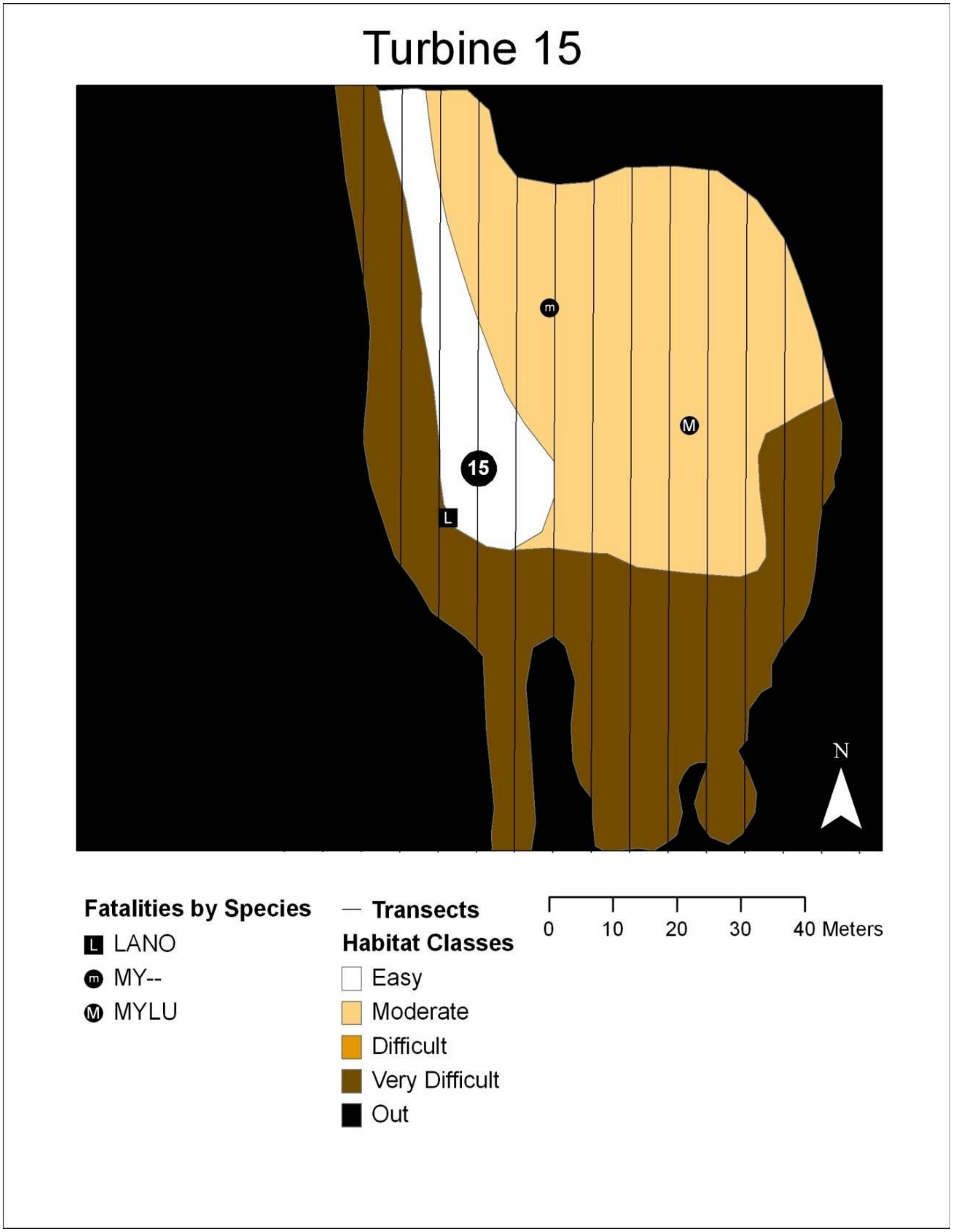
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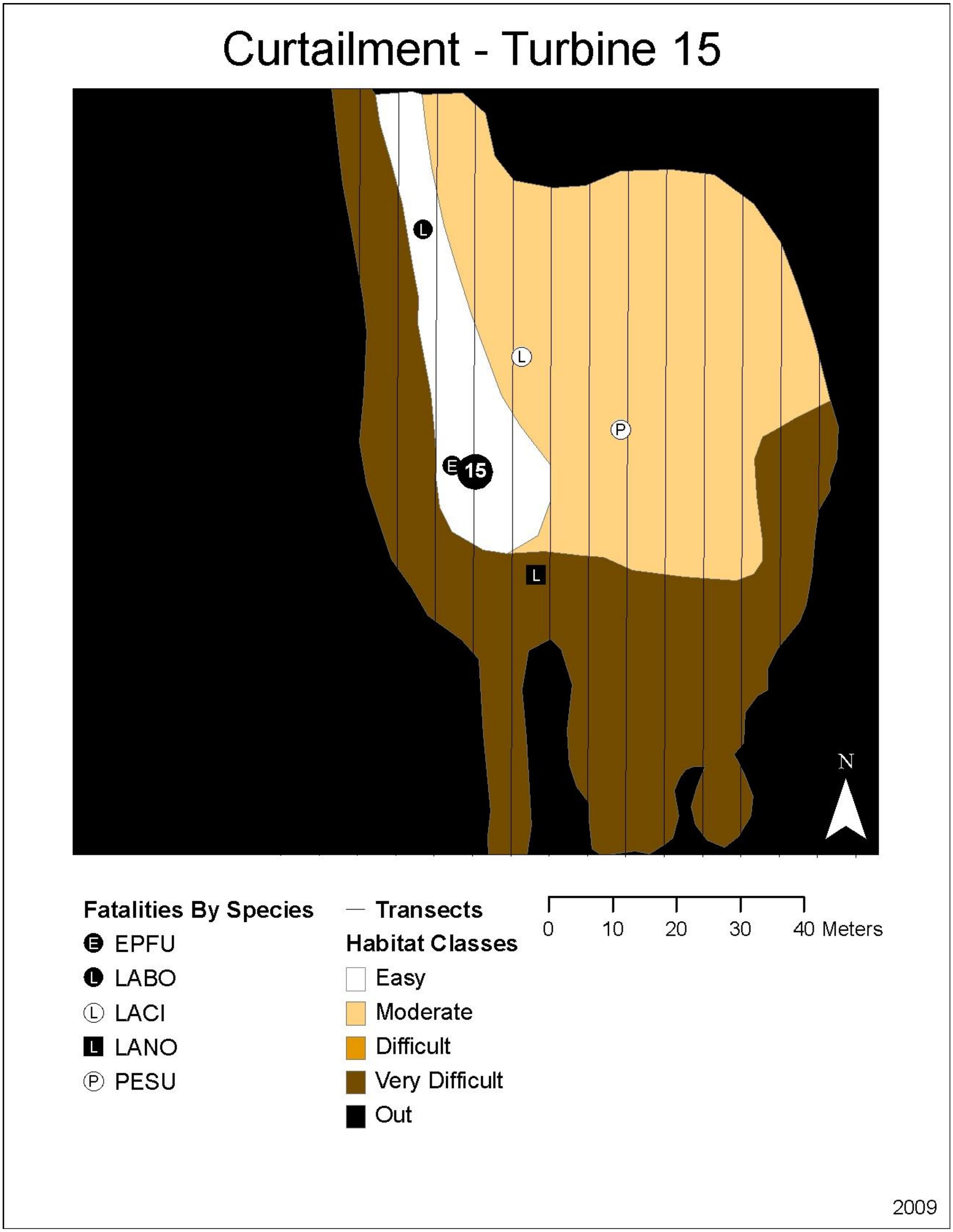
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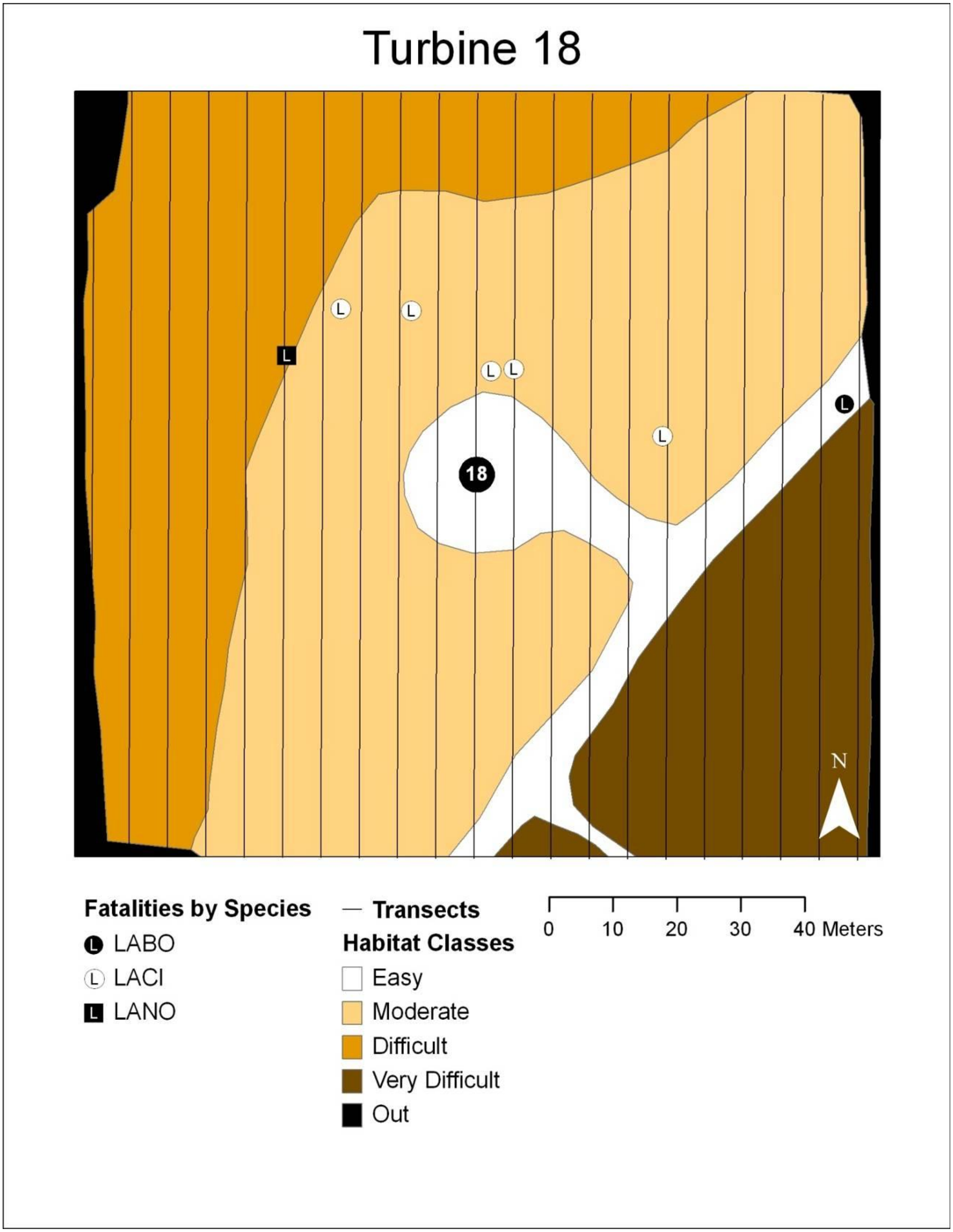
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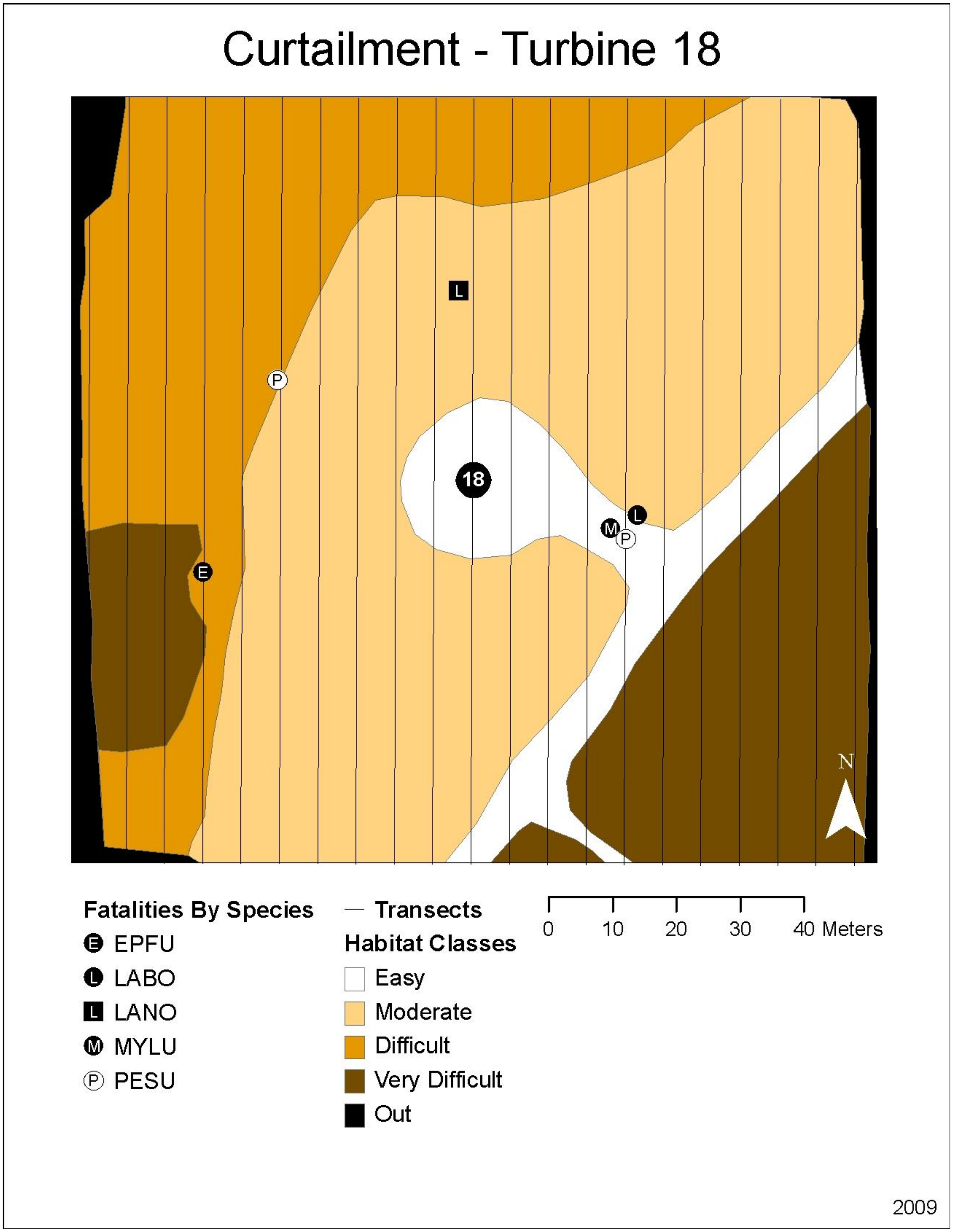
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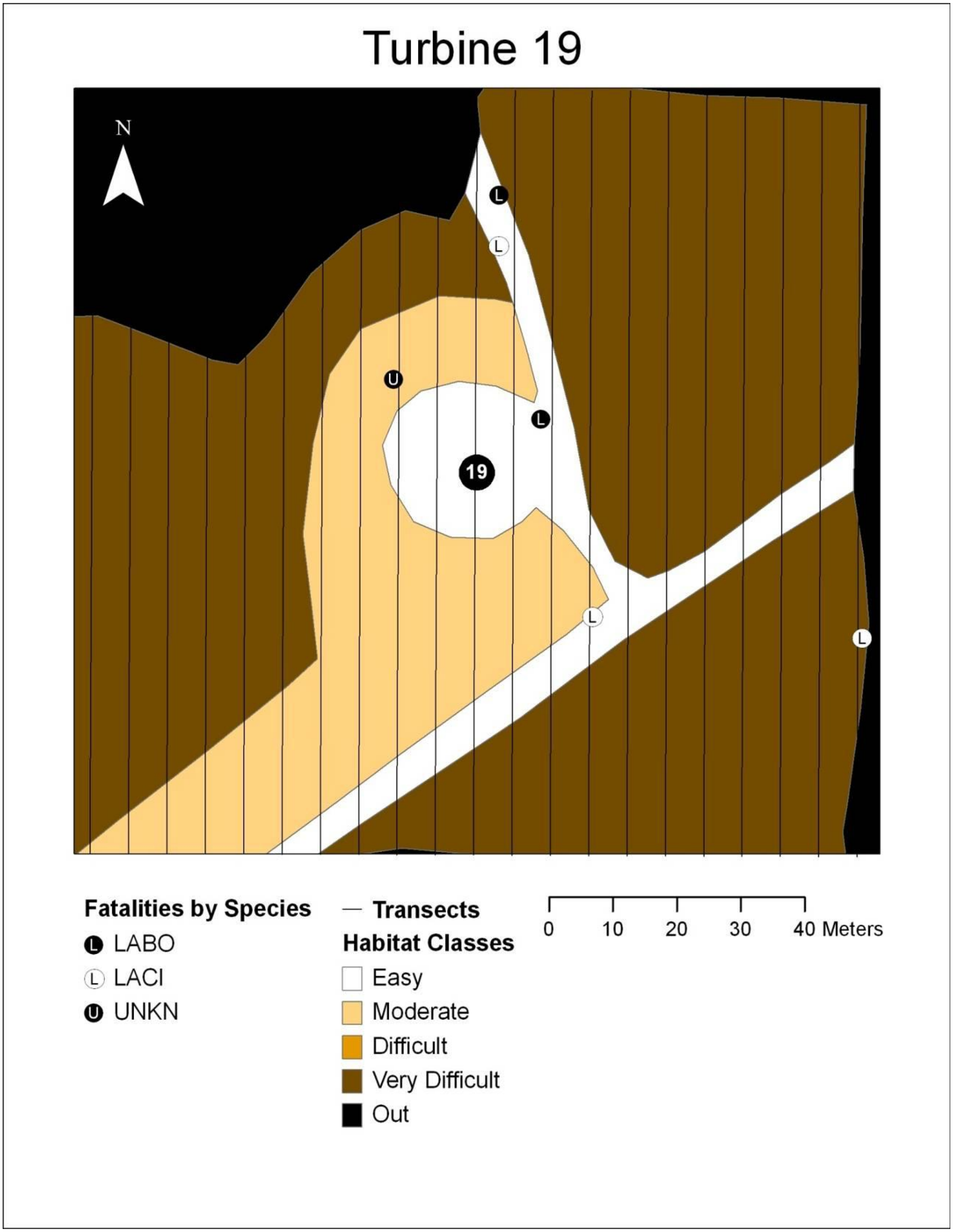
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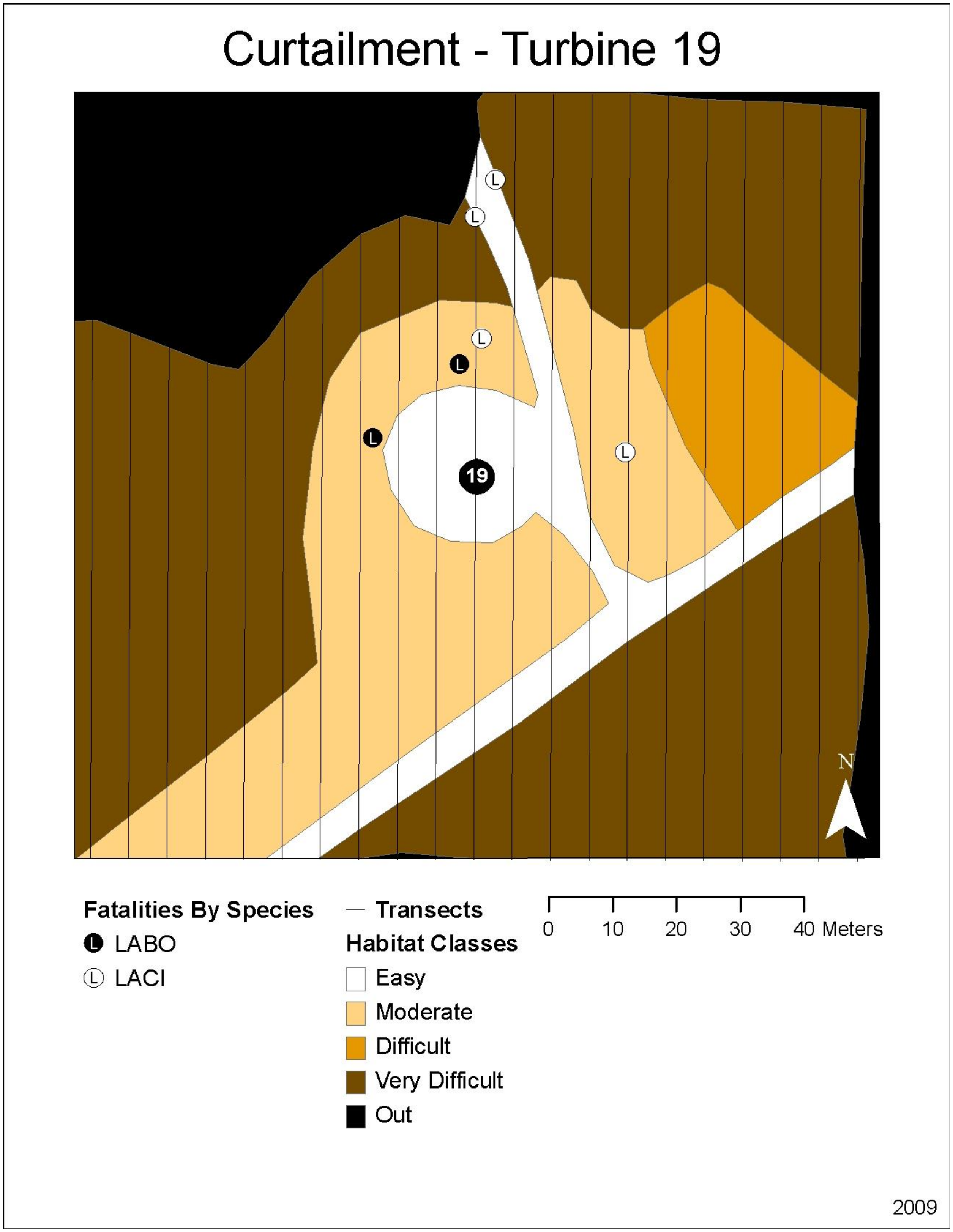
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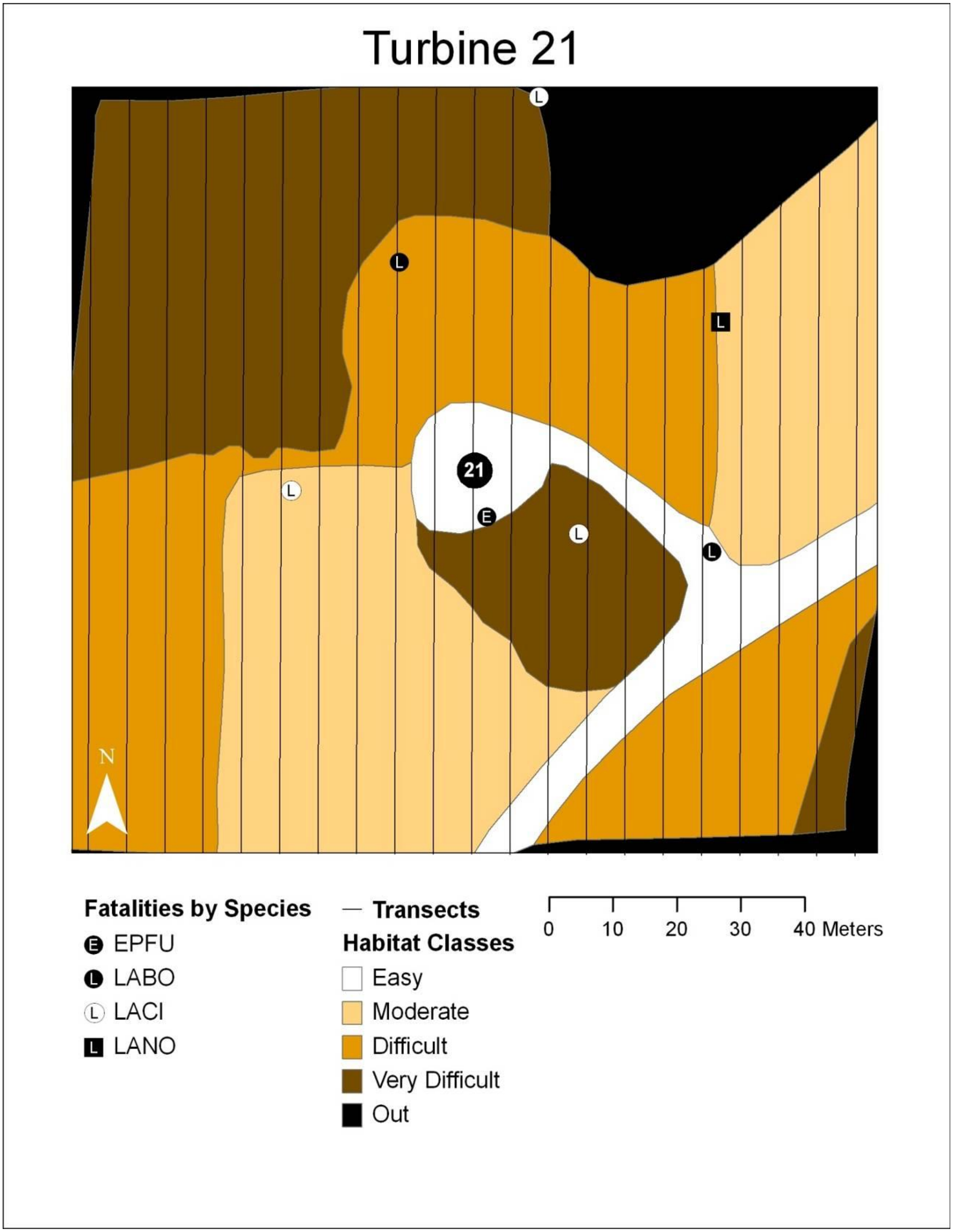
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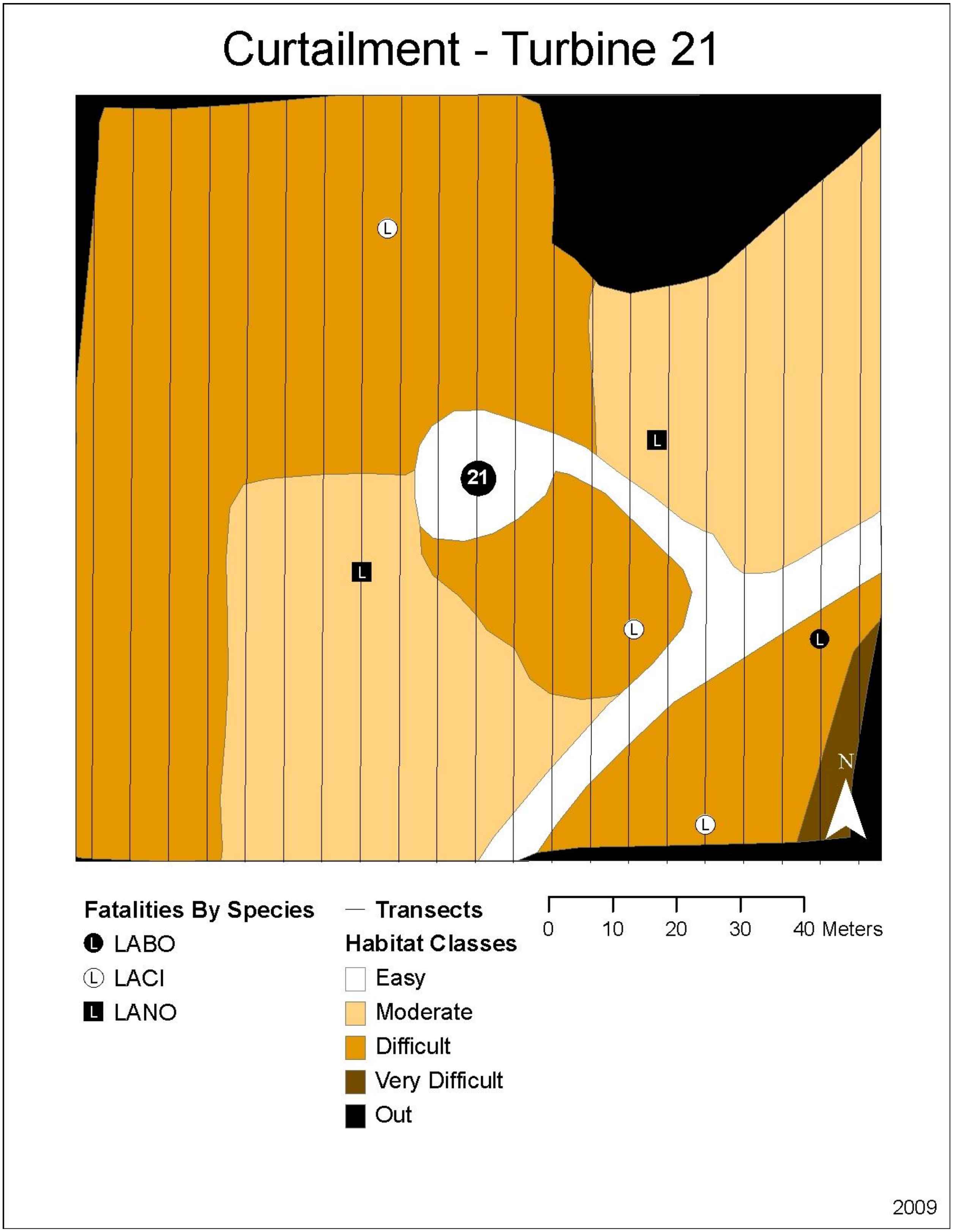

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