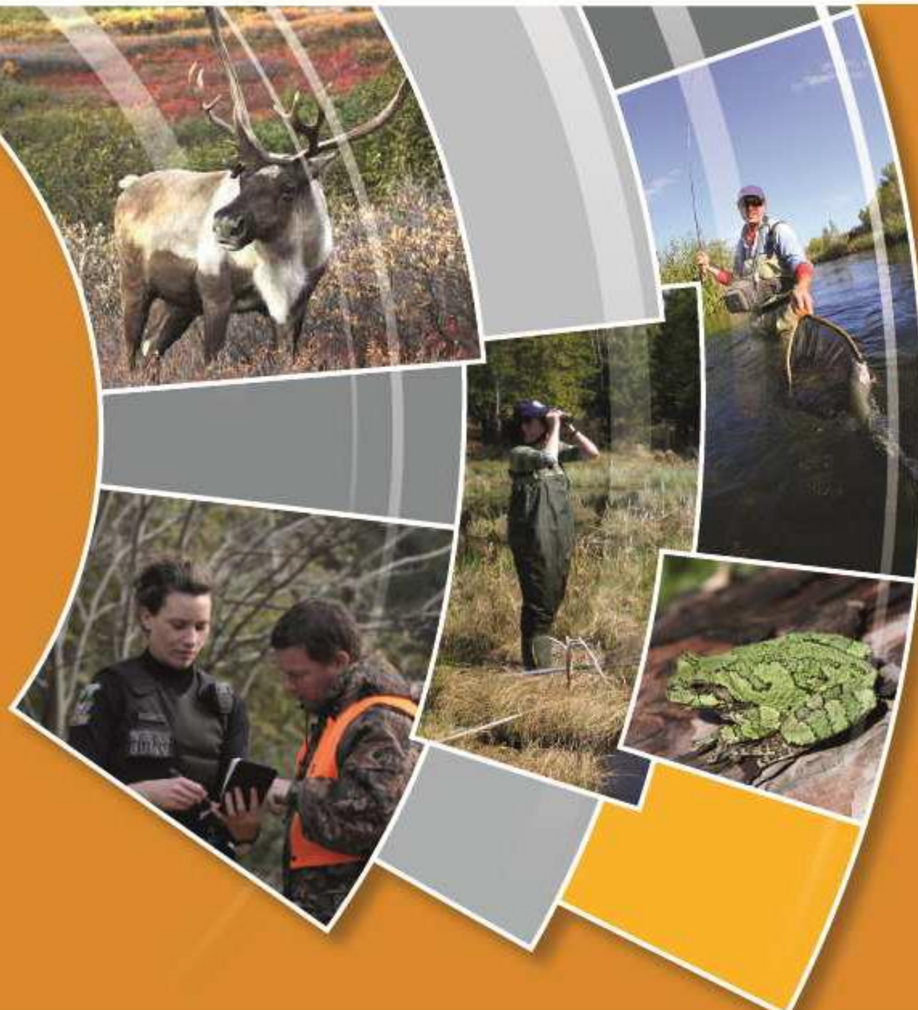

Bat Mortality Caused by Wind Turbines

Review of Impacts and Mitigation Measures

ENSEMBLE
on fait avancer le Québec

Québec

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Executive Summary

Most bat species in Québec are at risk owing, among other things, to the human-induced threats facing bat populations. Wind energy development is one of those threats. This document presents a review of the literature, with several objectives. First of all, we document the extent and impacts of bat collisions in wind farms in North America and Québec and we explain certain methodological biases that could affect mortality estimates. Then, we identify the factors that influence bat mortality in wind farms as well as the mitigation measures tested to date which have proven effective in reducing this mortality. Finally, we present a review of the application of the mitigation measures used in certain jurisdictions of North America.

According to the estimates in the literature, bat collisions with wind turbines total tens (even hundreds) of thousands of individuals a year in North America. However, it is difficult to compare wind energy projects among themselves, since the estimation of bat and bird mortality rates in wind farms is complex and evolving rapidly. These numbers are estimated based on carcass counts, corrected by an overall detection probability, which takes into account the area sampled, detection efficiency and carcass persistence. In 2016, we counted no less than three generations of estimators that have been applied to resolve this mathematical problem, with mixed success. Despite some uncertainty associated with mortality estimates, most authors agree that the main factor influencing bat activity, and therefore collisions with wind turbines, is wind speed. Bats are more active on nights with low wind speed (less than 6 m/s), and mortality rates are higher at these times.

Of the various mitigation measures studied, adjusting turbine cut-in speed is currently the only one that is clearly effective in reducing the number of bats killed while entailing relatively low implementation costs. Raising the cut-in threshold of wind turbines to 5 m/s reduced the number of bat mortalities by half, and raising the threshold to 6.5 m/s eliminated most collisions. Adjusting the cut-in speed caused financial losses equivalent to less than 1% of the annual production of wind power. Despite the scientific consensus on the effectiveness of this measure in reducing the number of bat collisions with wind turbines, it is not applied consistently. For example, Maine and Vermont have made it mandatory to increase the turbine cut-in speed in all their wind farms. Elsewhere in the United States, the members of the American Wind Energy Association (AWEA) voluntarily increase turbine cut-in speed during bats' fall migration. Other jurisdictions, such as Ontario and Alberta, use a mortality threshold to initiate the shutdown of certain wind turbines.

In conclusion, the development of wind power poses a threat to bats, several species of which are at risk. For installed or operational wind turbines, mitigation measures such as raising the cut-in speed, shutdown or feathering during critical periods make it possible to significantly reduce bat mortality, while entailing relatively low implementation costs.

Bats: A conservation issue

Québec is home to eight bat species, five of which are cave-dwelling and year-round residents of the province. In the spring and fall, they travel short distances between hibernacula (caves, caverns, abandoned mines, buildings), breeding sites and maternity roosts. The other three species are migratory and winter in southern North America (mainly in the United States and Mexico). In 2014, three cave-dwelling species received emergency listing as endangered species under the federal *Species at Risk Act* (SARA) (S.C., 2002; c. 29) owing to their dramatic and sudden declines in the eastern part of their range. In addition, five species are listed as species likely to be designated threatened or vulnerable under the Québec *Act respecting threatened or vulnerable species* (ARTVS) (CQLR, c. E-12.01), and four of them are currently in the process of being designated.

Table 1. Bats in Québec

English name	Latin name	Migratory status	ARTVS designation	SARA designation
Northern Myotis	*Myotis septentrionalis*	Resident	None; in the process of being designated	Endangered
Eastern Small-footed Bat	*Myotis leibii*	Resident	Likely to be designated	None
Little Brown Myotis	*Myotis lucifugus*	Resident	None; in the process of being designated	Endangered
Big Brown Bat	*Eptesicus fuscus*	Resident	None	None
Tri-coloured Bat	*Perimyotis subflavus*	Resident	Likely to be designated; in the process of being designated	Endangered
Silver-haired Bat	*Lasionycteris noctivagans*	Migratory	Likely to be designated	None
Hoary Bat	*Lasiurus cinereus*	Migratory	Likely to be designated	None
Eastern Red Bat	*Lasiurus borealis*	Migratory	Likely to be designated; in the process of being designated	None

Currently, most bat species are at risk owing to the threats facing them. Recently, Environment Canada (2015) published a proposed recovery strategy for the Little Brown Myotis, the Northern Myotis and the Tri-coloured Bat, three cave-dwelling species. The strategy provides a threat assessment for these species (Table 2). The most worrisome threat is a fungal infection called white-nose syndrome (WNS). This fungus, which originates in Europe, has spread to North America, and, after being first reported in New York State, is spreading at an average rate of 230 km/year (Lorch et al., 2011). Individuals that frequent infected hibernacula have been almost completely wiped out (Turner et al., 2011). In Québec, WNS was detected for the first time in Laflèche Cave, in the Outaouais region, in the spring of 2010. It has currently spread to all administrative regions in Québec with the exception of the North Shore, where it has not yet been confirmed (MFFP, unpublished data). Population declines of more than 90% have been observed in hibernacula in Québec for the Little Brown Myotis, Northern Myotis and Tri-coloured Bat (Turner et al., 2011; COSEWIC, 2013). Migratory bats do not appear to be affected by WNS.

In addition to WNS, bat populations face several other threats (Table 2). The threats with a high level of concern are of human origin: destruction and degradation of hibernacula, maternity sites and roosts; collisions with or barotrauma[i] from wind turbines; and intentional harm to individuals (Environment Canada, 2015).

Table 2. Threat assessment for the eastern Canada populations of Little Brown Myotis, Northern Myotis and Tri-coloured Bat (adapted from Environment Canada, 2015)

Threat	Level of concern[1]	Extent	Severity[2]	Causal certainty[3]
Exotic, Invasive or Introduced Species/Genome				
White-nose syndrome	Very high	Widespread	High	High
Feral and free-roaming cats	Unknown	Localized	Unknown	Low
Habitat Loss or Degradation				
Destruction or degradation of hibernacula or roosts	High	Localized	High	High
Destruction, degradation or conversion of foraging habitats	Medium	Widespread	Unknown	Medium
Disturbance or Harm				
Collisions with or barotrauma from wind turbines	High	Localized	High	High
Intentional harm to individuals	High	Localized	High	High
Recreational or scientific disturbance of individuals	Medium–High	Localized	High	Medium
Industrial disturbance of individuals (e.g., mining and forestry practices)	Medium–Low	Localized	Moderate	Low
Pollution				
Mercury	Unknown	Widespread (Eastern Canada)	Unknown	Low
Other toxic chemicals	Unknown	Widespread	Unknown	Low
Light pollution	Unknown	Widespread	Unknown	Low

[i] Internal injury caused by pressure changes near the moving blades of wind turbines (Cryan and Barclay, 2009).

Climate and Natural Disasters				
Alterations of habitat or prey dynamics resulting from climate change	Unknown	Widespread	Unknown	Low
Accidental Mortality				
Collisions with vehicles	Unknown	Widespread	Unknown	Low

[1] Signifies that managing the threat is of (high, medium or low) concern for the recovery of the species.
[2] Reflects the population-level effect (High: very large population-level effect, Moderate, Low, and Unknown).
[3] Reflects the degree of evidence that is known for the threat (High: available evidence strongly links the threat to stresses on population viability; Medium: there is a correlation between the threat and population viability, e.g., expert opinion; Low: the threat is assumed or plausible).

Although the Environment Canada (2015) assessment deals with only three bat species, the threats anticipated for the other five species are similar, with two exceptions. First, WNS appears to affect only cave-dwelling species and, second, migratory species account for 80% of the cases of bat mortality on wind farms in North America (Arnett et al., 2008; Kunz et al., 2007).

It is difficult to obtain accurate estimates of the declines specific to each species since the size of the populations and their abundance are unknown (Environment Canada, 2015). Furthermore, few studies have assessed the relative significance of the threats facing bat populations. In areas where local bat populations have decreased significantly due to WNS, the adverse effects of the other threats on the survival of individuals increase. Indeed, the mortality of a small number of the remaining individuals (particularly adults) can impact the survival of local populations, their recovery and, perhaps, the development of resistance to the fungus that causes WNS (Environment Canada, 2015).

The vulnerability of bats to human-induced threats is explained in particular by low recruitment of young in the population: a pair produces only one or two young a year (Barclay and Harder, 2003; Jones et al., 2009). Yearling survival is also low (0.23 to 0.46) (Frick et al., 2010b) and it takes one to three years before bats reach sexual maturity and produce young (Barclay and Harder, 2003; Jones et al., 2009). In a recent pre-WNS study from New Hampshire, the annual population growth rate of Little Brown Myotis over 16 years was estimated to be 1.008 (Frick et al., 2010b). In 22 subpopulations in the northeastern United States, the population growth rate was estimated to be 0.98–1.2 (Frick et al., 2010a). The growth rates of the Northern Myotis and Tri-coloured Bat populations were estimated to be 1.03 and 1.04, respectively (Langwig et al., 2012). The predicted population growth rate for Little Brown Myotis in the northeastern United States post-WNS was 0.95 (Maslo et al., 2015). Some authors fear the localized extinction of bat populations if mitigation measures are not taken to reduce pressures from human activity (Barclay and Harder, 2003; Jones et al., 2009).

This document presents a review of the literature in order to document the extent and impacts of bat collisions in wind farms in North America and Québec. This study also aims to identify the factors that influence bat mortality in wind farms as well as the mitigation measures that have proven effective in reducing it. Lastly, we present a review of the mitigation measures used in some North American jurisdictions.

Bat mortality in wind farms

There are two types of effects of wind energy development on birds and bats: direct and indirect. The main direct effect is the collision of individuals with turbines, resulting in their sudden mortality. Barotrauma also falls within this category. Indirect effects can adversely affect long-term survival and reproductive success, for example, through habitat loss and fragmentation caused by wind farm construction.

Indirect effects are relatively complicated to document, but direct effects are studied through programs that monitor bat and bird mortality at the base of and near wind turbines. These programs make it possible to estimate the total number of dead bats per wind farm, which can be converted to a mortality rate per wind turbine or per megawatt for comparison with other wind farms. Calculating the total number of dead bats based on the number of carcasses found at the base of and in close proximity to wind turbines requires the use of correction factors in order to (among other things) determine detection efficiency, duration of carcass persistence on the ground and the size of the search area (see methodological details in MRNF, 2008a and MDDEFP, 2013a). Currently, more than 100 bat mortality monitoring surveys have been published for North America, mainly in the United States (e.g., Strickland et al., 2011; Loss et al., 2013; Erickson et al., 2014), but also in Canada (e.g., Zimmerling et al., 2013; Zimmerling and Francis, 2016).

Although there is great variability in the numbers of mortalities observed, the cumulative estimates indicate that several tens (even hundreds) of thousands of bats are killed annually by wind turbines in North America. For example, Arnett and Baerwald (2013) estimated that between 650,000 and 1,300,000 bats were killed in wind farms in the United States and Canada during the 2000–2011 period. They projected additional numbers of 196,000 to 396,000 bats for 2012. Hayes (2013) estimated that 600,000 bats were killed by collisions in the United States in 2012 alone, while Smallwood (2013) estimated the figure for that year at 888,000.

Arnett and Baerwald (2013) compiled mortality estimates for different regions of North America (Figure 1). They estimated an average annual mortality of 8.30 individuals/megawatt (95% confidence interval: [6.08; 10.52]) for the northeast of the continent (Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, West Virginia, New Brunswick, southern Newfoundland and Labrador, Ontario, Québec, Prince Edward Island and Nova Scotia). According to another estimate, 15.5 ± 3.8 individuals/wind turbine (95% confidence interval) are killed every year in Canada (Zimmerling and Francis, 2016). It is possible to compare these figures by assuming that a wind turbine produces an average of 2 MW and by dividing the mortality rate per wind turbine by two to obtain an estimate of the mortality rate per megawatt. The study by Zimmerling and Francis (2016) would thus give a mortality rate of approximately 7.75 individuals/MW, which is very close to the figure calculated by Arnett and Baerwald (2013).

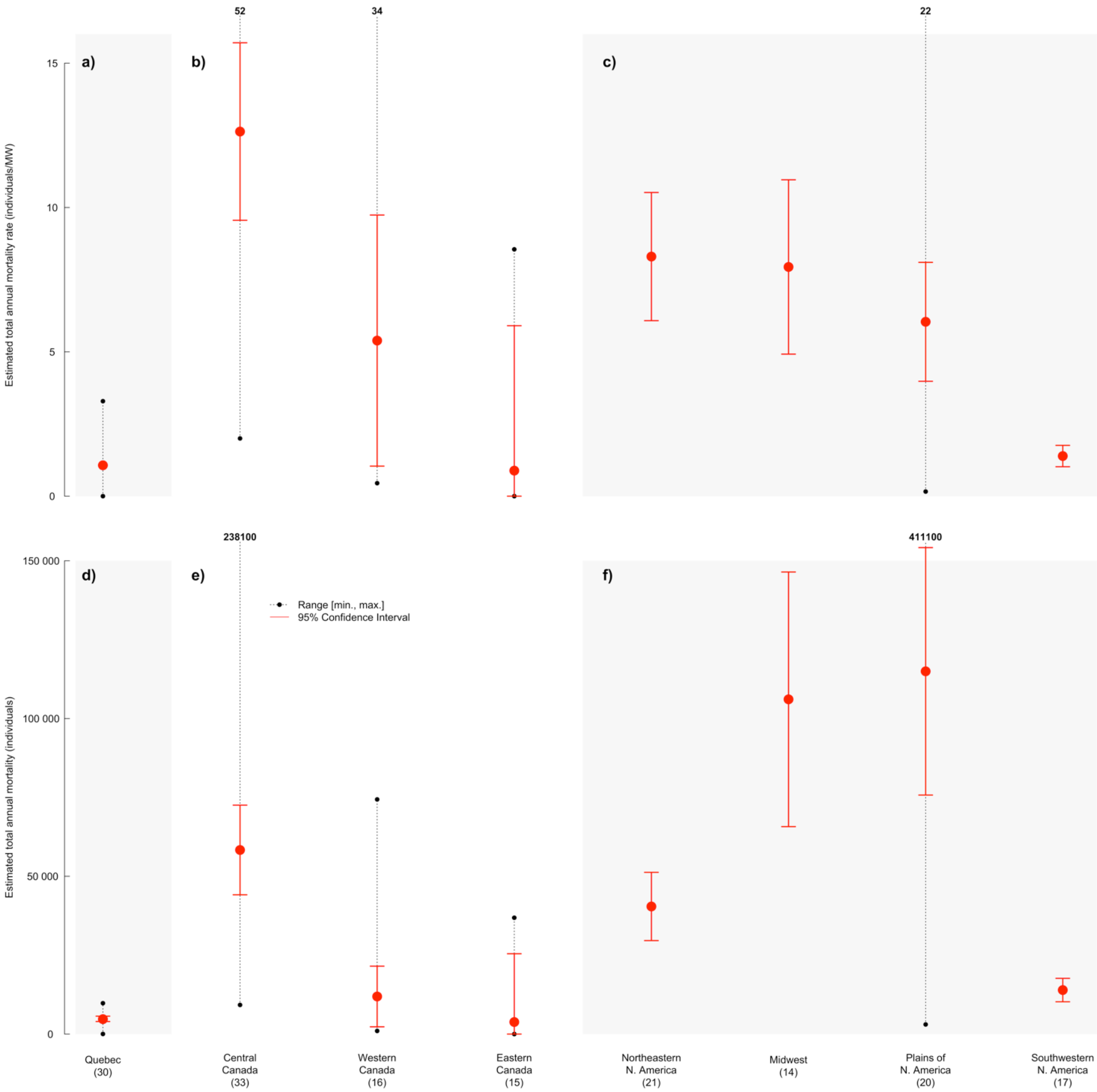

Figure 1. Mortality rate and annual mortality in wind farms in different regions of North America; a) and d) present the estimates for Québec and are taken from Tremblay (2012); b) and e) present the estimates for Canada and are taken from Zimmerling and Francis (2016); c) and f) present the estimates for North America and are taken from Arnett and Baerwald (2013). The number of wind farms used to produce the estimate is indicated in parentheses for each region.

In these studies, Québec, which is the second-largest wind energy market in Canada, after Ontario and before Alberta (CANWEA, 2016), is underrepresented. For example, Zimmerling and Francis (2016) in a sample of 64 Canadian wind farms, considered only 3 in Québec, while 31 were located in Ontario, 12 in the Maritimes and 11 in Alberta. This can be explained in part by the fact that mortality monitoring data are not made public in Québec, while they may be in other provinces.

Tremblay (2012) analyzed bat mortality data in the same 3 Québec wind farms as Zimmerling and Francis (2016) for the 2010–2011 period. The average mortality rate (min.; max.) was 2.14 (0; 6.57) bats per wind turbine, corresponding to 1.07 (0; 3.29) bats per megawatt. This rate is lower than most of the estimates provided by Arnett and Baerwald (2013). It is closer to the results obtained by Zimmerling and Francis (2016) for eastern Canada (Figure 1). Several factors could explain this result. First of all, it is probable that the sample of 3 wind farms is not representative of the 31 Québec wind farms currently in operation (see Hydro-Québec, 2016, for an update). MacGregor and Lemaître (in prep.) are currently compiling a Québec summary of mortality based on all the data available, which should provide a more complete picture of the situation. Second, it is possible that mortality rates are lower in eastern Canada owing to the smaller size of the bat populations. Given the lack of knowledge about bat population sizes (Environment Canada, 2015), it is currently impossible to assess this hypothesis. However, Zimmerling and Francis (2016) formulate a hypothesis which supports this view. Indeed, they suggest that the bat mortality rate is higher in Ontario owing to the configuration of the territory, since the Great Lakes region functions like a funnel for migratory bats which concentrate along the shorelines while passing through this region. In fact, most of the wind farms in the region are located less than 20 km from the shorelines. Lastly, estimating bat and bird mortality rates in wind farms is a complex and rapidly evolving process. Therefore, we cannot rule out the possibility that methodological biases may have influenced the results, particularly if different mathematical formulas were used to estimate the rates.

Impact of methodology on estimation of the mortality rate

To estimate the number of mortalities in a wind farm, we count the number of carcasses found at the bases of and in close proximity to wind turbines, then correct that number using an overall detection probability (g). The higher g is, the closer the correlation between the number of carcasses found during monitoring surveys and the actual number of mortalities in a wind farm and, consequently, the smaller the correction provided by g. Conversely, when g is low, there is more uncertainty about the actual number of mortalities in the wind farm, requiring more correction. Several correction factors are involved in calculating g (see Table 4 for examples).

From 2000 to 2016, three generations of estimators were developed. The first generation consisted of simple and intuitive estimators. However, these estimators were based on conditions that were difficult to meet in the natural environment. For example, the Johnson–Erickson estimator (Erickson et al., 2000; Johnson et al., 2003), recommended in the first version of the Québec mortality monitoring protocol (MRNF, 2008a), did not take into account the fact that the carcasses found during monitoring surveys were removed from the search area by the searchers. It was thus recognized that, with repeated visits, this estimator underestimates the number of mortalities (Huso et al., 2016).

Table 4. Main correction factors used to estimate the number of mortalities in a wind farm

Factor	Description
Carcass persistence	Probability that a carcass that has fallen to the ground will remain there for a specified period of time. Can also be presented as the average number of days during which a carcass remains on the ground. When persistence increases, g* increases.
Detection efficiency	Probability that the searcher will detect a carcass when the carcass is present on the site. When detection efficiency increases, g increases.
Proportion of the search area covered	In some cases, coverage of the carcass search area may be less than 100%, for example, owing to the topography or the presence of watercourses. When the proportion of the search area increases, g increases.

* Overall detection probability. See the text above for more detailed explanations.

The improvements made by the second generation of estimators included greater allowance for the biases associated with carcass persistence, which is no longer calculated in days, but rather as a probability that a carcass will remain in place until the next visit. This generation included the Huso (2010) and Korner-Nievergelt et al. (2011, 2015) estimators. The second version of the Québec mortality monitoring protocol (MDDEFP, 2013b) recommended the use of the Huso equation (2010), supported by a second estimator. At that time, Huso was one of the best methods available. Although the second-generation estimators are applicable in many cases, they have significant limitations: when the carcass count is low (approximately less than 15), the estimates are biased.

Recently, a third generation of estimators, such as the Dalthorp (2014) and Wolpert estimators (Warren-Hicks et al., 2013; Wolpert, 2015), has been developed to generalize the estimation process so that it is applicable under most circumstances. The Wolpert estimator includes the Johnson–Erickson, Huso and Korner-Nievergelt estimators as particular cases obtained when certain parameters are fixed at constant values. It is more flexible than the first- and second-generation estimators and makes it possible, for example, to take into account the variation in carcass persistence or detection efficiency over the course of the seasons and based on the state of decomposition. The Dalthorp estimator includes improvements similar to the Wolpert estimator; however, it is specifically designed to produce estimates in cases where the carcass count is low or zero.

Although the third generation of estimators offers promising advances for more reliable estimates of the number of mortalities, the data obtained from Québec monitoring surveys have so far been analyzed only with previous-generation estimators. Lemaître and Drapeau (2015) compiled a preliminary synthesis of the number of mortalities in 12 wind farms, based on data from 23 monitoring surveys conducted from 2009 to 2014. Eight of the 23 monitoring surveys (35%) did not report any mortalities. According to the data available during this study, it was impossible to determine whether this result represented an actual low mortality or was an artefact of the analysis methods (Huso et al., 2015). In other words, these monitoring campaigns did not gather sufficient data to produce reliable estimates of mortality using a second-generation estimator (Huso et al., 2015).

An experimental study also demonstrated that the search interval was a key parameter: twice as many carcasses were found when the frequency of visits was daily rather than weekly (Baerwald and Barclay, 2011). Korner-Nievergelt et al. (2011) demonstrated that the uncertainty associated with estimation of the mortality rate increased with the interval between visits. Also, the interval between visits interacted with carcass persistence: when carcass persistence was short (3 days) and the intervals between visits were long (7 and 14 days), the uncertainty of the mortality estimates was higher. In Québec, the average carcass persistence (± standard deviation) for all 23 monitoring surveys was 5.4 ± 3.8 days (MFFP, unpublished data), which is similar to the persistence of 5.6 days obtained by Baerwald and Barclay (2011) in Alberta. However, the average carcass persistence tended to be lower for the eight monitoring surveys that did not detect any carcasses (3.4 ± 1.9 days) compared to the 15 monitoring surveys that detected at least one carcass (6.1 ± 4.1 days).[2] The absence of mortality reported in eight of the monitoring surveys could be an artefact of a low duration of carcass persistence, combined with long search intervals. In eastern Canada (Ontario, Québec and New Brunswick), the interval between visits appears to be longer than in other regions. For example, of the 14 wind farms analyzed by Smallwood (2013) in the eastern United States, seven were visited on a daily basis and five had an interval of two to three days between visits. Even if certain monitoring surveys included weekly visits, they were always combined with daily visits. In Ontario, the visits were bi-weekly (Ontario Ministry of Natural Resources, 2011), while in New Brunswick they were bi-weekly or weekly.

In short, it is possible that the mortality rates calculated for Québec are lower than those for other regions owing to a combination of methodological factors, including a large number of monitoring surveys that did not compile sufficient data to produce reliable estimates of mortality, a longer interval between visits and a low probability of carcass persistence. Other elements of the first version of the monitoring protocol (MRNF, 2008a), which were corrected in the second version (MDDEFP, 2013b), may have also influenced the estimation of the mortality rate. For example, the monitoring period was increased from 8 to 11 weeks, the persistence test now takes carcass size into account to better represent the persistence of small carcasses such as those of bats, and the mortality rate calculation method has been improved (Huso, 2010). Nonetheless, in order to obtain robust and reliable estimates when numbers of carcasses are low, the overall detection probability (g) must be increased by adjusting one or several of the correction factors (Table 4) (Huso et al., 2015). For example, Arnett (2006) demonstrated the usefulness of dogs in increasing detection efficiency. Increasing the total area covered by the monitoring surveys would also make it possible to increase the overall detection probability. Other ways to accomplish this goal include increasing the proportion of wind turbines monitored, the size of the search areas or the proportion of the search areas surveyed.

Cumulative effects of mortality on populations

At present, relatively little information is available about the cumulative effects of wind energy development on bats. With only a few exceptions (e.g. Loss et al., 2013; Erickson et al., 2014; Zimmerling and Francis, 2016), the research has focused on estimating annual numbers of mortalities per wind turbine, per megawatt or per wind farm. Although this information is essential to understanding the phenomenon, it represents only part of the problem. To produce a more comprehensive overview, we must consider the cumulative effects at large spatial and temporal scales. The studies must take into account the fact that bat species have very large ranges, often covering several provinces or states. By compiling Canadian data, Zimmerling and Francis (2016), for example, estimated that approximately 47,400 bats (95% CI: 32,100 – 62,700) were killed every year across Canada. According to these authors, this number could quadruple in 10 years, since wind power, which currently represents approximately 5% of Canadian electrical supply, could represent 20% by 2025 (CANWEA, 2015; Zimmerling and Francis, 2016). In addition, as pointed out above, the number of direct mortalities is only part of the problem. To date, few studies have examined the indirect effects such as habitat loss and fragmentation or barrier effects for migratory species (Roscioni et al., 2013). In a United Nations Environment Program report, Rodrigues et al. (2015) also stressed the cumulative effects as one of the research priorities.

Biological, behavioural and environmental factors that influence mortality

In Québec, the most recent data indicate that 268 bat carcasses were reported during the 65 monitoring surveys, distributed over 31 wind farms, from 2004 to 2015 (MacGregor and Lemaître, in prep.). Of these carcasses, 192 (72%) belonged to migratory species, 54 (20%) were resident species and 22 (8%) could not be identified to the species. These findings are similar to those reported elsewhere in the literature (Arnett et al., 2008; Kunz et al., 2007). Of the carcasses of migratory bats, the three species found in

[2] It was possible to obtain these results because the persistence tests are conducted using control carcasses and are independent of the carcass survey (MRNF, 2008a; MDDEFP, 2013b).

Québec were detected, namely the Hoary Bat (66%), the Silver-haired Bat (25%) and the Eastern Red Bat (9%). This result is consistent with the bat abundance data, which indicate that the Hoary Bat is the most common migratory species (J. Faure Lacroix et al., unpublished data). The carcasses of resident bats identified include Northern Myotis, Big Brown Bat and Little Brown Myotis. To date, only a single Tri-coloured Bat and no Eastern Small-footed Bats have been reported in the monitoring surveys, but they may be among the 22 unidentified carcasses. In fact, Tri-coloured Bats accounted for up to 25% of the number of mortalities in wind farms in the eastern United States (Arnett et al., 2008).

The majority of the bat carcasses were found from June to September, with greater abundance in July and August (Figure 2). However, it should be noted that these data are not corrected using the overall detection probability and should be interpreted with caution. The majority of the studies conducted in North America observed a peak in bat mortality during the fall migration (Arnett et al., 2008). The earlier peak in Québec could be explained by the fact that bats in the province are at the northern limit of their range. The harsher weather conditions could reduce their activities beginning in the early fall. For example, the migratory species may begin their fall migration earlier than in other regions and thus be less abundant in Québec during this period. However, more data are necessary in order to test this hypothesis.

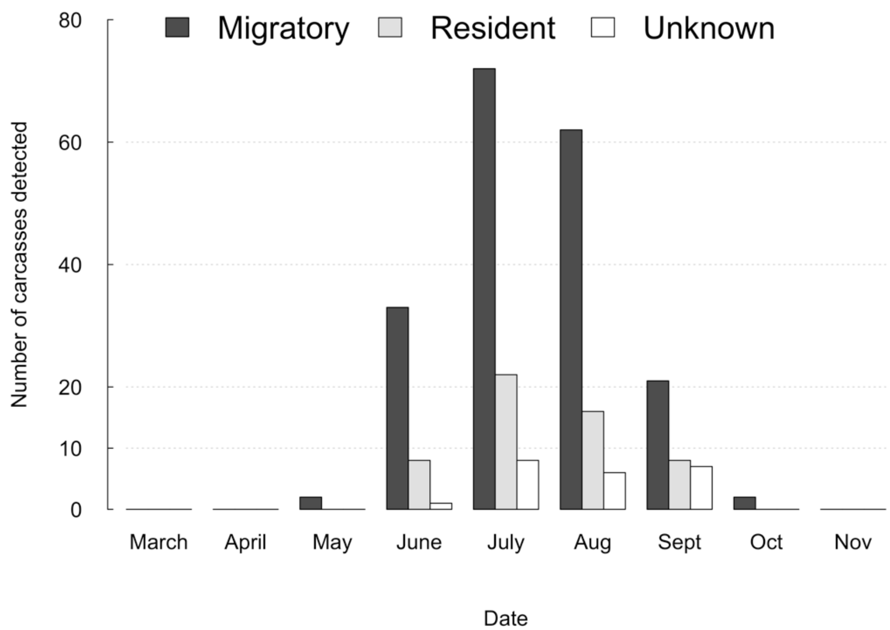

Figure 2. Monthly breakdown of bat carcasses detected in Québec wind farms by migratory status. The data are taken from 65 mortality monitoring surveys, distributed over 31 wind farms from 2004 to 2015. Most of the monitoring surveys covered the period from mid-May to mid-October. Some monitoring surveys covered the period from March to November. Several monitoring surveys did not cover the August 1–15 period. The figure therefore probably underestimates the number of carcasses observed in August.

Several authors have studied the influence of biological, behavioural and environmental factors on bat activity and the risks of collision and barotrauma (Table 5). They found that wind speed is the main factor that influences bat activity: bats are more active on nights with low wind speed, which is reflected in higher mortality rates under these conditions (Arnett et al., 2008; Baerwald and Barclay, 2011). This result may be explained by the fact that it is easier for bats to fly and hunt their prey under these conditions, although there is no consensus on this point (Kunz and Fenton, 2003).

Table 5. Summary of the hypotheses concerning the biological, behavioural and environmental factors that influence the risk of bat collisions with wind turbines (adapted from Koppel et al., 2014; Schuster et al., 2015)

Factor	Effect	Details
Risks associated with biological and behavioural factors		
Abundance	Low to moderate	All other factors being equal, we should expect the number of collisions to increase as a function of bat abundance in a wind farm (Cryan and Barclay, 2009). If the collisions occur randomly, then there will be more collisions involving abundant species than rare species (Huso et al., 2015).
Migratory status	High	In North America, 80% of collisions involve migratory bats (Kunz et al., 2007; Arnett et al., 2008; Cryan, 2008; Horn et al., 2008). In Québec, 72% of the bats reported are migratory species. The behavioural mechanics underlying these observations are currently unknown. In other words, we do not know whether it is migration behaviour that makes these species more susceptible to collisions or whether other factors are involved. For example, migratory species may have more similar habitat selection behaviour among themselves than with resident species. The phenomenon could therefore be due to their habitat selection behaviour, rather than their migratory status. Also, since the emergence of WNS, migratory species have been more numerous than resident species in Québec. More migratory bats may be detected in the monitoring surveys simply because they are more abundant (see “Abundance”).
Habitat selection	Unknown	The habitat selection behaviour of the species may influence the risk of collision. For example, in Europe, the species most at risk of being involved in collisions with wind turbines are those that select open environments for foraging (Rydell et al., 2010a).
High-risk behaviour	High	Behaviour such as breeding, swarming and foraging can involve repeated passes around wind turbines and increase the risk of collision (Cryan and Brown, 2007; Arnett et al., 2008; Rydell et al., 2010a; Roeleke et al., 2016).
Increased availability of prey	Unknown	A few studies have demonstrated that the number of insects present around wind turbines is influenced by the location and arrangement of the turbines (e.g. creation of an opening in the forest, aviation warning lights, roads, turbine colour and air currents created by movement of the blades) (Horn et al., 2008; Rydell et al., 2010b).

Risks associated with environmental factors		
Wind speed	High	The main factor influencing bat activity is wind speed. Bats are more active on nights with low wind speed (less than 6 m/s) and mortality rates are also higher (Arnett et al., 2008; Arnett et al., 2011; Baerwald and Barclay, 2011).
Season	High	Several studies have found a collision peak in late summer and early fall, which coincides with the bat migration season (Arnett et al., 2008; Baerwald and Barclay, 2009). A smaller mortality peak during the spring migration has been observed for certain species in a few wind farms (Arnett et al., 2008). In Québec, the collision peak appears to occur between July and August (Figure 2).
Period of the night	Moderate	The level of bat activity is not distributed equally over the course of the night. Several studies have found that there is a collision peak at sunset and during the following few hours (Cryan and Brown, 2007; Rydell et al., 2010b). There also appears to be a peak of activity around sunrise (Arnett et al., 2006).
Weather conditions	Low to moderate	Baerwald and Barclay (2011) conducted a review of the studies dealing with bat activity based on weather conditions (temperature, thunderstorm cells and rain, barometric pressure, etc.) and the lunar cycle. Although some studies indicate that temperature (e.g. Weller and Baldwin, 2012) or the passage of a depression affect bat activity, the results are often specific to the species, the location and the year of the study. Consequently, there is still no consensus on a demonstrated correlation concerning the effects of weather conditions on bat activity. However, several of these factors vary with wind speed.
Turbine characteristics	Unknown	The effects of turbine height and rotor-swept area remain unknown due to contradictory studies (Baerwald and Barclay, 2009; Loss et al., 2013; Strickland et al., 2011). Rydell (2010b) suggests that turbines taller than 150 m are high enough to penetrate the air space used by migrating insects and that these insects attract bats. This hypothesis has not yet been verified.
Landscape	Low	There do not appear to be significant differences in the number of mortalities according to the type of landscape surrounding wind farms (e.g. agricultural, forest, agri-forest) (review in Arnett et al., 2008), but little is known about this factor.
Region (eastern vs western North America)	Low to moderate	There appears to be greater intra-regional than inter-regional variation in mortality (American Wind Wildlife Institute, 2014; Arnett et al., 2013).

Review of the mitigation measures applicable to operational wind turbines

Wildlife conservation actions are generally implemented according to a mitigation hierarchy. First, development projects must endeavour to avoid impacts on wildlife. If avoidance is impossible, efforts must then be made to minimize the impacts. Lastly, if this also proves impossible, compensation measures must be evaluated. In Québec, this mitigation hierarchy is governed by the *Lignes directrices pour la conservation des habitats fauniques* [guidelines for the conservation of wildlife habitats] (MFFP, 2015).

The bat survey protocol adopted for wind energy projects (MRNF, 2008b) is part of the first step in the mitigation hierarchy and provides information on use of the site by bats before the construction phase. If it is demonstrated that the planned wind farm encompasses bat concentration areas (e.g. maternity roosts, migration corridors), avoidance measures can be implemented, up to and including banning wind turbines (MRNF, 2008b). Given the importance of hibernacula for resident species, a 1-km protection zone is established around known hibernacula (MRNF, 2008b). According to the scientific literature, the effect of avoidance measures is generally low or moderate (Arnett et al., 2013b; Arnett and May, 2016; Table 6). In fact, given the lack of knowledge about the status of bat populations and the difficulty of surveying these populations, our ability to predict the locations of high importance for bats remains limited. For example, if a hibernaculum is occupied but unknown, no protection measure will be associated with it.

Table 6. Effectiveness of avoidance and mitigation measures in reducing the number of bat mortalities caused by the development of wind energy (adapted from Arnett and May, 2016; Arnett et al., 2013b)

Mitigation measure	Effectiveness	Reduction in mortality (%)	Specifications
Avoidance measures			
Wind farm site selection	Moderate	No estimate	Depends on the quality of the information available (e.g. pre-construction surveys, data on hibernacula). Can be effective at large spatial scales.
Micro-siting of wind turbines	Low	No estimate	Very difficult to implement. Very limited information at this spatial scale to evaluate the effect on populations, species and their use of the habitat.
Mitigation measures			
Raising turbine cut-in speed*	High	36% to 82%	Proven effective for all bat species
Acoustic deterrence (ultrasound)	Moderate	n/a**	Variable effectiveness depending on the species and the site
Visual deterrence (turbine lighting, ultraviolet (UV)-reflective paint on rotor blades)	Low to Moderate	n/a	Variable effectiveness depending on the species and the site

* Below a specified rotational speed, wind turbines are stopped. This can be achieved by using one of the turbine's braking systems (e.g. mechanical, electrical or hydraulic) or by feathering, which means angling the blades parallel to the wind so that they do not catch the wind, reducing the rotational speed to zero or almost zero.
** Data not available.

Despite the implementation of first-level mitigation measures, mortalities can still occur. The Québec mortality monitoring protocols (MRNF, 2008a; MDDEFP, 2013b) are part of the second level of the mitigation hierarchy and are intended to document the effects of the development of wind energy on birds and bats. Various mitigation measures have been tested in an effort to reduce bat collisions with or barotrauma from wind turbines (Arnett et al., 2013b; Arnett and May, 2016). To date, only one measure has been clearly proven effective (Table 6). Since bats are more active on nights with low wind speed, it has been found that limiting the operation of wind turbines during these periods significantly reduces the number of mortalities. Turbines can be completely shut down during critical periods or their cut-in threshold (i.e., the minimum speed at which wind turbines can begin to turn and generate electricity) can be raised.

Experiments involving turbine lighting (Kerlinger et al., 2010) and the application of UV-reflective paint on the blades (Young et al., 2003) have not demonstrated the effectiveness of these techniques in reducing mortality rates (Table 6). Recent studies also suggest that ultrasound may reduce the number of bat mortalities by deterring bats from approaching the sound source (Arnett et al., 2013a; Table 6). However, more research is currently needed, since the signal appears to be rapidly attenuated with distance and to be influenced by humidity levels and therefore effective only under certain environmental conditions (Arnett et al., 2013b).

Additional information about turbine cut-in speed

In an experimental study conducted in Pennsylvania over two successive years, Arnett et al. (2010) demonstrated that raising the cut-in threshold of wind turbines reduced the number of bat mortalities by 82% in the first year and by 72% in the second year. There was no difference between the two cut-in thresholds tested (5.0 m/s and 6.5 m/s). In other words, the benefits of the reduction in the number of mortalities were already evident with a cut-in threshold set at 5.0 m/s. However, other data indicate that raising the cut-in speed is associated with a further reduction in the number of mortalities (Figure 3). These results agree with a review of bat mortality patterns in 19 wind farms in the United States and Canada, which indicates that most collisions occurred when the wind speed was less than 6 m/s (Arnett et al., 2008).

Another review covering 10 wind farms showed that there was a reduction of at least 50% in the number of bat mortalities when turbine cut-in speed was increased by 1.5 m/s above the manufacturer's recommended cut-in speed, which was 3 to 4 m/s (Arnett et al., 2013). This review also noted that feathering below the cut-in speed resulted in a 72% reduction in mortalities. Raising turbine cut-in speed and feathering thus effectively reduced the number of bat mortalities.

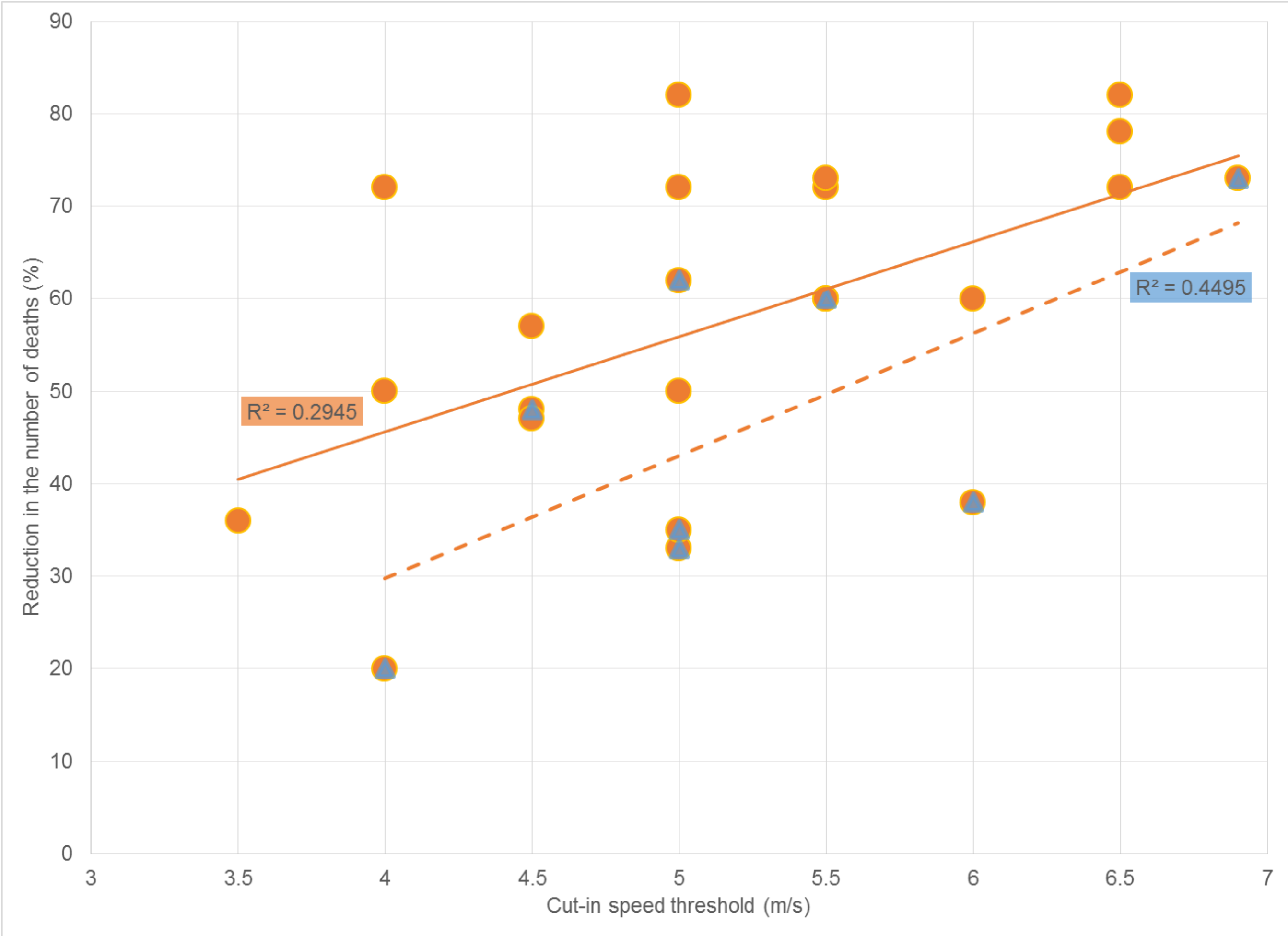

Figure 3. Reduction in the number of bat mortalities as a function of the threshold of turbine cut-in speed (adapted from Arnett et al., 2013b). The orange dots and the solid line represent all the data used, while the blue triangles and the dotted line represent only the significant data.

Another advantage of this mitigation measure is its relatively low implementation cost. First of all, the measure applies only during bat activity periods, which in Québec extend from early June to mid-October. Second, this measure applies only at night, since bats are not active during the day. Third, these periods of low wind generate less electricity and, consequently, less revenue than windier periods. Although few studies have made public the lost revenue caused by this measure, those that have done so have indicated losses equivalent to less than 1% of annual production, including lost energy production and the labour cost to implement and manage the process (Arnett et al., 2013b; Table 7). These measures may also have the advantage of extending the lifetime of wind turbines (Baerwald et al., 2009). In Québec, nearly 85% of currently installed wind turbines have a cut-in speed of 3 to 4 m/s (MFFP, unpublished data). Other models may have cut-in speeds as low as 2.0 or 2.5 m/s. However, their optimal operating speed is 12 to 16 m/s, i.e. well above the most effective cut-in speed for reducing the number of bat mortalities.

Table 7. Reduction in the number of bat mortalities and estimate of lost revenue as a function of the adjustment of turbine cut-in speed and blade feathering for wind farms in North America (adapted from Arnett et al., 2013b)

Region	Manufacturer's cut-in speed (m/s)	Cut-in speed used (m/s)	Feathering	Average reduction in number of mortalities	Lost production*	Landscape
Alberta	4.0	4.0	Yes	57%	n/a	Agricultural
		5.5 (24 hrs a day)	No	60%	$200 to $267/ wind turbine/ month	
Ontario	4.0	4.5	No	48% (n/s)	n/a	Pasture, crops, grassland
		5.5	No	60% (n/s)		
Pennsylvania 2008	3.5	5.0	No	82% (n/s)	0.3%	Deciduous forest, grassland
		6.5			1.0%	
Pennsylvania 2009	3.5	5.0	No	72% (n/s)	n/a	
		6.5				
Indiana 2010	3.5	5.0	No	50%	n/a	Agricultural (soybeans, corn)
		6.5	No	78%		
Indiana 2011	3.5	3.5	Yes	36%		
		4.5	Yes	57%		
		5.5	Yes	73%		
Vermont	4.0	6.0	No	60%	n/a	Deciduous forest
Midwest	3.5	4.5	No	47%	0.2%	Agricultural (soybeans, corn)
		5.5	No	72%	0.8%	
Pacific Southwest	3.0	4.0 (for 4 hrs after sunset)	No	20% (n/s)	n/a	Sagebrush/ salt meadow
		5.0 (for 4 hrs after sunset)	No	35% (n/s)		
		5.0 (all night)	No	33% (n/s)		
		6.0 (for 4 hrs after sunset)	No	38% (n/s)		
West Virginia (Mount Storm) 2010	4.0	4.0	Yes; for 5 hrs after sunset	72%	n/a	Deciduous forest

		4.0	Yes; for 5 hrs before sunrise	50% (evenings with no treatment excluded)		
West Virginia (Mount Storm) 2011	4.0	4.0	Yes	n/s; but very few mortalities; total compared to 2010 and many nights with wind speed > 6 m/s	n/a	Deciduous forest
West Virginia (Beech Ridge)	3.5	6.9	Yes	73% (n/s; compared to the average for other wind farms; no control treatment)	n/a	Deciduous forest
Maryland 2012	4.0	5.0	Yes (rpm of 2)	62% (n/s; compared to 2011 when blades were not feathered)	n/a	Deciduous forest, mountain ridge, hayfields

Notes: n/a: data not available; n/s: no significant difference between treatments; *: % are calculated based on total annual revenue.

Mitigation measures applied in other jurisdictions

Although there appears to be a consensus on the effectiveness of adjusting the cut-in threshold of wind turbines to reduce the number of bat mortalities, this measure is not applied consistently. In some jurisdictions, there are very specific rules for applying mitigation measures, while in others the rules are less clear (Table 8). This lack of consistency could be explained by a lack of knowledge about bat populations. In fact, even if mitigation measures prove effective in reducing the number of mortalities in wind farms, the effect of these reductions on bat populations is still unknown. In other words, we do not know whether or not the reduction in the number of mortalities resulting from mitigation measures is sufficient to prevent or limit population declines (Arnett and Baerwald, 2013). Ideally, application of the mitigation measures should be associated with a mortality threshold of biological significance, which would be based on population size and would take cumulative mortality into account. Estimating the absolute abundance of bats is nonetheless very complicated and it would be unrealistic to think that accurate population estimates could be obtained in the short or medium term.

In the absence of a biological threshold, some jurisdictions, such as Maine (MDIFW, 2014) and Vermont (Scott Darling, Vermont Fish and Wildlife Department, personal communication), apply a cautionary principle and ask turbine operators to increase turbine cut-in speed on all wind farms in order to reduce the number of bat mortalities (Table 8).

Other jurisdictions, such as Ontario (Ontario Ministry of Natural Resources, 2011) and Alberta (Alberta Government, 2013), use a mortality threshold to trigger the shutdown of certain wind turbines during specific periods. Note that this threshold has no biological significance, since it is based not on population size but on a comparison of mortality rates at various wind farms in the province. Wind farms with higher-than-average levels are therefore required to apply the mitigation measure, while those with below-average levels do not. This approach makes it possible to limit the number of mortalities at the sites where fatalities are highest. However, without reliable population size data, it is impossible to know whether the mitigation measure is effective in maintaining viable bat populations. Likewise, it is unknown whether not applying a mitigation measure in wind farms that have a threshold below the level set by the authorities will make it possible to maintain bat population levels. Obtaining more detailed data on bat populations therefore continues to be a priority in order to assess the biological impacts (Arnett and Baerwald, 2013).

In the United States, the AWEA announced on September 3, 2015, that 17 of its member corporations would voluntarily apply best management practices by reducing wind turbine speed by 1 to 3 revolutions per minute during the fall bat migration season; the AWEA anticipates that this measure will reduce the number of bat mortalities by at least 30% (AWEA, 2015). In Canada, following the federal government's addition of three bat species to the List of Wildlife Species at Risk in 2014, operators of wind turbines located on federal lands under the authority of the Minister of Environment and Climate Change Canada (ECCC) or the Parks Canada Agency must comply with the General Prohibitions of the *Species at Risk Act*, including the prohibition against the killing or harming of individuals of the three bat species. Environment and Climate Change Canada advocates adopting beneficial management practices that can contribute to the protection of bats, including shutting down wind turbines during critical periods, raising the cut-in speed and feathering (https://www.registrelep-sararegistry.gc.ca/virtual_sara/files/gen_info/fs_eolienne_windenergy_chs_v03_0215_e.pdf).

In conclusion, the development of wind power represents a threat to bats, several species of which are at risk. For installed wind turbines, mitigation measures such as raising the cut-in speed, shutdown or feathering during critical periods make it possible to significantly reduce bat mortality, while entailing relatively low implementation costs. Several jurisdictions of North America already apply some of these mitigation measures.

Table 8. Mitigation measures introduced in certain North American jurisdictions

Jurisdiction	Measure	Period	Sector	Details	Reference
Alberta	- Cut-in threshold of 5.5 m/sec. - Feathering.	- August 1 to September 10 - Can be adapted based on the regional migration peaks at different wind farms. - Night: from 30 min after sunset to 30 min after sunrise	- Wind farm - Wind turbine cluster if the mortalities are concentrated in a particular sector	- If application of the mitigation measures does not reduce mortality rates, complete shutdown of the wind turbines can be ordered during the period.	(Alberta Government, 2013)
Maine	- Cut-in threshold of 6.0 m/sec. - Feathering.	- April 20 to October 15 - Night: at least 30 min before sunset to at least 30 min after sunrise	- All wind farms in the state (unless otherwise instructed)	- Average speed measured at the height of the hub for 10 minutes. - The methodology of the studies recommended may vary depending on the project location. - Additional wildlife studies or concerns can be considered depending on the project location.	(MDIFW, 2014)
New Brunswick	- Selective operational shutdown of wind turbines	- During periods of high bat activity and concentration or depending on atmospheric conditions (low wind).	- Localized by wind turbine	- Measures applied if the mortality rates are high compared to other monitoring surveys carried out in North America or unexpected. - Applied under certain weather conditions. - When the mortality rate cannot be reduced by other methods or other measures. - Other monitoring efforts or studies may be necessary if the post-construction measures are ineffective.	(New Brunswick Fish and Wildlife Branch, 2011)
Ontario	- Cut-in threshold of 5.5 m/sec when the mortality rate exceeds 10 bats/turbine/year	- July 15 to September 30 - Night: from sunset to sunrise	- Entire wind farm or by wind turbine cluster	- Speed measured at the height of the hub. - For the entire operational lifetime of the wind farm.	(Ontario Ministry of Natural Resources, 2011)

	- Feathering when wind speed is < 5.5 m/sec.			- At a specific site: • the period of application of the measures may vary depending on the peak mortality period; • measures must be maintained for at least 10 weeks. - When the mitigation measures are applied, three years of additional monitoring is required.	
Pennsylvania	Adjustment of the cut-in threshold based on the initial “risk” category assigned to the project. - High risk: cut-in threshold varies from 5.0 to 5.5 m/s depending on the particular month during the period. - Low risk low: cut-in threshold of 5.0 m/s	- High risk: from April 1 to November 15, 30 min before sunset to 30 min after sunrise. - Low risk: from July 1 to September 30, 30 min before sunset and during the following 5 hrs.	Entire wind farm	- The measures are implemented when mortality is > 4 bats/1,000 m^2/year. - Measures implemented when temperature >10°C.	(Pennsylvania Game Commission, 2013)
Vermont	- Cut-in threshold of 6.0 m/sec.	- June 1 to September 20			Scott Darling, Vermont Fish and Wildlife Department, personal communication

Note: This table was prepared based on data collected in 2015 and 2016.

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