Bird Conservation International (2020) 30:194–209. © BirdLife International, 2020
doi:10.1017/S095927092000012X

Effects of wind energy production on a threatened species, the Bicknell's Thrush *Catharus bicknelli*, with and without mitigation

JÉRÔME LEMAÎTRE* and VINCENT LAMARRE

Ministère des Forêts, de la Faune et des Parcs, Quebec, Quebec, Canada G1S 4X4.

**Author for correspondence; email: jerome.lemaitre@mffp.gouv.qc.ca*

(Received 17 November 2018; revision accepted 29 January 2020)

Summary

Renewable energy helps meet the growing energetic demand while reducing greenhouse gas emissions. Despite its environmental benefits, production of wind energy can adversely affect wildlife populations, including birds. In some species, indirect impacts such as habitat loss and disturbance may be more important than fatalities caused by collisions with turbines. Bicknell's Thrush *Catharus bicknelli*, one of the most endangered bird species in North America, may be threatened by wind energy production because it breeds at high elevation sites, which are often prized for their wind potential. Our study had two objectives: we first aimed to document the impacts of the construction and operation of a wind energy facility without mitigation strategy on the occurrence of the Bicknell's Thrush. At a second facility, we then tested the effectiveness of turbine micro-siting as an effective mitigation strategy to reduce the impacts of wind-energy development on the species. We conducted avian point-counts at 143 locations spread across both facilities in Quebec (Canada) at different periods: before, during and after construction. We modelled the probability of occurrence of the species at point-counts as a function of period, forest loss caused by wind energy development, distance to the nearest turbine and habitat suitability. At the facility without mitigation, we found that the probability of occurrence decreased during construction and early operation at high elevation sites, where most of the turbines were erected. However, the Bicknell's Thrush recolonized high elevation sites eight years post-construction. In addition, we did not detect a significant impact of wind energy production on the species' occurrence at the facility where micro-siting was applied. We conclude that habitat loss and disturbance during construction are the main impacts of wind energy production on the Bicknell's Thrush and that micro-siting appears to be a promising mitigation strategy.

Keywords: renewable energy, wind and wildlife impacts, mitigation strategy, turbine micro-siting, bird occurrence, Bicknell's Thrush

Introduction

Renewable energies play a key role in meeting the global energy demand while reducing the human footprint on Earth (Wiser *et al.* 2011). Among these energies, the wind industry has been experiencing one of the fastest growths worldwide (Leung and Yang 2012, Bruckner *et al.* 2014). Although wind energy provides various environmental benefits, such as the reduction of greenhouse gas emissions for energy production, there is a growing concern that it may have adverse effects on wildlife, especially birds (Kuvlesky *et al.* 2007, Saidur *et al.* 2011). Recent estimates indicate that monopole wind turbines are responsible for 140,000 to 328,000 bird fatalities annually in the contiguous United States, where the installed capacity reached 61,000 megawatt (MW) (Loss *et al.* 2013, American Wind Energy Association 2014). In Canada, where the installed capacity is 7,800 MW (Zimmerling *et al.* 2013, CanWEA 2018), more than 23,000 birds collide with turbines annually (Zimmerling *et al.* 2013). At the Canadian scale, turbines kill fewer birds than buildings or power lines do (Calvert *et al.* 2013). However, these impacts are cumulative on bird populations. Moreover, the number of turbines is expected to grow in the near future, which may also increase bird mortality (D.O.E. 2008, CanWEA 2017).

Wind energy production can also have non-lethal impacts on birds (Drewitt and Langston 2006, Arnett *et al.* 2007, Smith and Dwyer 2016). For example, the construction of turbine pads, roads and buildings leads to habitat loss and fragmentation (Strickland *et al.* 2011). The negative impacts of habitat loss and fragmentation have been extensively documented in wildlife studies (Fahrig 2001, 2003). Although the permanent footprint of a wind energy facility is relatively small (i.e. one hectare per turbine or less than 10% of the facility's size (Strickland *et al.* 2011)), it is still larger, per unit of energy, than that of other types of energy production facilities (Kiesecker *et al.* 2011). Accordingly, habitat loss and fragmentation due to wind energy production have been shown to negatively impact bird populations (Drewitt and Langston 2006, Zimmerling *et al.* 2013, Marques *et al.* 2019).

Furthermore, the construction and operation of wind energy facilities create disturbances such as heavy machinery activity, vehicular traffic, maintenance visits, turbine noise and movement (Strickland *et al.* 2011). For its part, disturbance can lead to behavioural avoidance such as individual displacement (Marques *et al.* 2014, May 2015). For example, several grassland birds were displaced from turbine pads (Leddy *et al.* 1999, Pearce-Higgins *et al.* 2012, Shaffer and Buhl 2016). To our knowledge, very little information is available on the response of high elevation songbirds to wind energy production (but see Parrish 2013). This is a concern because, in mountainous regions, facilities are often installed on mountaintops, where orographic winds provide higher potential incomes (Katzner *et al.* 2012, CanWEA 2017). Therefore, further research is needed to assess the impacts of wind energy production on birds that live at high elevation.

Not all species are equal when it comes to the impacts of wind turbines. On one hand, some birds are not impacted by wind turbines (Minderman *et al.* 2012, Hale *et al.* 2014), and others are even attracted to them (Pearce-Higgins *et al.* 2012, Vanermen *et al.* 2013). On the other hand, some species may be critically threatened by the wind industry. This is the case for the Bicknell's Thrush *Catharus bicknelli*, a species of conservation concern that is among the most range-restricted birds in North America (COSEWIC 2009, BirdLife International 2016). This thrush breeds in high elevation forests that are prized by the wind industry (Lambert *et al.* 2005, Environnement and Climate Change Canada 2016, Hill and Lloyd 2017). Consequently, both Canadian and international conservation plans called for an urgent investigation of the effects of wind energy production on this species (Environnement and Climate Change Canada 2016, Lloyd and McFarland 2017).

To date, only one study answered the call. In a master's thesis, Parrish (2013) found no difference in the abundance of Bicknell's Thrush before, during and after the construction a 15-turbine wind farm in New Hampshire, United States. Although these results seem encouraging, they may not represent the larger facilities frequently found in the species' breeding range. For example, facilities in the province of Quebec, Canada, have an average of 50 turbines. Considering that this province houses 95% of the species breeding habitat in Canada, understanding the potential impact of larger facilities is essential to ensure the conservation of the species. In addition, Parrish (2013) documented the species' response to the wind farm only one year following its construction. He may not have detected the full range of response of this species, which exhibits high site fidelity and tends to return to previously-used breeding areas (Nixon *et al.* 2001, Rimmer *et al.* 2004). For this reason, researchers have advocated for longer environmental impact assessments (Drewitt and Langston 2006, Farfán *et al.* 2017).

A set of mitigation strategies have been developed to reconcile the wind industry to the needs of wildlife (Strickland *et al.* 2011). One of these strategies is micro-siting, which aims to mitigate the impacts of wind farms by avoiding to build turbines and roads in the habitat of the focal species (Marques *et al.* 2014). While this appear to be a promising strategy, the effectiveness of mitigation strategies is rarely tested empirically (Marques *et al.* 2014), and, consequently, ineffective strategies could further impair the preservation of vulnerable species.

In our study, we tested the impacts of wind energy production on the Bicknell's Thrush in cases where mitigation strategies were and were not applied. Our first objective was to test the hypothesis that the occurrence of the species would be lower during the construction and short-term operation of wind farms than later after construction when mitigation strategies were not applied. We predicted that the occurrence of the species would decrease with the proportion of forest loss and that it would increase with distance from turbines, at least in the short term. Our second objective was to test the hypothesis that micro-siting was an effective mitigation strategy. We predicted that the occurrence of the species would be the same before and after the construction of a facility applying micro-siting. We also predicted that, in this facility, the occurrence of the species would be more strongly linked to habitat characteristics than to wind farm characteristics.

Methods

First study area: a wind energy facility without mitigation

We selected a 60-turbine facility without mitigation strategies to test our first hypothesis. It was located in the balsam fir-white birch domain of the continuous boreal forest, near the town of Murdochville, Quebec, Canada (48.96°N; 65.52°W; Figure 1a). NextEra Energy Canada built this facility between 2003 and 2005, and it has exploited its 1.8 MW Vestas V80 turbines since then. In Quebec, the Bicknell's Thrush was designated as a vulnerable species only in 2009 (MFFP 2019). Therefore, at the time of the construction, no mitigation strategy was mandatory nor applied even though the facility was located in one of the core areas of the species' breeding range (MDDEFP 2013). Turbines were shared between two mountains (Copper and Miller) separated by approximately 5 km and located west and east from the town. Turbines were distributed in a 26.8 km^2 area (2.24 tubines.km^{-2}). Mean elevation above sea level at turbine location ± standard deviation (SD) was 831 ± 48 m (range: 727–927 m) and mean distance between adjacent turbines ± SD was 386 ± 80 m (range: 308–694 m).

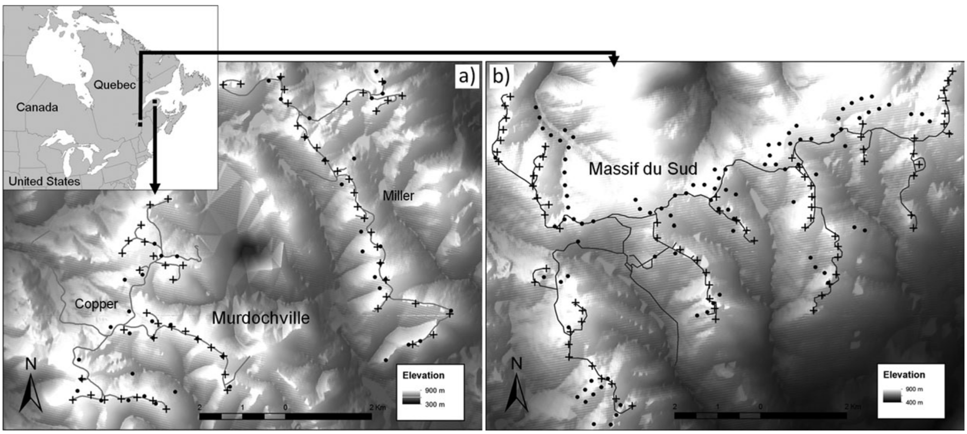

Figure 1. Location and configuration of two wind energy facilities located in Quebec, Canada. a) Murdochville had no mitigation strategy. b) Massif du Sud applied micro-siting as a mitigation strategy. Point-count stations, wind turbines and road networks are respectively represented by black dots, crosses and grey lines.

https://doi.org/10.1017/S095927092000012X Published online by Cambridge University Press

The Bicknell's Thrush was monitored using a repeated impact gradient design. Forty-six point-count stations were distributed in the facility (23 per mountain) to cover a distance gradient from turbines, i.e. from 11 to 725 m from turbines (mean ± SD: 202 ± 164 m). The mean distance between adjacent point-count stations was 439 ± 166 m. In 2004, point-count stations were sampled in the middle of the three-year construction timeframe. At the time, deforestation for access roads and turbine pads was underway and 10 out of 60 turbines were installed, although none was operational. Stations were revisited one year after the end of the construction (2006) and again eight years post-construction (2013).

Second study area: a wind energy facility with a mitigation strategy

We selected a 75-turbine facility with a mitigation strategy to test our second hypothesis. It was also located in a core area of the species' breeding range. It was located on a high elevation plateau dominated by balsam fir *Abies balsamea* in the sugar maple-yellow birch domain, near the Massif du Sud, Quebec (46.6°N, 70.5°W; Figure 1b). Enbridge and EDF EN Canada built the facility between 2011 and 2013, and they have exploited their 31 MM82 and 44 MM93 2 MW turbines since then.

The potential impacts of the facility on the species were mitigated using micro-siting, i.e. avoiding construction of turbine pads and roads in the species' habitat (Marques *et al.* 2014). To do so, the guidelines of the provincial authorities were followed (MDDEFP 2013). The occurrence of the Bicknell's Thrush was monitored before the construction at all the predetermined locations of turbines pads and roads, as well as at locations outside planned disturbances, which represented 'control' treatments. Then, turbine sitting was guided by the species' occurrence and by habitat characterisation: when a station was occupied and its habitat was classified as 'optimal', turbines were excluded from a 250 m buffer zone surrounding the station (MDDEFP 2013). Here, 'optimal' was defined as follows: stem density > 15,000 stems/ha; species composition ≥ 75% balsam fir; height of small stems (1–7 cm diameter at breast height) between 2 and 12 m (MDDEFP 2013).

Turbines were distributed in a 56.2 km^2 area (1.33 $turbines.km^{-2}$). The mean elevation of turbines ± SD was 770 ± 38 m (range: 676–841 m), and the mean distance between adjacent turbines ± SD was 289 ± 55 m (range: 226–469 m).

In 2007, 97 stations were sampled six years before construction. In 2013, these stations were resampled three years after construction. Although the sampling design resembled to a before-after-control-impact (BACI) design, we did not use this approach because other social, economic, and environmental factors also influenced turbine location, which unbalanced the BACI design. Instead, we used a repeated impact design gradient, like we did in the first study area. Here, however, we did have data for the before period. Stations covered a distance gradient from turbines, i.e. from 34 to 797 m from turbines (mean ± SD: 440 ± 199 m).

Bicknell's thrush surveys

At the facility without mitigation, we monitored point-count stations between 3 and 19 June (median sampling date: 12 June in 2004, 16 June in 2006 and 8 June in 2013), during the peak of the breeding period (Townsend *et al.* 2015). Sampling periods were longer at the facility with mitigation, in part because we had twice as many stations to monitor and varied from 30 May to 27 July. However, most stations were also sampled during the peak of the breeding period (median sampling date: 10 June in 2007 and 2 June in 2016). At the end of May, pair formation is well underway, and nest building starts in early June; clutch initiation dates can vary from 6 June to 20 July in Québec, and fledging dates vary from 8 to 24 July (Townsend *et al.* 2015).

We sampled the species during the dawn (03h00 to 06h30 eastern daylight time) and dusk (18h00 to 21h00 eastern daylight time) choruses (Ball 2000). Each point-count lasted 26 min including a 1-min period at minute 15 during which we broadcast conspecific calls to increase the probability of detection of the species. We recorded the number of thrushes within 100 m of the observer at each station using a conservative approach to ensure that new individuals were added only if the observer could eliminate the possibility of double counting (Aubry *et al.* 2016).

Data analyses

We tested a similar set of candidate models for each facility in order to determine which combination of variables best explained the probability of occurrence of the species while taking into account habitat covariates and period since construction. We chose to model the probability of occurrence rather than abundance because only one individual was detected at most point-count stations (78% at the facility without mitigation, and 91% at the facility with mitigation). Therefore, both variables were strongly correlated (point-biserial correlation at the facility without mitigation: $r_{pb} = 0.82$; at the facility with mitigation: $r_{pb} = 0.83$). This finding had previously been reported (Aubry *et al.* 2016).

We used generalized linear mixed models with a binomial family, and we took into account the repetition among the years by considering point-count stations as a random effect ('lme4' library version 1.1-12; Bates *et al.* 2015, R Development Core Team 2016). In Murdochville, nesting stations within mountains, i.e. Copper or Miller, did not influence the model selection, so we only kept stations as a random effect.

We carefully selected the candidate models to respect the concept of parsimony, and we only included interactions that we believed to be meaningful *a priori* (Burnham and Anderson 2002). In addition, each set of models included a null model as well as a model testing only for a period effect. We did not include strongly correlated variables ($r \geq |0.60|$) in the same candidate model to reduce multicollinearity. We ranked candidate models based on the second order Akaike's information criterion (AIC_c; Burnham and Anderson 2002) using the 'aictab' function of the AICcmodavg library version 2.1-0 (Mazerolle 2016). Also, we used model averaging to minimize the effect of uninformative parameters, using the mod.avg function of the MuMIn library version 1.40.0 (Bartoń 2017). We computed parameter-averaged predictions using the modavgPred function of the AICcmodavg library (Anderson 2007, Mazerolle 2016). Parameter-averaged predictions were presented over the measured range of each variable of interest while holding other variables at their mean value. Prior to model building, environmental variables were scaled to account for different ranges of measurement among them according to the following formula: $(x_i - \bar{x})/SD(x)$.

Environmental and anthropic variables

We tested the impacts of two variables directly linked to the facility (forest loss and distance to the nearest turbine), while taking into account important habitat covariates for the species (i.e. elevation and an index of habitat suitability), and the period since construction (during, one year post-, and eight years post-construction at the facility without mitigation; six years before or three years after construction at the facility with mitigation). First, we calculated the proportion of forest loss in a 250 m buffer centred on the point-count stations (~ 196,000 m^2), which corresponds to the mean home range size of the species in Eastern Canada (Aubry *et al.* 2011). We quantified forest loss caused by roads and pads using ArcMap 10.4.2 (ESRI 2016), based on satellites images provided by Google Earth. We included reforested pads and road borders in this calculation because plantations are not occupied by Bicknell's Thrush until they are at least 11 to 25 years old (Connolly *et al.* 2002, Chisholm and Leonard 2008).

Second, we calculated the distance of each point-count station to the nearest turbine in ArcMap. Third, we measured elevation (m) at the centre of each point-count station using a Global Positioning System (Garmin International Inc., Olathe, KS, USA; Table 1) because elevation is a well-documented predictor of the species distribution (Aubry *et al.* 2016).

Fourth, we calculated an index of habitat suitability inspired by the one created by the provincial authorities (MDDEFP 2013). We could not directly use their index as it was calculated from field

https://doi.org/10.1017/S095927092000012X Published online by Cambridge University Press

Table 1. Description of the four environmental variables used in the model comparisons aiming to explain the probability of occurrence of the Bicknell's Thrush at two wind energy facilities located in Quebec, Canada.

		Facility with mitigation				Facility without mitigation			
Variable	Description	Min.	Max.	Median	Mean ± SD	Min.	Max.	Median	Mean ± SD
Forest loss	Proportion of forest habitat lost for the construction of the facility in a 250 m buffer centred on point-count station	0.00	0.19	0.02	0.04 ± 0.05	0.00	0.23	0.08	0.09 ± 0.06
distance	Distance (m) from point-count station to the nearest turbine	37	797	460	440 ± 199	11	725	189	202 ± 164
elevation	Elevation (m) above sea level at point-count station	680	880	768	766 ± 48	699	896	799	801 ± 61
habitat suitability	Proportion of regenerating stands, i.e. 2-12 m high, dominated by balsam fir in a 250 m buffer centred on point-count station l of 250 mzone	0.00	0.95	0.15	0.28 ± 0.29	0.00	0.96	0.65	0.59 ± 0.26

surveys at occupied stations, but we needed this information for all our stations, including the unoccupied ones. Therefore, we calculated the proportion of regenerating stands (i.e. stands ranging from 2 to 12 m in height) dominated by balsam fir in a 250 m radius buffer centred on a point-count station, based on eco-forestry maps updated for each year of sampling (Lord and Faucher 2003, Government of Quebec 2009).

Results

Effects of a wind energy facility without mitigation

In line with our first hypothesis, the probability of occurrence of the Bicknell's Thrush increased on the medium term (eight years post-construction) compared to during construction or the short term (one-year post-construction) (Figure 2a). However, this effect only applied at higher elevations, i.e. above 800 m, whereas species occurrence remained stable at lower elevations during, one year after, or eight years after construction (Figure 2a). Moreover, the species was positively associated with forest loss, which is opposite to our prediction (Figure 2b). Also, contrary to our prediction, the occurrence of the thrush did not seem influenced by distance from turbines (Table 2a).

Among the 11 candidate models, only two had a substantial level of empirical support (i.e. $\Delta AIC_c < 2$), and together they accounted for 50% of the model selection's weight (Appendix S1a in the online supplementary material). The first model indicated that, eight years post-construction, the probability of occurrence of the species was greater at higher elevations. This effect was strong in the averaged model (Table 2a). The second model included the same variables plus an index of habitat suitability (Appendix S1a). However, when two models differ by only one variable, the empirical support for the model with the extra variable is weak (Burnham and Anderson 2002, Arnold 2010). Accordingly, the habitat suitability index was a poor predictor of the probability of occurrence of the Bicknell's Thrush in the averaged model (Table 2a).

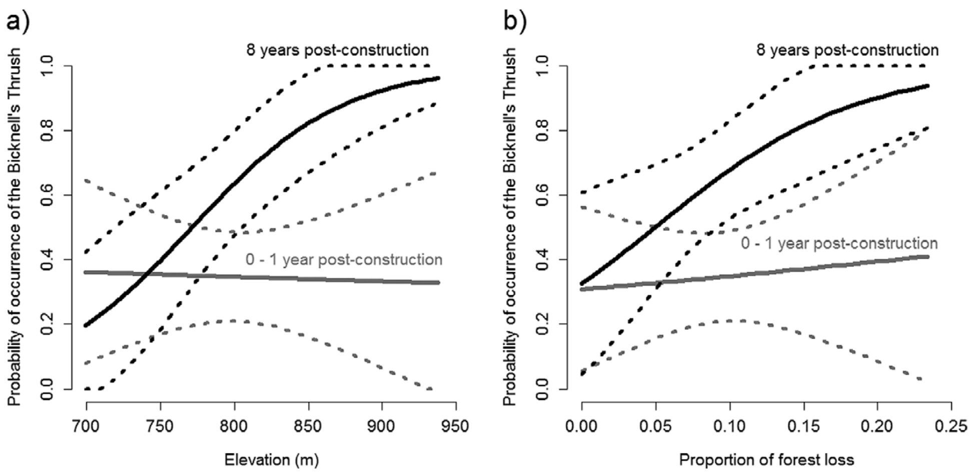

Figure 2. Multi-model averaged predictions representing the probability of occurrence of the Bicknell's Thrush at a facility without mitigation as a function of a) elevation (m) at point-count station, and b) forest loss. Effects of elevation and forest loss on the probability of occurrence of the species were not significant during the construction or one-year post-construction. Grey lines therefore represent the fitted regression and 95% confidence interval averaged during these two periods. Black lines represent the fitted regression and 95% confidence interval eight years after the construction.

https://doi.org/10.1017/S095927092000012X Published online by Cambridge University Press

Table 2. Estimated coefficients (β), standard errors (SE) and 95% confidence intervals (lower and upper CI) of environmental variables included in the averaged model explaining the probability of occurrence of the Bicknell's Thrush at two wind energy facilities located in Quebec, Canada.

Variable	*B*	SE	lower CI	upper CI
a) Facility without mitigation				
elevation (construction)	-0.04	0.33	-0.69	0.61
elevation (1 year post-construction)	-0.03	0.33	-0.68	0.62
elevation (8 years post-construction)	**1.19**	**0.43**	**-2.03**	**-0.35**
distance (construction)	-0.32	0.38	-1.06	0.42
distance (1 year post-construction)	0.28	0.35	-0.97	0.41
distance (8 years post-construction)	-0.37	0.48	-1.31	0.57
forest loss (construction)	0.22	0.32	-0.85	0.41
forest loss (1 year post-construction)	-0.01	0.32	-0.64	0.62
forest loss (8 years post-construction)	**0.84**	**0.40**	**-1.62**	**-0.06**
habitat suitability	0.26	0.20	-0.65	0.13
b) Facility with mitigation elevation	**1.10**	**0.30**	**-1.69**	**-0.51**
distance (6 years pre-construction)	0.35	0.31	-0.96	0.26
distance (3 years post-construction)	0.46	0.37	-1.19	0.27
forest loss (6 years pre-construction)	**-0.86**	**0.39**	**-1.62**	**-0.10**
forest loss (3 years post-construction)	-0.32	0.36	-1.03	0.39
habitat suitability	-0.03	0.27	-0.38	0.50

Forest loss and elevation were not included in the same candidate model because turbines were erected on mountaintops in this facility. Consequently, forest loss was correlated with elevation (r = 0.68). However, forest loss did not strongly compete for the best model. While elevation was included in the top model, the model including forest loss only ranked fourth ($\Delta AIC_c = 5.02$; $AIC_\omega = 0.02$; Appendix S1a). Therefore, elevation played a stronger role than forest loss in predicting the probability of occurrence of the Bicknell's Thrush. Despite their correlation, both variables ended up in the averaged model (Table 2a), in which the effect of forest loss on the species was similar to the effect of elevation (Figure 2).

Distance to the nearest turbine was also correlated with elevation (r = -0.55). However, we included both variables in the same candidate models as their correlation was below our selected threshold ($r \geq |0.60|$). Nonetheless, distance from turbines did not influence the species' occurrence, and it was only included in the models ranking fifth and lower ($\Delta AIC_c = 5.08$; $AIC_\omega = 0.02$; Appendix S1a). Lastly, the influence of distance from turbines was weak in the averaged model, suggesting that the species did not respond to this variable (Table 2a).

Effects of a wind energy facility with a mitigation strategy

Although overall occurrence of the Bicknell's Thrush decreased from 28% (27 out of 97 occupied stations) before construction to 18% (17 out of 97 occupied stations) after construction of a facility with a mitigation strategy, we could not detect any effect of wind energy development when micro-siting was applied as indicated by the weak effect of the period (Table 2b). Also as predicted, habitat characteristics were stronger predictors than facility characteristics. When micro-siting was applied, the strongest predictor of the probability of occurrence of the species was elevation (Table 2b). Elevation was part of the unique model that had a substantial level of empirical support ($\Delta AIC_c < 2$; $AIC\omega = 0.52$; Appendix S1b). Similar to the facility without mitigation, the probability of occurrence of the Bicknell's Thrush strongly increased with elevation (Figure 3a). Here, however, the effect was not influenced by period, indicating that the species seemed to weakly respond to the construction of the facility with mitigation (Table 2b). Together, these results tended to support our second hypothesis that micro-siting was an effective mitigation strategy.

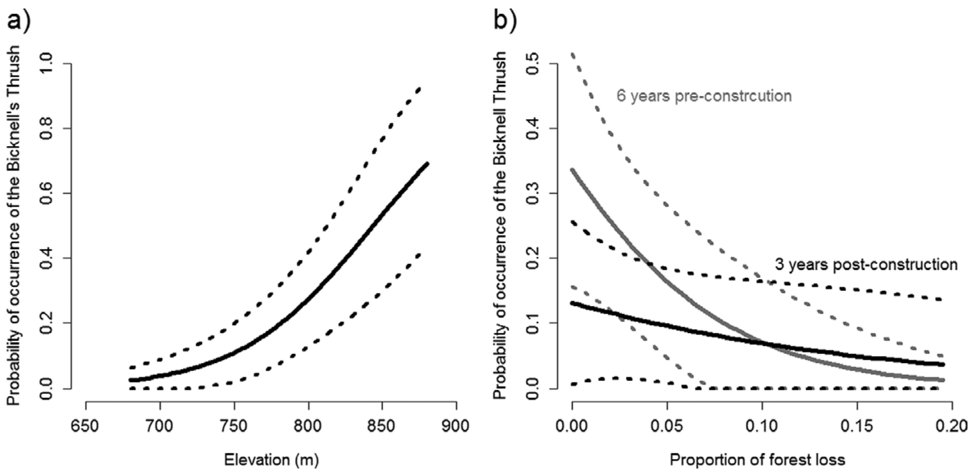

Figure 3. Multi-model averaged predictions representing the probability of occurrence of the Bicknell's Thrush at a facility with micro-siting as mitigation strategy as a function of a) elevation (m) ASL at point-count station and b) forest loss. The effect of elevation on the probability of occurrence of the species was significant during the construction and one-year post-construction. Black lines in a) therefore represent the fitted regression and 95% confidence interval averaged during these two periods.

Nonetheless, the sampling period did have a weak effect on the species when in interaction with forest loss (Table 2b). Indeed, the probability of occurrence seemed to decrease with forest loss, and this effect tended to by higher six years before construction rather than three years after (Figure 3b). However, the strong overlap of the confidence intervals indicates that the difference between periods was weak (Figure 3b). Moreover, the meaning of forest loss was not intuitive six years before construction. Indeed, no construction was underway at that time, so no forest was really lost. Instead, this variable represented the projected amount of forest to be lost due to construction. Therefore, its negative relationship with the Bicknell's probability of occurrence indicated that forest loss was preferentially planned at unoccupied stations.

Finally, as for the facility without mitigation, the distance to the nearest turbine and the habitat suitability index were poor predictors of the species' probability of occurrence (Appendix S1b; Table 2b).

Discussion

For many bird species, the impacts of wind energy production still need to be clarified. In addition, the effectiveness of mitigation strategies still needs to be demonstrated in order to design sustainable, bird-friendly facilities. Our study showed that the construction of a wind energy facility and its short-term operation (one-year post-construction) had greater impacts on the threatened Bicknell's Thrush than mid-term operation (eight years post-construction). We also suggest that turbine micro-siting is an effective mitigation strategy. Indeed, despite a robust sampling design and an important sample size, we could not detect a significant impact of wind energy development on the species' occurrence when micro-siting was applied.

Construction had greater impacts than operation

Without mitigation, the construction of a facility decreased the occurrence of the Bicknell's Thrush at higher elevations. In the literature, the species is almost always found at higher elevations

(Nixon *et al.* 2001, Chisholm and Leonard 2008, Aubry *et al.* 2016). Accordingly, we found a strong association with elevation eight years post-construction. However, the Bicknell's Thrush was not associated with elevation during or one year after construction. During these periods, the probability of occurrence at higher elevations (above 800 m) was half the one found eight years post-construction. For its part, abundance should have followed a similar pattern because, as found elsewhere (Aubry *et al.* 2016), it was strongly correlated with occurrence in our study area. We believe that individuals that left the mountaintops migrated outside the facility as we did not detect a corresponding increase in abundance at lower elevations.

In addition, the species did not respond to distance from turbines in any of the two study areas. This result supports the assertion that operation had fewer impacts than construction, a result already reported elsewhere (Pearce-Higgins *et al.* 2012, Garcia *et al.* 2015). Construction impacts cannot entirely be attributed to forest loss because the construction of roads and pads causes permanent forest loss, so its effect should remain stable over several years (Strickland *et al.* 2011). Instead, we propose that construction noise and activity, caused by the presence of heavy machinery, have the greatest impacts on the bird. Indeed, negative impacts of traffic noise have been empirically demonstrated on birds (McClure *et al.* 2013). Considering the remoteness of our study areas, traffic activity and noise were mostly only present during the construction phase. Consequently, we recommend constructing wind farms outside of the breeding period to mitigate impacts on bird species.

Turbine micro-siting: an effective mitigation strategy

We suggest that turbine micro-siting is an effective mitigation strategy. Indeed, we only found weak support for differential use of the facility's area by the Bicknell's Thrush before and after the construction of a facility applying this strategy. Of course, when the null hypothesis is not rejected (here, no difference before and after the construction), the observed pattern might be caused by an absence of evidence, instead of being evidence of absence. However, we believe that our study was robust to such an issue, and that the species actually did not strongly respond to the construction because turbine micro-siting was an effective mitigation strategy.

First, the sample size seemed adequate to detect a potential effect of period on the probability of occurrence of the Bicknell's Thrush. Indeed, an effect of period was detected in the facility without mitigation even though its number of sampling points was half that of the facility with mitigation (46 vs. 97 point-counts). In addition, the different findings cannot be associated with different methodologies because the modelling approach and the variable selections were the same for both facilities. Moreover, we demonstrated that, in the facility with mitigation, forest loss was adequately planned outside of occupied sites. Second, we are confident that our modelling approach represented actual biological patterns because, as was the case for the first study area, the well-known relationship of the Bicknell's Thrush with elevation was adequately identified (Atwood *et al.* 1996, Nixon *et al.* 2001, Lambert *et al.* 2005, Chisholm and Leonard 2008, Aubry *et al.* 2016). Therefore, we suggest that if no mitigation strategy had been applied to this 75-turbine facility, an impact of construction would have been detected, as was the case for the 60-turbine facility.

Adaptive management calls for testing the effectiveness of mitigation strategies, but it is rarely done in practice (May 2017). To our knowledge, our study is the first to test and demonstrate the effectiveness of turbine micro-siting to reduce the impact of wind energy production on the Bicknell's Thrush. We expect smaller facilities to have even lower impacts on the species, as long as turbines are adequately located outside of occupied sites.

Potential positive impacts on the medium term

Our study design did not allow us to determine the level of recovery of the Bicknell's Thrush after the construction without mitigation, because we could not assess the population abundance prior to impact at that facility. Therefore, we are unsure whether the local population was on its way to recovery after eight years, or if it had already recovered or was even higher than before. Indeed, the Bicknell's Thrush has already been observed near disturbed areas such as roads (Rimmer *et al.* 2004, Townsend *et al.* 2015), and it may preferentially use edge habitats in the industrial forest landscape (Aubry *et al.* 2011). We suggest that future studies verify whether wind farms could benefit the Bicknell's Thrush in the medium term. If this is the case, mitigation strategies could be enhanced by taking into account both the negative short-term impacts, and the 'potentially' positive impacts on the medium term.

In addition, our study underlined the importance of studying animal responses to human disturbance over several years. Indeed, we found no difference between the periods during construction and one-year post-construction of a wind farm without mitigation, and it was only eight years after construction that we gained a better insight of the species' response. Similarly, the only other study on the subject did not find a differential response of the Bicknell's Thrush one year before, during or one year after the construction of a 15-turbine facility in New Hampshire (Parrish 2013). Maybe the high site fidelity expressed by the Bicknell's Thrush prevented individuals from responding quickly to the construction of wind farms, and thus generating a delayed response (Nixon *et al.* 2001, Parrish 2013). Also, the species may have responded less strongly in Parrish's study because the facility was four times smaller than ours and thus had less impact on the bird. However, large facilities are more frequent than smaller ones in the Canadian breeding range (average size is about 50 turbines).

Mitigating impacts for the Bicknell's Thrush: a bird community's perspective

Nowadays, species-specific conservation measures may raise concerns because of the number of vulnerable species that may need protection. However, not all species are equal regarding conservation actions. Whereas some species may be pooled together in a coarse filter approach, some species have species-specific needs that still must be addressed separately, according to the fine-filter approach (Tingley *et al.* 2014). This is the case for the Bicknell's Thrush because it is one of the most threatened and most range-restricted bird species in North America (Lloyd and McFarland 2017). Nonetheless, this so-called fine-filter should benefit 11 other species co-occurring with the Bicknell's Thrush, such as the American Three-toed Woodpecker *Picoides dorsalis*, the Bay-breasted Warbler *Setophaga castanea* or the Blackpoll Warbler *Setophaga striata*) (Environnement and Climate Change Canada 2016, Lloyd and McFarland 2017). Moreover, the Olive-sided Flycatcher *Contopus cooperi*, another species of concern, is among the species that should benefit from conservation actions directed toward the Bicknell's Thrush (Environnement and Climate Change Canada 2016, Lloyd and McFarland 2017).

Challenges in modelling habitat selection of the Bicknell's Thrush

The Bicknell's Thrush did not respond to our index of habitat suitability in any of the two study areas. On the one hand, the scientific community seems to know relatively well its habitats preferences. For example, the species exhibited a preference for dense (≥ 10,000–15,000 stems. ha^{-1}) coniferous stands dominated by balsam fir (Connolly *et al.* 2002, Aubry *et al.* 2011). On the other hand, elevation often outperformed habitat predictors (e.g. Aubry *et al.* 2016). To date, it is not clear whether this represents a true biological mechanism or is simply an artefact of a technological issue. For example, the species may respond to habitat characteristics that are not yet detected by current eco-forest layers. Hopefully, with the democratization of more advanced mapping tools such as the LIDAR technology, the effects of elevation could be disentangled from those of habitat characteristics.

Also, other biological variables may influence the species' habitat selection and, ultimately, the modelling approaches. For example, predation is a known influencer of songbird population dynamics (Schmidt and Ostfeld 2003). In our study, we limited the number of independent variables according to the parsimonious principle (Burnham and Anderson 2002). If possible, the next variable that we would have included in our models would have been predation. The main predator of Bicknell's Thrush nests is the American red squirrel *Tamiasciurus hudsonicus*, and it can easily be monitored by its alarm calls and vocalizations during point-counts (McFarland *et al.* 2008). However, we doubt that predation would have influenced our models because the squirrel's occurrence at point-count stations was low and constant over the course of our study (3–4%).

Conclusion

The rapid increase in wind energy production poses important conservation challenges. On the one hand, this renewable resource should help reduce the human footprint on Earth, but on the other hand, it may negatively impact some of the most vulnerable wildlife populations, including the threatened Bicknell's Thrush. Our study aimed to document the impacts of wind energy facilities on the bird, as well as assess the effectiveness of turbine micro-siting to mitigate the impacts, thus answering an urgent need identified by the conservation community (Lloyd and McFarland 2017).

We showed that construction, rather than operation, had greater impacts on the species. In addition, we demonstrated that turbine micro-siting, a mitigation strategy that aims to avoid constructing turbines and roads in the species' habitat, was effective in further reducing the impacts on the threatened thrush. Therefore, we propose to extend turbine micro-siting to the entire breeding range of the species, which is concentrated in north-eastern North America, in order to preserve the species. Also, greater impacts of construction were probably linked to activity and noise of heavy machinery. Therefore, we suggest constructing wind energy facilities outside of the breeding period of songbirds to further mitigate the impacts.

Encouragingly, the Bicknell's Thrush returned to disturbed sites a few years after the construction. This pattern would need further investigation because it might indicate that wind energy facilities could even favour the species on the medium term by creating suitable habitat through disturbances. However, this hypothesis still needs to be tested.

Supplementary Materials

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/S095927092000012X.

Acknowledgements

This study would not have been possible without the contribution of several stakeholders. First, we thank NextEra Energy Canada, Enbridge, and EDF EN Canada, who provided access to the wind energy facilities and offered logistical support. We are deeply grateful to Yves Aubry, Junior Tremblay, Environment and Climate Change Canada and the Canadian Wildlife Service for offering incredible support for this study by sharing the pre-construction data from the Massif du Sud, contributing to field work, and providing invaluable advice. Y. Aubry also reviewed an earlier version of this manuscript. We are also grateful to two anonymous reviewers who provided helpful comments. We would also like to thank SNC-Lavalin and Activa Environnement, who conducted the 2004 and 2006 surveys at Murdocvhille. Finally, we are grateful to the biologists and wildlife technicians at the Ministère des Forêts, de la Faune et des Parcs and QuebecOiseaux for tracking the species in its most remote habitats (in alphabetical order): P. Beaupré, S. Déry, C. Dion, R. Faubert, D, Guérin, M.F. Julien, C. Laurendeau, D. Lavergne, S. Pelletier, G. Roy, S. Sherman-Quirion, G. Tremblay and E. Trépanier. This research was funded by the Ministère des Forêts, de la Faune et des Parcs. Environment and Climate Change Canada and the Canadian Wildlife Service funded the field work of 2007 at Massif du Sud, and Énergie Éolienne du Miller funded the field works of 2004 and 2006 at Murdochville.

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