Using residential proximity to wind turbines as an alternative exposure measure to investigate the association between wind turbines and human health

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This analysis uses data from the Community Noise and Health Study developed by Statistics Canada to investigate the association between residential proximity to wind turbines and health-related outcomes in a dataset that also provides objective measures of wind turbine noise. The findings indicate that residential proximity to wind turbines is correlated with annoyance and health-related quality of life measures. These associations differ in some respects from associations with noise measurements. Results can be used to support discussions between communities and wind-turbine developers regarding potential health effects of wind turbines.
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I. INTRODUCTION

Despite support for developing renewable energy sources, wind farm projects have been the subject of controversy. The human health concerns that have been raised have been attributed to exposures to audible sound, low-frequency sound pressures (i.e., sub-audible or "infra-sound"), vibrations and shadow flicker patterns from the rotation of the blades (Feder *et al.*, 2015; McCunney *et al.*, 2014; Michaud *et al.*, 2012). To date, the epidemiological literature has demonstrated an association between wind turbine noise and annoyance, between wind turbine noise and quality of life indicators, and between wind turbine noise and sleep disturbances (Michaud *et al.*, 2016; Onakpoya *et al.*, 2015).

Health Canada and Statistics Canada conducted a study of wind turbines and health, the Community Noise and Health Survey (CNHS), which included both objective and subjective measures of health and exposure (Feder *et al.*, 2015; Michaud *et al.*, 2012). Several rigorous analyses have been published that examine the relationship between objective measures of wind turbine noise (WTN) and self-reported sleep-related measures, quality of life indicators, stress-related responses, health effects, and annoyance.

The main exposure used in the Community Noise and Health Survey was modelled outdoor A-weighted wind turbine sound pressure levels using the ISO 9613-1 and the ISO 9613-2 (Feder *et al.*, 2015; Keith *et al.*, 2016). This measure is based on manufacturers' octave band sound power spectra at an assumed wind speed of 8 m/s. It assumes that the dwelling is located downwind of the sound source, that there is a stable atmosphere, and that there is a moderate ground based temperature inversion (Feder *et al.*, 2015; Keith *et al.*, 2016). The manufacturers' sound power levels were validated for 10 of the 399 wind turbines included in the study (Keith *et al.*, 2016). Published findings from the Community Noise and Health Survey suggest that wind turbine noise is not associated with any adverse outcomes except for annoyance (Michaud *et al.*, 2016).

A-weighted measures are a standard method of quantifying exposure to wind turbine noise, although there is some debate over which noise measurement approach is the most appropriate to relate to human response (Keith *et al.*, 2016). If the reported annoyance is not due to noise, then sound pressure levels may serve as a surrogate for factors that are more closely associated with annoyance. We aimed to evaluate whether some aspect of living in proximity to wind turbines, perhaps summarized as a subjective experience, may explain the health and annoyance effects of WTN that have been reported in the CNHS and other studies. The CNHS dataset allows for direct comparison between analyses that evaluate the association between the objective WTN measure (i.e., sound pressure levels), and analyses evaluating residential distance to wind turbines as a measure that might capture at least some of the subjective element of wind turbine (WT) exposure.

II. METHODS

A. Study sample

The study sample comprised people living in proximity to a wind turbine in Ontario or Prince Edward Island, who participated in the CNHS, a one-time survey conducted in 2012–2013. The sample size was 1238 people. Sampling methods are described in multiple previous papers by Michaud *et al.* (2012, 2015, 2016). To summarize, all homes within 600 m of wind turbine were selected, and homes up to 10 km from wind turbines were randomly selected. One participant from each residence who was between ages 18−79 yr was selected randomly to participate. No substitutions were permitted. The response rate was 78.9% (Michaud *et al.*, 2012).

B. Analysis

Distance to wind turbines in kilometres was used as the primary predictor to build each of the models. Distance was modelled as a continuous variable and log-transformed to

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normalize the distribution. The outcomes of interest included quality of life indicators in the environmental, physical, social, and psychological domains measured using the WHOQOL-BREF (WHOQOL Group, 1998). The environment domain included the following facets: financial resources, freedom, physical safety and security, social care, home environment, opportunities for new skills and information, recreation, and leisure activities. The physical health domain included the following facets: activities of daily living, energy and fatigue, mobility, dependence on medicinal substances, pain and discomfort, sleep and rest, and work capacity. The social relationships domain included: personal relationships, social support, and sexual activity. The psychological domain included: body image, negative and positive feelings, self-esteem, and spirituality, thinking, learning, memory and concentration. Other outcomes of interest included reported annoyance, sleep measures (rate of awakenings, sleep efficiency, sleep latency, awakenings after sleep onset, and total sleep time) measured with sleep actigraphs, sleep quality measured using the Pittsburgh Sleep Quality Index, blood pressure, hair cortisol levels, perceived stress measured using the perceived stress scale and heart rate.

Potential covariates were explored through multiple individual multivariable analyses where each potential covariate was modelled to predict the outcomes of interest. If the p-value for the relationship between the potential covariate and the outcome of interest was less than 0.20, the covariate was included in the final model (Jewell, 2003). Then, stepwise elimination was performed to exclude covariates with a p-value greater than 0.10. Potential for interaction terms and effect modification by province were examined. Generalized estimating equations (GEE) were used for repeated-measures data. For each outcome, province and reported personal benefit were forced in the final models; this is consistent with the methods described by Michaud *et al.* (Michaud, 2015; Michaud *et al.*, 2016). A second analysis was also completed where distance was substituted as the primary predictor in models previously developed by Michaud *et al.* and Feder *et al.* (Feder *et al.*, 2015; Michaud, 2015; Michaud *et al.*, 2016). This was a direct substitution, and the final models are identical, with the same covariates as those obtained using modelled WTN as the primary predictor of interest. Data management and analysis was completed using SAS version 9.4 (SAS Institute, 2013).

III. RESULTS

Results suggest that proximity to wind turbines is inversely associated with the environment domain quality of life score ($\beta = -1.23$, SE $= 0.145$, $p = 0.046$). This association suggests that every kilometre a person lives further away from a wind turbine is associated with a 1.23 point increase in score on the environmental health quality of life scale (Table I). A higher score is indicative of a higher environmental quality of life. The marginal means presented in this table show the group means for levels of each variable, controlling for all other covariates in the model. For example, people who report experiencing migraines have a lower mean environmental quality of life score (mean score = 15.18) compared to those that do not report having migraines (mean score = 15.55, $p < 0.001$), when accounting for all other covariates.

Distance to wind turbines was also found to be strongly associated with increased annoyance (OR = 0.19; 95% CI = 0.07, 0.53, $p = 0.001$). This suggests that the odds of reporting being annoyed by a turbine are reduced by about 20% for every kilometer a person lives further away from a wind turbine (Table II).

In models where proximity to wind turbines was directly substituted into the models developed using modelled wind turbine noise, the association between distance to wind turbines and annoyance was also statistically significant and demonstrated a decrease in the likelihood of annoyance with increasing residential distance from the turbine (OR = 0.31; 95% CI: 0.11, 0.84, $p = 0.022$). Michaud *et al.* also found a significant association between wind turbine noise and annoyance (OR = 2.38, 95% CI: 1.42, 3.99) (Michaud *et al.*, 2016). There was a positive association between distance to wind turbines and the scores for the physical health quality of life domain ($\beta = 1.26$, SE $= 0.20$, $p = 0.043$) where there was not a significant association between wind turbine noise and physical health [Least squared means (LSM) = 13.111 95% CI: 12.32, 13.90 for < 25 dB vs LSM = 13.45, 95% CI: 12.81, 14.10 for 40–46 dB, $p = 0.1689$] (Feder *et al.*, 2015). There were no statistically significant associations found between residential proximity to wind turbines and the other outcomes.

IV. DISCUSSION

These results show that living closer in proximity to wind turbines is negatively correlated with self-rated environmental quality of life and physical health quality of life. These findings suggest that the mechanism of effect may not be noise, or not noise alone, and may include visual sight, vibrations, shadow flicker, sub-audible low frequency sound, or mechanisms that include individual subjective experiences and attitudes towards wind turbines. These data are consistent with findings published by Shepherd *et al.* who reported that those living within 2 km of a wind turbine scored lower on both physical and environmental domains also measured using the WHOQOL-BREF, than those in a comparison group among people living in semirural New Zealand (Shepherd *et al.*, 2011). These findings are also consistent with the findings by Onakpoya *et al.* where a systematic review demonstrated an association between wind turbine noise and annoyance, and between wind turbine noise and quality of life measures (using varied instruments; Onakpoya *et al.*, 2015). The difference in findings for the different exposure measures (modeled noise vs residential distance) could also be due to characteristics of the measurements, however. Specifically, distance is measured on a continuous scale, whereas wind turbine noise was also measured on a continuous scale but then categorized, ignoring variation within each category. Also, modelled sound measures were based on multiple measures (including distance) and therefore possibly susceptible to greater measurement error.

The associations between residential distance to wind turbines and both environmental and physical quality of life scores could indicate visual disturbances due to the presence of

TABLE I. Environment domain modelled with distance as primary predictor and wind turbine noise as a primary predictor.

Variable	Groups in variable	Marginal means[a] (95% CI) ($R^2 = 0.24$, n = 985)	*p*-Value	Marginal means[b] (95% CI) ($R^2 = 0.24$, n = 985)	*p*-Value
Distance to wind turbine		1.23 (0.145)[a]	0.046		
WTN levels (dB)	<25	—		16.28 (15.58–16.98)	0.368
	25–<30	—		15.71 (14.99–16.44)	
	30–<35	—		15.75 (15.16–16.34)	
	35–<40	—		15.82 (15.28–16.36)	
	40–46	—		15.73 (15.17–16.28)	
Province	PEI	15.27 (14.69–15.85)	0.285	15.76 (15.15–16.36)	0.276
	ON	15.46 (15.00–15.94)		15.96 (15.45–16.47)	
Personal benefit from having wind turbine in the area	Yes	15.42 (14.80–16.04)	0.618	15.92 (15.26–16.57)	0.632
	No	15.31 (14.85–15.76)		15.80 (15.31–16.29)	
Age group	≤24	15.78 (15.03–16.53)	<0.001	16.34 (15.56–17.12)	<0.001
	25–44	14.95 (14.42–15.48)		15.45 (14.90–16.00)	
	44–64	14.93 (14.43–15.43)		15.42 (14.89–15.95)	
	65+	15.81 (15.25–16.37)		16.22 (15.63–16.82)	
Level of education	≤High school	—		15.60 (15.06–16.14)	0.023
	Trade/certificate/college	—		15.67 (15.13–16.21)	
	University	—		16.31 (15.63–16.99)	
Income	<60k	14.79 (14.29–15.30)	<0.001	15.33 (14.78–15.89)	<0.001
	60–100k	15.44 (14.90–15.98)		15.95 (15.37–16.52)	
	≥100k	15.86 (15.31–16.42)		16.29 (15.72–16.87)	
Property ownership	Own	15.54 (15.05–16.03)	0.091	16.05 (15.52–16.58)	0.059
	Rent	15.19 (14.62–15.77)		15.66 (15.06–16.27)	
Facade type	Fully bricked	15.60 (15.07–16.12)	0.046	16.09 (15.53–16.64)	0.079
	Partially bricked	15.26 (14.68–15.85)		15.74 (15.12–16.35)	
	No brick/other	15.24 (14.74–15.74)		15.75 (15.21–16.30)	
Number of years hearing wind turbines	Do not hear wind turbines	—		15.89 (15.38–16.39)	0.073
	Less than 1 year	—		16.10 (15.35–16.86)	
	1 year or more	—		15.59 (15.05–16.12)	
Wind turbine annoyance	Yes	15.64 (15.15–16.13)	<0.0001	—	0.001
	No	15.09 (14.45–15.73)		—	
Visual annoyance to turbines	High	15.18 (14.65–15.71)	0.005	15.58 (14.97–16.18)	
	Low	15.55 (15.03–16.07)		16.14 (15.60–16.68)	
Turbine shadow flicker annoyance	High	15.11 (14.59–15.62)	0.055	16.08 (15.43–16.73)	0.092
	Low	15.63 (15.01–16.23)		15.64 (15.11–16.16)	
Alcohol use	None	15.32 (14.78–15.86)	0.002	15.79 (15.22–16.37)	0.069
	≤3 Times per month	15.23 (14.73–15.75)		15.73 (15.19–16.28)	
	1–3 Times/week	15.65 (15.11–16.19)		16.14 (15.56–16.72)	
	≥4 Times/week	15.25 (14.66–15.85)		15.77 (15.15–16.39)	
Smoking status	Current	15.04 (14.50–15.58)	<0.0001	15.56 (14.98–16.13)	0.013
	Former	15.45 (14.92–15.98)		15.95 (15.39–16.51)	
	Never	15.61 (15.08–16.13)		16.07 (15.51–16.62)	
Migraines	Yes	15.18 (14.65–15.71)	<0.001	15.68 (15.12–16.24)	0.035
	No	15.55 (15.03-16.07)		16.04 (15.49–16.59)	
Dizziness	Yes	15.11 (14.58–15.64)	<0.001	15.58 (15.01–16.21)	0.001
	No	15.63 (15.11–16.14)		16.14 (15.59–16.69)	
Tinnitus	Yes	15.16 (14.63–15.68)	0.003	15.65 (15.09–16.21)	0.013
	No	15.58 (15.06–16.10)		16.06 (15.51–16.62)	
Chronic pain	Yes	15.10 (14.59–15.63)	<0.001	15.60 (15.04–16.16)	0.001
	No	15.62 (15.11–16.14)		16.12 (15.57–16.66)	
Asthma	Yes	15.11 (14.49–15.72)	0.030	15.61 (14.96–16.25)	0.037
	No	15.63 (15.15–16.10)		16.11 (15.60–16.622)	
High blood pressure	Yes	15.22 (14.68–15.77)	0.044	—	
	No	15.50 (15.01–16.00)		—	
Diagnosed sleep disorder	Yes	15.07 (14.48–15.66)	0.010	15.51 (14.89–16.14)	0.002
	No	15.66 (15.17–16.15)		16.20 (15.68–16.73)	

[a]Distance as primary predictor.
[b]Wind turbine noise as a primary predictor.

TABLE II. Multiple logistic regression model.

	Multiple logistic regression model[a] (n = 1086, R^2 = 0.62, H-L p = 0.428)		Multiple logistic regression model[b] (n = 934, R^2 = 0.58, H-L p = 0.702)	
Variable	OR (CI)	*p*-value	OR (CI)	*p*-value
Distance to wind turbine (per km)	0.19 (0.07–0.53)	0.001	—	—
Wind turbine noise (dB)	—	—	2.38 (1.42–3.99)	0.001
Province	12.13 (2.14–68.21)	0.005	4.98 (1.15–21.58)	0.032
Closure of bedroom window due to wind turbines	5.03 (1.80–14.05)	0.002	8.45 (3.67–19.46)	<0.001
Hear traffic noise	0.36 (0.15–0.85)	0.021	—	—
Annoyance with blinking lights	—	—	3.26 (1.40–7.56)	0.006
Annoyance with vibrations, rattles	3.79 (1.14–12.61)	0.030	3.99 (1.22–13.07)	0.023
Visual annoyance to wind turbine	6.89 (3.41–13.95)	<0.001	2.77 (1.22–6.29)	0.015
Closure of bedroom window due to road traffic	0.39 (0.16–0.95)	0.037	0.42 (0.17–1.05)	0.063
Sensitivity to noise	3.27 (1.56–4.86)	0.002	2.11 (0.97–4.59)	0.061
Concerned about physical safety	2.59 (1.13–5.93)	0.024	2.56 (1.08–6.07)	0.033
Complaint about wind turbine	3.45 (0.92–12.94)	0.067	3.22 (0.85–12.20)	0.085
Air conditioner in dwelling	0.40 (0.14–1.13)	0.083	—	—
Window type (ref = single pane)			—	—
Double pane	0.062 (0.10–3.99)	0.616	—	—
Triple pane	0.06 (001–0.84)	0.037	—	—
Tinnitus	2.43 (1.18–5.03)	0.016	—	—
Environmental quality of life domain	0.73 (0.60–0.88)	0.001	—	—
Psychological quality of life domain	1.15 (0.99–1.34)	0.063	—	—

[a]Annoyance outcome with distance to wind turbine.
[b]Annoyance outcome with wind turbine noise.

turbines, greater disturbances or stresses at a neighbourhood-wide level, or the effects of poor relations with the wind power companies. Alternatively, the wind turbines might have been situated in locations where quality of life and environmental factors were already compromised. The cross-sectional design of the survey will not distinguish between effects caused by and those simply correlated with distance to the turbines.

The association found between proximity to wind turbines and annoyance is consistent with the findings reported by Michaud *et al.* (2016) where modelled WTN was found to be associated with annoyance (OR = 2.38; 95% CI: 1.42, 3.99; Table II). Our findings strengthen the argument that wind turbines are associated with annoyance, as this association is now found with both modelled A-weighted sound pressure levels and with residential distance to wind turbines. Other research has found that individuals reporting annoyance due to environmental noise also report health conditions including ischemic heart disease, depression, and migraines (Babisch *et al.*, 2003; Maschke and Niemann, 2007). A recent study conducted in China found that noise sensitivity, attitudes towards the visual impact of wind turbines on the surrounding landscape, general opinions on wind turbines and noise intensity moderates the relationship between WTN and annoyance (Song *et al.*, 2016). Together, these data suggest that preventive measures, including positive engagement between the community and the wind power companies, could reduce annoyance among residents.

Our analysis has limitations. Raw sound data were not available to us with the Community Noise and Health dataset. Only background-level noises and the modelled wind turbine sound were. Therefore, it was not possible to model sound using alternative methods, such as using G-weighted modelled sound, which would better account for low frequency sound waves (Jakobsen, 2001). Additional limitations are that the CNHS was a cross-sectional study and causality cannot be inferred, and that it may be subject to volunteer bias, where those who have strong feelings about wind turbines—either negative or positive—may be more likely to participate in the survey. Additionally, "survivor bias" may be present as those most affected by WTN may be more likely to have moved away from the wind turbines. Our team did not have access to information about those who were not included in the final study sample, although Michaud *et al.* reported that response rates did not vary by province or by proximity to wind turbines (Michaud, 2015). Finally, we did not have access to environmental quality scores prior to the installation of the wind turbines. It is possible that neighbourhoods closer in proximity to wind turbines already had conditions that result in perceived lower environmental and physical health quality of life prior to the installation of the wind turbines.

Through using an alternative wind turbine exposure measurement, this analysis demonstrated that living in close proximity to wind turbines is associated with lower environmental and physical quality of life measures. It also strengthened the notion that wind turbines are associated with annoyance, by finding a significant association between closer residential proximity to wind turbines and increased annoyance. Future research could focus on alternative exposures related to wind turbines that may be related to human health besides noise. Studies that examine outcomes prior to and following wind turbine installations may be better positioned to examine the potential causal association between wind turbines and health, and should include both specific, objective exposure measures and validated measures of the subjective experience of living near a wind farm.

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