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Vibrational noise from wind energy-turbines negatively impacts earthworm abundance

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Oikos
130: 844–849, 2021
doi: 10.1111/oik.08166

Subject Editor and
Editor-in-Chief: Pedro Peres-Neto
Accepted 29 March 2021

Human activities often impact the sensory environment of organisms. Wind energy turbines are a fast-growing potential source of anthropogenic vibrational noise that can affect soil animals sensitive to vibrations and thereby alter soil community functioning. Larger soil animals, such as earthworms (macrofauna, > 1 cm in size), are particularly likely to be impacted by the low-frequency turbine waves that can travel through soils over large distances. Here we examine the effect of wind turbine-induced vibrational noise on the abundance of soil animals. We measured vibrational noise generated by seven different turbines located in organically-farmed crop fields in the Netherlands. Vibratory noise levels dropped by an average of 23 ± 7 dB over a distance of 200 m away from the wind turbines. Earthworm abundance showed a strong decrease with increasing vibratory noise. When comparing the nearest sampling points in proximity of the wind energy turbines with the points furthest away, abundance dropped on average by 40% across all seven fields. The abundance of small-sized soil animals (mesofauna, < 10 mm in size) differed between crop fields, but was not related to local noise levels. Our results suggest that anthropogenic vibratory noise levels can impact larger soil fauna, which has important consequences for soil functioning. Earthworms, for instance, are considered to be crucial ecosystem engineers and an impact on their abundance, survival and reproduction may have knock-on effects on important processes such as water filtration, nutrient cycling and carbon sequestration.

Keywords: earthworm abundance, sensory pollution, soil fauna, soil functioning, vibrational noise, wind energy-turbines

Introduction

Animals rely on different sensory stimuli to acquire and process information from their environment. The ability to acquire this information is essential for an animal's reproductive success and survival (e.g. finding a mate and detecting a predator) (Dall et al. 2005, Dominoni et al. 2020). Activities tightly linked to human population growth are however interfering with environmental information processing of many animal species, with important population- and community-level consequences (Derryberry et al. 2020, Dominoni et al. 2020, Halfwerk 2020). Sensory pollutants, such as artificial light

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at night and traffic sounds have been shown to cause negative effects on animal behavior and physiology, which can translate to reduced survival and reproduction, and ultimately to population declines (Barber et al. 2010, Kight and Swaddle 2011, Francis and Barber 2013).

Human activities are responsible for 50% of the earth's seismic noise levels (Lecocq et al. 2020), but the impact of this sensory pollutant on animals and their communities living in the soil remains largely unknown. However, vibrational noise of natural and anthropogenic sources has been shown to affect mating interactions, predator prey dynamics and competition in different species (Caldwell et al. 2010, McNett et al. 2010, Roberts et al. 2016, Caorsi et al. 2019, Phillips et al. 2020, Velilla et al. 2020). A major contributing source of anthropogenic vibrational noise comes from wind energy turbines, which are mainly found in rural or farming areas and sometimes cover a large land surface. The blades, the rotor and the shafts from wind turbines are supported by a tower that is usually anchored to a heavy concrete and steel rebar platform reaching up to nine meters in depth (Stammler and Ceranna 2016). These platforms are needed to withstand the weight of the turbine, and although they may additionally reduce some of the vibrational noise created by the turbine, they induce vibrations in the soil, mostly in the low frequency range < 500 Hz (Stammler and Ceranna 2016). So far, we have little knowledge on how wind-turbine generated noise affects soil animals.

The potential impact of noise on animals may depend on the overlap between an animal's body size and the spectral distribution of the vibrations that travel through the soil. Vibrations generated by wind energy turbines are typically low in frequency (< 500 Hz) and small-bodied animals (mesofauna, < 10 mm in size) might not be able to perceive, or even experience any strain from these low-frequency waves. Larger soil animals (macrofauna, > 1 cm in size), however, might be able to perceive low-frequency vibrations and can therefore be impacted by turbine noise through a perceptual mechanism. Among macrofauna, earthworms are particularly sensitive to low-frequency vibrations as they use vibrational cues to detect approaching predators (Catania 2008, Farina 2014). Earthworms are crucial ecosystem engineers (Jones et al. 1997) that are well known to influence soil structure, hydrology and nutrient quality as well as plant production (Clements et al. 1991, Van Groenigen et al. 2014, Bertrand et al. 2015). Vibratory noise from turbines may either mask, or mimic vibratory cues produced by approaching predators, such as moles, and earthworms may surface in response (Catania 2008, Dominoni et al. 2020). An increased perception of predation pressure, or decreased response to predatory cues could both lead to a decline in earthworm abundance in areas with high vibrational noise, consequently affecting soil structure, water infiltration, nutrient cycling, carbon sequestration and more (Blouin et al. 2013, Bertrand et al. 2015).

In the current study we assessed the effect of wind turbine-induced vibrational noise on earthworm abundance, and on the abundance of soil mesofauna. We hypothesized that vibrational noise would have a body-size dependent effect on soil animals and therefore expected a negative impact on earthworm abundance and no direct impact on the smaller mesofauna (although they could still be affected indirectly through an impact on earthworms). To test our predictions, we selected seven turbines stationed in agricultural fields in the Netherlands. We measured vibrational noise induced by wind turbines along a 14 transects and related these noise levels to earthworm and mesofauna abundance.

Material and methods

We measured vibrational noise with a vertical geophone for seven turbines along two transects on exponentially increasing distances, starting at 2 m up to 256 m from the turbines between April and June 2019 in the fields belonging to the biological farms: van Andel Bio B.V. and Douwe Monsma Beheer in the province of Flevoland, the Netherlands (see Supporting information for orientation of the transects). Additionally, we measured soil compaction with a hand-pushing penetrometer, as this was the main factor we expected to covary with distance to the turbine base due to the use of heavy machinery during construction and maintenance. The province of Flevoland has the highest densities of turbines in the Netherlands and it was therefore not possible to find an appropriate control site (lacking a turbine) on similarly managed soil.

To measure earthworm abundance, we sampled 15 625 cm^3 of soil (25 × 25 × 25 cm), and deposited the soil in a plastic tray (70 × 40 cm). We then hand-sorted the soil to search for earthworms, counting the total number of individuals. We monitored earthworm abundance for 46 sample points in total, along two transects per wind turbine at 8, 32, 64 and 128 m for the seven turbines (these four sites were on homogeneous soils). Furthermore, we collected soil animal samples of the first 5 cm of the top soil layer using a soil corer (10 cm ø). Soil animals other than earthworms were extracted from the soil using Tullgren funnel extraction and collected in vials with 75% ethanol.

To test the effect of vibrational noise on abundance of macro and mesofauna, we used the information theoretic approach (Burnham et al. 2011). We created two sets of linear mixed effects candidate models (Lmm) using the package 'lme4' (Bates et al. 2015) that included noise amplitude, distance to the wind turbine, soil compaction and crop type as predictors. In the set of models explaining abundance of mesofauna, we also included earthworm abundance as a predictor. We included transect nested within wind turbine as a random effect with a random intercept.

For full materials and methods, including analyses see the Supporting information.

Results

Wind turbine-induced vibrational noise

We recorded soil vibrations for up to two minutes per sampling location. Wind turbines with actively rotating blades produce a continuous, slowly fluctuating humming sound with most of its spectral energy below 500 Hz (Fig. 1, Soundfile 1 and 2). For each of the two transects per turbine we calculated relative amplitude (expressed in RMS dB values) separately. We found vibrational noise on average to be 23 ± 7 dB SD louder at 2 m when compared to at 256 m in the transects (see the Supporting information for mean ± SD attenuation per distance point). The highest attenuation at 256 m was 29 dB, measured on the field of turbine three at site one, while the lowest attenuation at 256 m was 16 dB on the field of turbine seven at site two (Fig. 2).

We found a significant correlation between distance to the wind turbines and vibrational noise levels, with vibrational noise levels decreasing with increasing distance (Lmm, distance, $\beta = -0.08$, SE = 0.005, $p < 0.01$, see the Supporting information for estimates of all fixed factors). Noise levels were not correlated to soil compaction values.

Earthworm abundance is related to noise amplitude and distance to wind turbines

We counted an average of 183.6 ± 116.2 SD earthworms per m^2, per wind turbine field. Turbine six at site two had the lowest number of earthworms with a mean of 86.8 ± 58.3 SD per m^2, whereas turbine one at site one had the highest mean count of 248 ± 168.9 SD earthworms per m^2.

Our model selection procedure revealed that distance to turbine and vibrational noise levels were important predictors of earthworm abundance (Supporting information). Earthworm abundance increased with distance to the turbines and therefore decreased with increasing vibrational noise level (Fig. 3, Table 1). None of the crop types significantly affected earthworm abundance (Table 1). Soil compaction and crop

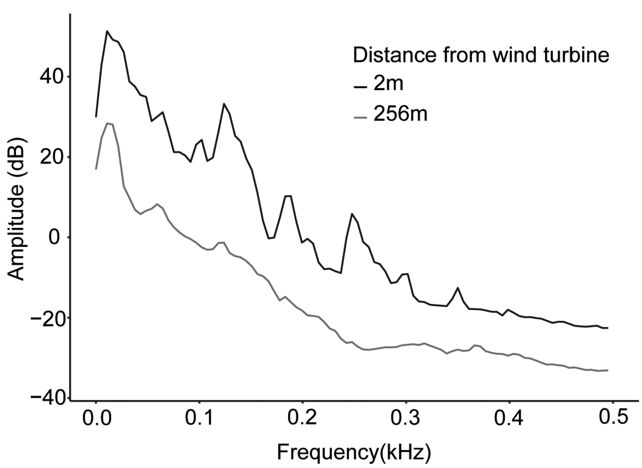

Figure 1. Mean spectra of vibrational noise in the soil induced by wind turbines, measured at 2 m and 256 m from the turbine. Sampling rate, 44 100 Hz; window length, 8192. Most energy in wind turbine vibrational noise is biased towards the low frequencies (< 500 Hz). Note several clear peaks on the nearby recording, which likely reflects the resonance frequencies of the vibrating turbine, as can also be heard on the associated sound files.

type were not considered important predictors, nor were they statistically significantly related to earthworm abundance on our sampling fields.

Abundance of mesofauna is not related to noise amplitude

Abundance of mesofauna was not related to noise amplitude or to distance to the turbines, or to soil compaction (see the Supporting information for full results).

Discussion

We assessed the relationship between subterranean vibrational noise levels induced by wind turbines and the abundance of mesofauna. Sampling seven different agricultural fields, we found that vibrational noise levels were significantly higher closer to the wind turbines and that earthworm abundance was negatively related to vibrational noise levels. We found no relationship between noise levels and smaller-sized soil animals.

Earthworm abundance was negatively related to vibrational noise

We found that, on average, the number of earthworms decreased by 40% at the point furthest away from the turbines compared to the closest point to the turbines where we measured (128 m versus 8 m). Our results confirm that earthworm abundance decreased substantially as the amplitude of vibrational noise increased. The maximum amplitude difference over the range at which we surveyed earthworms was on average 13 dB. We therefore predict the impact of vibratory noise to be even bigger when measured over the whole transect, as vibrational noise levels near the base of the turbine are up to 30 dB higher than at our furthest sites (> 200 m from the turbine). We did not survey earthworm densities close to the turbine base as the composition of the soil differed substantially between the nearest points (2 m and 4 m) and remaining points of the transect. While we accounted for variation in soil compaction and crop type, neither of these factors was related to earthworm densities. Soil compaction and crop type also did not co-vary with distance to the wind turbines (Supporting information). Although vibration-specific receptors have not been described for any earthworm species, earthworms can detect tactile stimuli along their entire body (Laverack 1960), and tactile stimulation has been shown to induce activity in the segmental nerves (Laverack 1960, Mill and Knapp 1967). Earthworms also have distinct sensory cell bumps found along their body surface that contain multiciliate sensory cells (Langdon 1895, Knapp and Mill 1971, Gardner 1976, Mill 1982). A combination of sensory cell bumps and tactile sensitivity in earthworms, makes them a good candidate for vibration reception (Mitra 2009).

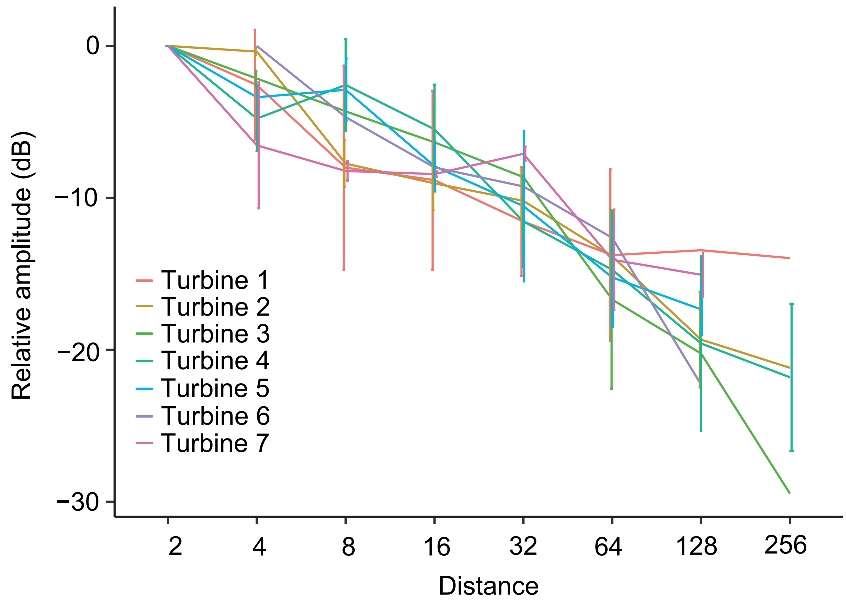

Figure 2. Wind turbine-induced vibrational noise relative amplitude (dB) change with increasing distance (m) to the base of the wind turbine. We recorded noise levels on two transects per wind turbine. Standard deviation between the transects is shown with error bars per turbine per distance point. Vibrational recordings of different turbines were carried out on different days and variation in amplitude and attenuation between turbines could therefore be either related to variation in wind levels or soil structure.

Sensory pollution consequences

Human-induced sensory pollutants can directly affect organisms through an impact on their perception, physiology and behavior (Brumm and Slabbekoorn 2005, Barber et al. 2010, Kight and Swaddle 2011, Naguib 2013, Velilla and Halfwerk 2019). It is possible that wind turbine-induced vibrational noise masks the vibrational cues of approaching foraging moles, making earthworms in noisy areas more prone to predation (Dominoni et al. 2020). Vibratory noise could also be misleading to earthworms (Dominoni et al. 2020), who may not be able to distinguish between vibratory cues coming from an approaching predator such as a mole, and the subterranean waves from the turbines. As matter of fact, earthworms are well known to be misled by other organisms, including humans who have developed so-called 'worm grunting' techniques that mimic soil vibrations from approaching moles (Catania 2008). Future studies should experimentally test which sensory mechanism is responsible for the patterns we revealed in this study. Alternatively, soil vibrations induced by wind turbines could alter the direct physical environment, e.g. through soil particle sorting or an impact on eartworm tunnel structures, thereby influencing water drainage and other abiotic conditions. Such physical impact should however also impact the mesofauna, which we did not report on our study. However it is clear that more data on the effects of vibrations on soil structure are needed, and vice versa.

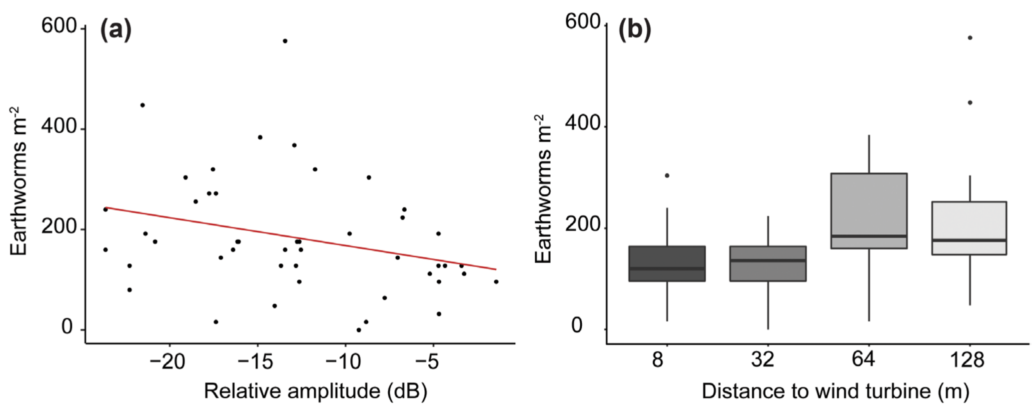

Figure 3. (a) Scatterplot showing earthworm abundance in response to wind turbine-induced vibrational noise levels. Earthworm abundance statistically significantly decreased with increasing noise levels. The red line is the fit of a linear model testing the relationship between earthworm abundance and noise levels. (b) Boxplot showing earthworm abundance in response to distance to the base of the turbine. Earthworm abundance is statistically significantly higher further away from the from base of the turbine.

Table 1. Model-averaged means (Estimate), their conditional standard errors (SE), z-value, p-value and 95% confidence intervals (95% CI) for the fixed effects of relative amplitude, crop type (crop) and distance explaining abundance of earthworms. Relative amplitude and distance to the wind turbine had a significant effect on earthworm abundance.

Parameter	Estimate	SE	z-value	p-value	95% CI Lower	95% CI Upper
Relative amplitude	−0.35889	0.13962	1.897	0.0129*	−0.64178638	−0.07599278
Crop						
Grass	2.19179	5.32917	0.398	0.6907	−8.60273484	12.98631093
No crop	2.03672	4.38416	0.450	0.6530	−6.84309861	10.91653972
Spring onions	−5.92106	5.33132	1.075	0.2825	−16.71974234	4.87762537
Wheat	−1.43302	5.36955	0.258	0.7962	−12.30550855	9.43946564
Distance	0.04672	0.01682	2.688	0.0072**	0.01264768	0.08079120

Our findings suggest that noise could decrease earthworm densities, and ultimately modify the distribution of species that depend or interact with earthworms (Gutiérrez-López et al. 2010). In our study we did not find evidence for an effect of variation in earthworm abundance on the abundance of smaller soil animals. However, our measurements and observations were carried out in agricultural fields, possibly influencing the effects that earthworms would have under natural wild conditions, or in a different season. Further studies should examine the effect of vibrational noise on earthworm abundance in non-managed fields and its consequences on other soil organisms.

Earthworms play a crucial role in several soil processes including: soil formation, soil structure, water infiltration, nutrient cycling, carbon sequestration, climate regulation and primary production (Blouin et al. 2013, Bertrand et al. 2015). Furthermore, earthworms are known to play an important role in plant production (Baker et al. 2006, Blouin et al. 2013). Therefore, the negative relationship we find between wind turbine noise levels and earthworm abundance could potentially have cascading effects on other soil organisms and processes and should also draw attention to other sources of seismic noise (Lecocq et al. 2020).

Wind energy is an important renewable source of energy needed to battle climate change. It is however also important to stay alert on their potential negative side-effects on a more local scale. Wind energy turbines have already been shown to affect mating interactions in anurans, vigilance behavior in ground-squirrels and population dynamics across trophic levels (Rabin et al. 2006, Thaker et al. 2018, Caorsi et al. 2019). Moreover, wind energy turbines have been shown to increase bird and bat mortality (Johnson et al. 2003, Barrios and Rodríguez 2004, Rydell et al. 2010, Bellebaum et al. 2013), some of which can be mitigated by temporarily shutting turbines down. We argue that attention should also be given to reducing vibrational noise levels induced by anthropogenic sources in situations where this is feasible and appropriate. Alternatively, clear negative side-effects can be offset, either directly by taking additional measures at the impacted soils, or at the landscape scale by securing or improving more dedicated nature areas.

Acknowledgements – We are especially thankful to Piet van Andel and Jan-Harm Welleweerd from van Andel Bio and to Douwe Monsma from Douwe Monsma B.V. for providing us access to the fields where the measurements involved in this study were made. We are also grateful to Beth Mortimer for her advice on soil vibrations measuring techniques and for her advice on the hypotheses presented in this study. Furthermore, we thank Rudo Verwij and Jurgen van Hal for their help with the mesofauna analysis, Ivor Keesmaat for his help in the field data collection, Kees van Geestel for his advice on earthworm ecology, Oscar Franken for his input in the field sampling techniques and Jacintha Ellers for commenting on earlier versions of this manuscript.

Author contributions

Estefania Velilla: Conceptualization (equal); Data curation (lead); Formal analysis (lead); Investigation (lead); Methodology (equal); Supervision (equal); Visualization (lead); Writing – original draft (lead); Writing – review and editing (lead). **Eleanor Collinson**: Investigation (supporting); Methodology (supporting). **Laura Bellato**: Investigation (supporting); Methodology (supporting). **Matty P. Berg**: Conceptualization (supporting); Methodology (supporting); Resources (supporting); Supervision (supporting); Writing – original draft (supporting); Writing – review and editing (supporting). **Wouter Halfwerk**: Conceptualization (equal); Methodology (equal); Project administration (supporting); Resources (lead); Supervision (equal); Writing – original draft (supporting); Writing – review and editing (supporting).

Data availability statement

Data available from the Dryad Digital Repository: <http://dx.doi.org/10.5061/dryad.kkwh70s46> (Velilla et al. 2021).

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