Original Study

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Reducing bat mortality at wind farms using site-specific mitigation measures: a case study in the Mediterranean region, Croatia

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Abstract: A 4-year monitoring of bat fauna at Rudine wind farm in Croatia aimed to produce mitigation measures to minimize both the number of bat fatalities and power loss in energy production. During the first 2 years, a high number of carcasses was found from mid-July to the end of October, indicating the need for some mitigation strategy. Based on the results of carcass searches, meteorological data and bat activity monitored at a weather mast and four wind turbine nacelles, mitigation measures were proposed. During the next 2 years, wind turbine curtailment was implemented in the high collision risk period based on critical wind speed thresholds varying from 5.0 to 6.5 ms^{-1}. Estimation of a total number of bat fatalities was conducted with the GenEst software for each monitoring year. A 78% reduction in estimated number of fatalities was recorded indicating the effectiveness of implemented measures.

Keywords: acoustic activity; Chiroptera; collision risk; curtailment; post-construction monitoring.

1 Introduction

Following the last century characterized by intensive development based mainly on fossil energy sources, accompanied by climate change, severe devastation of many ecosystems and the loss of biodiversity, humans face with the necessity of directing their existence in accordance with the principles of sustainability. Therefore, European Union adopted the “European Green Deal” (European Commission 2019) as a set of policies aiming, among others, at producing clean energy. The energy obtained from the wind as a renewable source should, at least in the short term, be one of the mainstays in the coming civilizational changes (Wind Europe 2021). At the same time, bats, as strictly protected animals with an important role in terrestrial ecosystems, are considered as one of the most affected fauna group during wind farm operations (e.g., Arnett and May 2016; Baerwald and Barclay 2009; Frick et al. 2017; Grodsky et al. 2011; Voigt et al. 2022). This issue is also recognized by the Agreement on the conservation of Populations of European Bats (UNEP/ EUROBATS Resolution 8.4). Its member countries are urged to consider impacts on bats on different geographical scales and encourage all stakeholders to engage in finding the best mitigation methods for mutual benefit. Unfortunately, many wind farms still operate without any mitigations (EUROBATS 2017; Voigt et al. 2022), with up to hundreds of thousands potentially killed bats per year in some countries (Voigt et al. 2015).

Acoustic ultrasonic deterrent systems were tested in the USA as potential mitigation method (Arnett et al. 2013; Romano et al. 2019; Weaver et al. 2020), in addition to radar deterrence (Gilmour et al. 2020), but so far, they have shown success only for a limited range of species. The effectiveness of automated acoustic detector systems which stop the rotor in real-time has still not been assessed, with particular difficulties being a delay between the time at which a bat is detected, the time required to stop the turbine rotation (Hanagasioglu et al. 2015), and the bioacoustic detection range of some species (e.g., *Pipistrellus nathusii*) (Lindemann et al. 2018). On the other hand, a mitigation strategy referred to as blanket curtailment was proven to be effective but can produce unnecessary losses in energy production. It causes all wind turbines at a wind farm location to rotate slowly (less than one rpm) when wind speed is below a certain general threshold often achieved by raising cut-in speed (e.g., 5.0–6.5 ms^{-1}), given that fatality risk increases during

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low wind speed (Arnett et al. 2008, 2010, 2011; Horn et al. 2008; Măntoiu et al. 2020). Since the blades of most wind turbines can still rotate below cut-in speed and cause bat fatalities, preventing turbines from freewheeling by blade feathering (adjusting the angle of the rotor blade) is also an additional important factor in reducing bat fatalities (Baerwald et al. 2009). Meanwhile, the correlation between bat activity and other meteorological conditions was detected as well, including the observation that more bat fatalities occur during high temperatures and nights with no rainfall (Amorim et al. 2012; Horn et al. 2008; Santos et al. 2013). To avoid unnecessary production losses, more complex operational mitigation design started to develop (Martin et al. 2017; Pettersson and Rydell 2017). Different smart curtailment algorithms are used to make predictions about bat fatality risk, combining bat activity data at nacelle height in correlation to wind speed and other factors such are air temperature, precipitation, time of year and night (Lagrange et al. 2013; Topwind 2019). Only one model-based approach for curtailment algorithm was published so far (Behr et al. 2017), implemented in a software tool ProBat used in Germany (Behr et al. 2015, 2018; Brinkmann et al. 2011). Unfortunately, its effectiveness in other parts of Europe is still not proven, given that species composition, bat activity, wind tolerance, and correlation to other weather conditions may differ significantly on a geographical scale due to the difference in present habitats and microclimate. This is especially the case with the Mediterranean basin, known as a biodiversity hotspot (Myers et al. 2000), with 43 bat species out of 46 known in Europe (IUCN 2022). High bat fatality rates at wind farms in this region are more likely to occur, generally of the same genera as those in northern parts of Europe (*Pipistrellus* and *Nyctalus* spp.), but more often of some different species, such are *Pipistrellus kuhlii* and *Hypsugo savii* (Arnett et al. 2015; EUROBATS 2019). Only a few papers on bat mortality at wind farms originate from the Mediterranean. Some provide evidence of bat fatalities in Portugal, Spain and Greece (Amorim et al. 2012; Camina 2012; Georgiakakis et al. 2012; Sánchez-Navarro et al. 2020), but little is known about implemented mitigation measures and their effectiveness.

Due to its specific geographical position within several biogeographic regions (including Mediterranean) and high habitat heterogeneity, Croatia is one of the richest European countries in terms of biodiversity. This includes bat fauna (Radović et al. 2006; Ulrich et al. 2007), with 33 bat species (Hamidović et al. 2019). It is also a country with an intensive development of wind farms, increasing the share of wind power generation in total electricity production from 0.5% in 2010 to 9% in 2016 (Bajo et al. 2018). This continued increase is expected in the future in the context of European and global promotion of renewable energy sources (MINGOR 2021). Our case study was located in the Mediterranean region at Rudine wind farm (WF) in Croatia. Our research aimed to develop an accessible tool in defining site-specific mitigation measures acceptable in the context of electricity production, while significantly reducing bat fatalities. We created a time-specific mitigation scheme concentrated on more frequent bat activity. The main part of the mitigation was to define critical wind speed values for wind turbine curtailment within pre-defined time intervals. The mitigation scheme was partially based on the precautionary principle (Cooney 2004), given that bat population sizes in Croatia are not known and bat activity thresholds, which would indicate high collision risk, are not defined (MZOE; HAOP 2018).

2 Materials and methods

2.1 Study site

Rudine WF includes 12 General Electric wind turbines (WTs), 2.85 MW each, with 85 m nacelle height and 103 m rotor diameter. It is located in the southern part of Croatia 1.3 km from the Adriatic Sea (Figure 1) at 320–380 m a.s.l. It is predominantly covered with dry grasslands and degradative vegetation forms of mixed (deciduous and evergreen) eumediterranean holm oak (*Quercus ilex*) forests, such are garrigue and maquis (Jasprica and Kovačić 2000).

2.2 Study design

Initial post-construction bat monitoring was conducted in 2016 and 2017 including bat carcass searches according to the requirements of the relevant Ministry and national guidelines (MZOPUG; APO 2010). Due to a high number of bat carcasses detected in 2016, additional activities were conducted simultaneously in 2017 to design site-specific mitigation scheme, the effectiveness of which was tested in 2019 and 2020 (Figure 2).

2.3 Carcass searches and bat fatality estimation

During initial post-construction monitoring carcasses were searched from 15th March to 15th November 2016 and 2017 on average every 8 days. To test the effectiveness of implemented measures, searches continued from 15th July to 31st October in 2019 and 2020 on average every 7 days. In both cases search intervals varied to some extent due to factors such are weather conditions and wind farm maintenance. They were conducted at approx. 45–60 min/man/WT, during early morning hours whenever possible. For each carcass the following data was documented: position (GPS coordinates, relative distance to the closest WT), type of visible injury, taxonomic affiliation (Dietz and Kiefer 2016; Tvrtković 2017), sex and age (if possible, depending on the state of the carcass).

Areas of high and low visibility were distinguished within a 70 m radius of each WT considering vegetation height and density (ground cover) as well as terrain morphology. Areas of low visibility were mostly covered with shrub vegetation and grass up to 80 cm in height (depending on the seasonal period) and determined as inadequate search

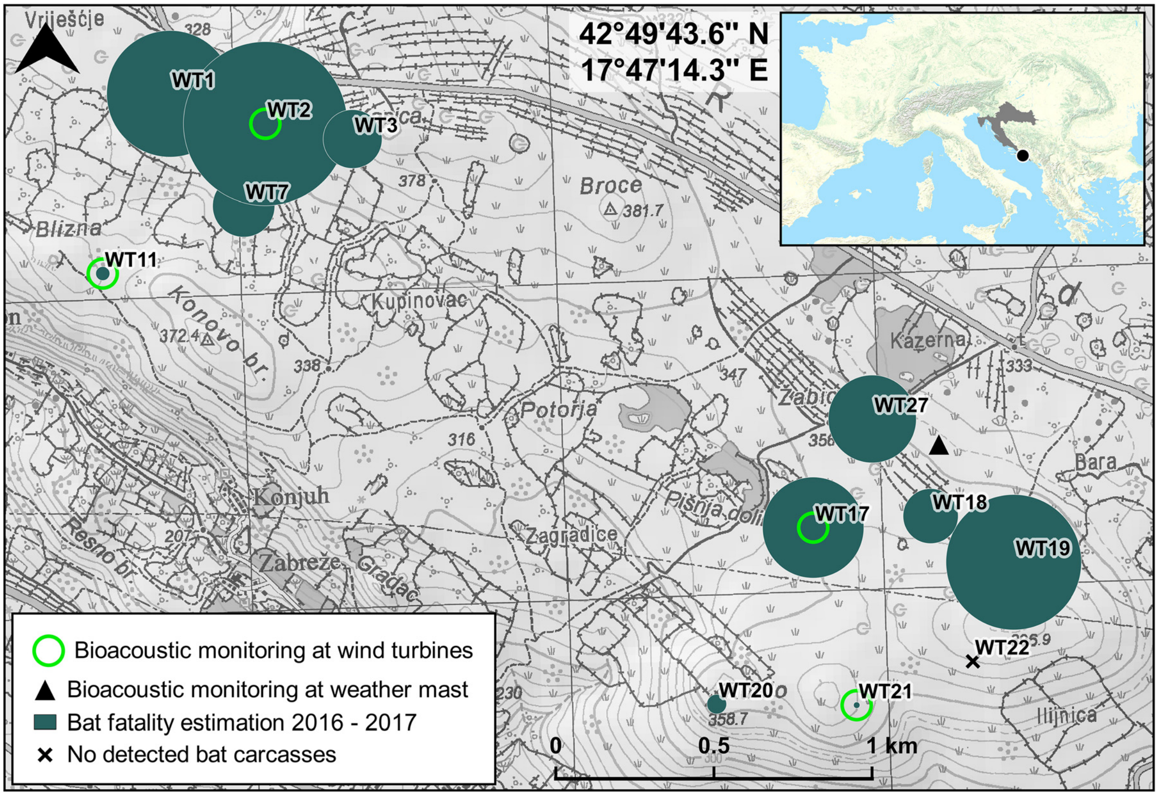

Figure 1: Location of Rudine wind farm (Croatia): activity monitoring and bat fatalities per wind turbine (size of the circle is in correlation with the estimated number of bat fatalities in 2016 and 2017) (QGIS v.3.10).

areas given the detectability and size of bat carcasses, as well as quick changes in carcass appearance (from fresh carcass to skeleton). In addition, extreme slopes and rocky terrain made some parts impossible to survey. For these reasons, carcass searches were conducted in high visibility areas which include access roads and pads, mostly covered with gravel.

Estimation of a total number of bat carcasses was conducted for each monitoring year using a statistical software GenEst v1.4.6 (Dalthorp et al. 2018; Rabie et al. 2021; Simonis et al. 2018). Searchers efficiency trials were conducted in August and October 2019, as well as in May, July, and September 2020. Each trial was conducted using 20–30 carcasses of laboratory specimens of *Mus musculus* with the searchers not knowing the number (0–4) placed around each WT. The collected data was used as a single data set regardless of the season. Carcass persistence was derived by trials (Simonis et al. 2018) using randomly placed 20–30 carcasses of *M. musculus* for 10 consecutive days in May 2016 and 2017, September 2016 and 2017, July and September 2020. Trial results were used as two data sets which include the lowest and highest collision risk period. All model inputs were selected using Akaike information criterion (Δ AICc) which provides a small-sample bias correction (Burnham and Anderson 2004). The estimation also took into account irregular search intervals, the date and the WT where each carcass was found, as well as the distance from it. Density-weighted proportion was calculated in SAGA GIS v. 2.3.2 for each year as an average expected share of carcasses of the searched area around each WT. Carcasses were "binned" into 5 m rings around each WT out to the maximum distance of 70 m. Carcass density (number of found carcasses/m^2) was calculated for the surveyed area within each ring separately. Obtained values were fitted in terms of distance from WT by cubic polynomial regression function, which were later applied for each m^2 unit of the 70 m buffer area for each WT, providing a WT-specific density-weighted proportion for the searched area (Arnett et al. 2009).

2.4 Bat activity and weather conditions

Within the initial 2 year post-construction monitoring, bioacoustic data were collected at the weather mast 60 m above the ground from 15th March to 15th November 2016 and 2017. To define site-specific mitigation measures, additional data were collected from 15th July to 15th November 2017, based on the results of the initial post-construction monitoring in 2016, which indicated this period as of potentially higher collision risk for bats. This included bioacoustic data collected at nacelle height of four WTs (Figure 1) and wind speed data measured with an anemometer recorded by the SCADA-System (Supervisory Control and Data Acquisition System) controlling the turbine. Also, air temperature and precipitation data were measured at the weather mast 60 m and 10 m above ground respectively. Bioacoustic monitoring at weather mast was repeated while testing the effectiveness of implemented measures from 15th July to 31st October in 2019 and 2020. All bioacoustic data were collected each night from 1 h before sunset to 1 h after sunrise using SM2BAT + Song Meter ultrasound detectors with SMX-U1 microphones and the following settings: Sample Rate 192–384 kHz, Gain 12 dB, Trigger Level 12 SNR, High-pass filter 8 kHz, Trigger Win 2.0 s, Trigger Max Length 5.0 s.

The number of 5 s intervals (5 s recordings) with detected bat echolocation or social calls within 10 min intervals was used as a unit of

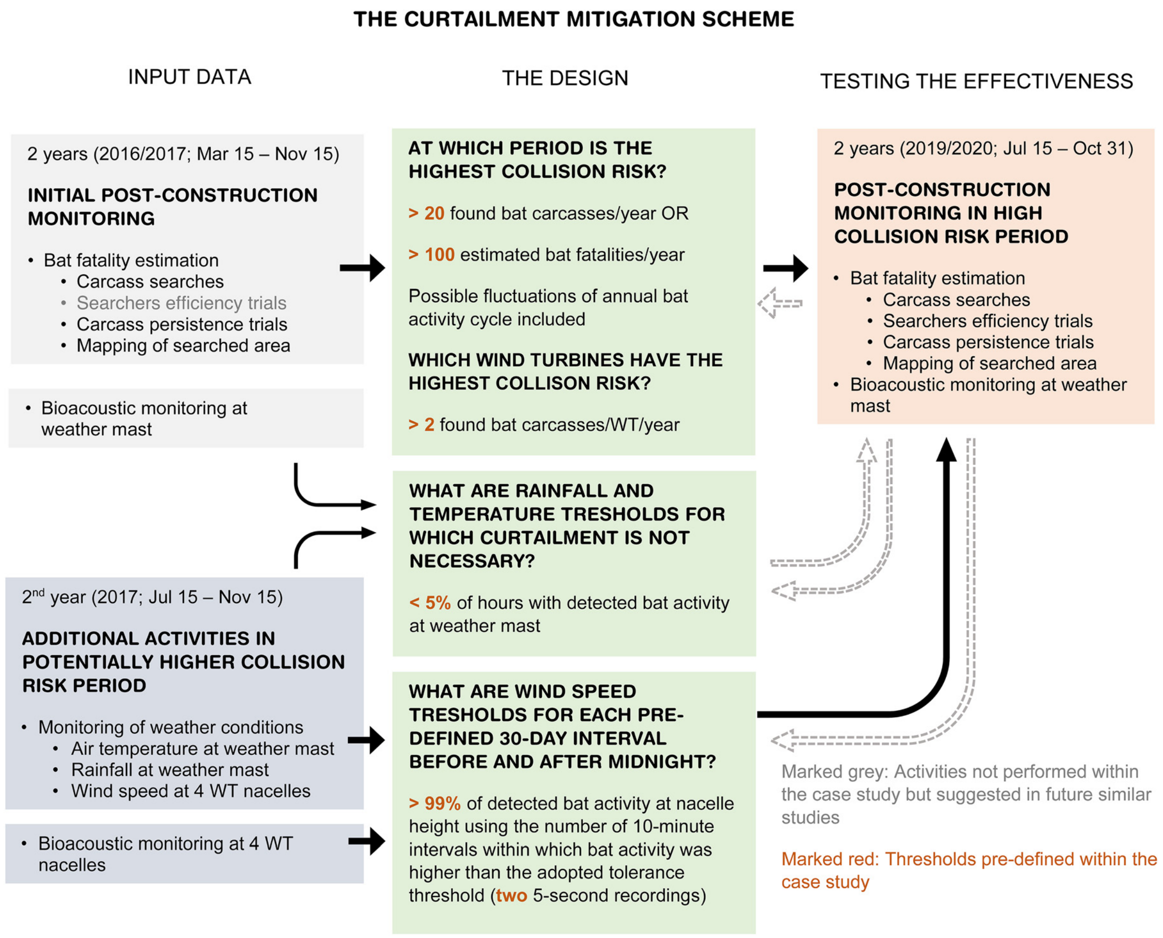

Figure 2: The curtailment mitigation scheme designed within the case study at Rudine wind farm.

bat activity. This time interval was more easily related to mean values of wind speed and temperature provided by the wind farm owners. Precipitation was also assigned to 10 min mean values. The application of such time frame is considered effective in fast responding to changes in wind speed according to Behr et al. (2017). The distribution of bat activity in relation to weather conditions (wind speed, air temperature and precipitation) was analysed.

A total of 1,029,944 recordings was collected at four WT nacelles and 1,178,796 recordings at the weather mast. All acoustic data were filtered from noise recordings, manually verified (Kaleidoscope Lite v.4.5.4) for a final set of 20,002 5 s recordings from WTs and 16,775 5 s recordings from the weather mast with detected bat activity. Since all Croatian bat species are strictly protected (Official Gazette of the Republic of Croatia, No. 80/13, 15/18, 14/19, 127/19), all 5 s recordings were included in the analysis, regardless of the taxonomic affiliation of recorded bats. Still, to have a general insight on present species composition, species or phonic species groups were manually assigned to 5 s recordings (Sonobat v.3.1.4p) collected at the weather mast throughout the entire study (Barataud 2015).

2.5 Mitigation measures design

A period further referred to as the highest collision risk period was determined as part of the year with more than 20 bat carcasses found or estimation of more than 100 bat fatalities during the first or second year of initial post-construction monitoring, considering also potential annual variations in the biological cycle of bats. Mitigation measures were implemented for WTs with two or more found bat carcasses/WT/year within the highest collision risk period. The conditions under which mitigation measures are not needed were defined (in sense of ranges of temperature and precipitation with low bat activity), with less than 5% of hours with recorded bat activity. The analysis was based on the number of hours during the night with recorded bat activity, classified by the number of 5 s recordings per hour and assigned to classes of measured average air temperature and total precipitation.

Critical wind speed thresholds (CWS) were proposed under which turbines should be prevented from rotating, along with the use of blade feathering. They were defined as wind speed values up to which 99.0% of 10 min intervals above the tolerance threshold was detected. For this purpose, the number of 10 min intervals with recorded bat activity was assigned to the corresponding wind speed 0.5 ms^{-1} intervals. To focus on periods with frequent bat activity compared to occasional overflights, a tolerance threshold was used in the analysis to include only 10 min intervals with more than two 5 s recordings. Lower tolerance threshold was not considered since even single bat contacts were sometimes observed in two consecutive 5 s recordings. To reduce unnecessary power loss often detected in blanket curtailment, the analysis was conducted for each 30 day period separately for parts of the night before and after midnight. This mitigation scheme took into account that bat activity and its relation to wind speed could vary overnight and during the biological cycle of bats.

Table 1: Bat fatality estimation (with 90% confidence intervals) at Rudine wind farm for the lowest (LCR) and before and after the implementation of mitigation measures within the highest collision risk period (HCR) during four monitoring years calculated in GenEst v1.4.6 (*n* = number of found bat carcasses).

		Before		**After**	
		2016	**2017**		
LCR	March	– *n* = 0	– *n* = 0		
	April	3.4 (1.0–8.8.) *n* = 1	– *n* = 0		
	May	– *n* = 0	4.0 (1.0–10.3) *n* = 1		
	June	4.1 (1.0–10.5) *n* = 1	5.3 (1.0–15.3) *n* = 1		
	July, 1st part	– *n* = 0	9.6 (2.0–21.7) *n* = 2		
	November	– *n* = 0	11.3 (2.0–26.5) *n* = 2		
	TOTAL	**7.4 (2.0–11.1)** ***n* = 2**	**30.7 (12.9–39.5)** ***n* = 6**		
		2016	**2017**	**2019**	**2020**
HCR	July, 2nd part	27.3 (11.2–47.5) *n* = 6	3.4 (1.0–8.4) *n* = 1	– *n* = 0	– *n* = 0
	August	31.0 (12.1–55.4) *n* = 6	9.0 (1.0–25.7) *n* = 1	9.8 (2.0–24.0) *n* = 2	– *n* = 0
	September	93.8 (57.1–140.6) *n* = 16	96.3 (65.2–133.8) *n* = 20	20.6 (5.5–41.9) *n* = 3	29.4 (12.4–50.4) *n* = 6
	October	15.7 (2.0–35.0) *n* = 2	17.3 (5.1–33.8) *n* = 4	– *n* = 0	5.8 (1.0–16.7) *n* = 1
	TOTAL	**170.0 (119.4–230.8)** ***n* = 30**	**126.8 (89.8–173.1)** ***n* = 26**	**31.0 (11.7–56.0)** ***n* = 5**	**35.3 (16.3–59.2)** ***n* = 7**
				Implemented measures according to mitigation scheme	
			Yes (8 wind turbines):	*27.9 (7.7–52.2)* *n = 4*	*17.9 (5.5–33.9)* *n = 4*
			No (4 wind turbines):	*3.2 (1.0–7.4)* *n = 1*	*16.8 (4.4–34.3)* *n = 3*

2.6 Testing the effectiveness

The effectiveness of the curtailment was tested, regardless of the exceptions related to temperature and precipitation (according to the decision of wind farm owners to implement technically simpler measures). The test was based on the comparison between the estimated number of bat fatalities in the highest collision risk period before and after the implementation of mitigation measures. The results from bioacoustic monitoring at the weather mast were used to confirm the continued presence of bats at the site.

3 Results

3.1 Carcass searches and bat fatality estimation

During initial post-construction monitoring in 2016 and 2017 a total of 64 bat carcasses was found, with 56 bats detected from mid-July to the end of October, determined as the highest collision risk period. Altogether 12 bat carcasses were found during the same period after the implementation of mitigation measures in 2019 and 2020. The total reduction by 78% of the estimated number of bat carcasses was noticed, with the overall decrease of 3.6 times (2020 as opposed to 2017) to 5.5 times (2019 as opposed to 2016) (Table 1). Four WTs without curtailment caused 10% of estimated bat fatalities in 2019 and 48% in 2020 (based on one found bat carcass in 2019 and three in 2020) (Table 1).

Out of 76 found bat carcasses during the 4 year monitoring, 11 bat species were identified, including six genera (Table 2). Most of the carcasses referred to *P. nathusii* (*n* = 19), *Nyctalus leisleri* (*n* = 18) and *H. savii* (*n* = 18) for which a noticeable decrease in the number of found bat carcasses was detected after the implementation of mitigation measures. For some carcasses, it was not possible to determine taxonomic affiliation, sex and/or age due to their state of decay

Table 2: Number of found bat carcasses at Rudine wind farm by species, year, and collision risk period during four monitoring years.

	Before				After	
	2016		2017		2019	2020
Bat species	**LCR**	**HCR**	**LCR**	**HCR**	**HCR**	**HCR**
Myotis blythii			1			
Nyctalus leisleri		5	1	6	3	3
Nyctalus noctula		1				
Nyctalus lasiopterus						1
Pipistrellus pipistrellus				1		
Pipistrellus pygmaeus		2		1		
Pipistrellus kuhlii		3		2		
Pipistrellus nathusii	1	3	2	10	1	2
Pipistrellus sp.		1		3		1
Hypsugo savii	1	13	2	1	1	
Vespertilio murinus		1				
Tadarida teniotis				2		
Chiroptera		1				
Total *N*	2	30	6	26	5	7

HCR, the highest collision risk; LCR, the lowest collision risk.

and/or obtained injuries. It was possible to determine sex for 31 females and 27 males, suggesting an equal ratio of both sexes. Age was assigned to 42 adults, 27 subadults, and four juveniles. Juvenile carcasses referred to *H. savii*, apart from one *Pipistrellus* sp. They were detected from mid-July to the beginning of August when also four adults were found, all referring to *H. savii*. External injuries like open wounds and broken wings were observed in 28 cases, while no visible injuries were observed in 11 cases, suggesting internal injuries. Carcasses were detected at all WTs, ranging up to seven found bat carcasses/WT/year, which finally results in up to 37 estimated bat fatalities/WT/year (with 90% confidence interval 16.6–64.6). They were detected within distances ranging from 0 to 45 m from the WTs, with only one bat carcass found at a larger distance, approximately 70 m from the WT.

Probability of 0.8 was calculated that a carcass that was present was found during the search. Carcass persistence time was approximated with a 0.9 probability that a bat carcass will remain within 24 h, and with 0.4 and 0.5 probability that it will remain for 7 days in the highest and lowest collision period respectively. Average searched area was 0.3 per WT, while the expected share of carcasses in the searched area averaged 0.6 per WT in 2016, 2017 and 2019, and 0.5 per WT in 2020. In the last monitoring year, it lowered mostly due to vegetation succession.

3.2 Acoustic data analysis

Monthly bat activity recorded at the weather mast during the entire study period is presented in Figure 3. A total of 3013 and 2249 5 s recordings was detected in the highest collision period of 2016 and 2017 respectively. Altogether 4700 and 4724 5 s recordings were detected in 2019 and 2020, namely a total increase of recorded bat activity by 79%. The highest activity was then detected in the second half of August and first half of September as in the former years. Constant high activity was still detected most of the nights

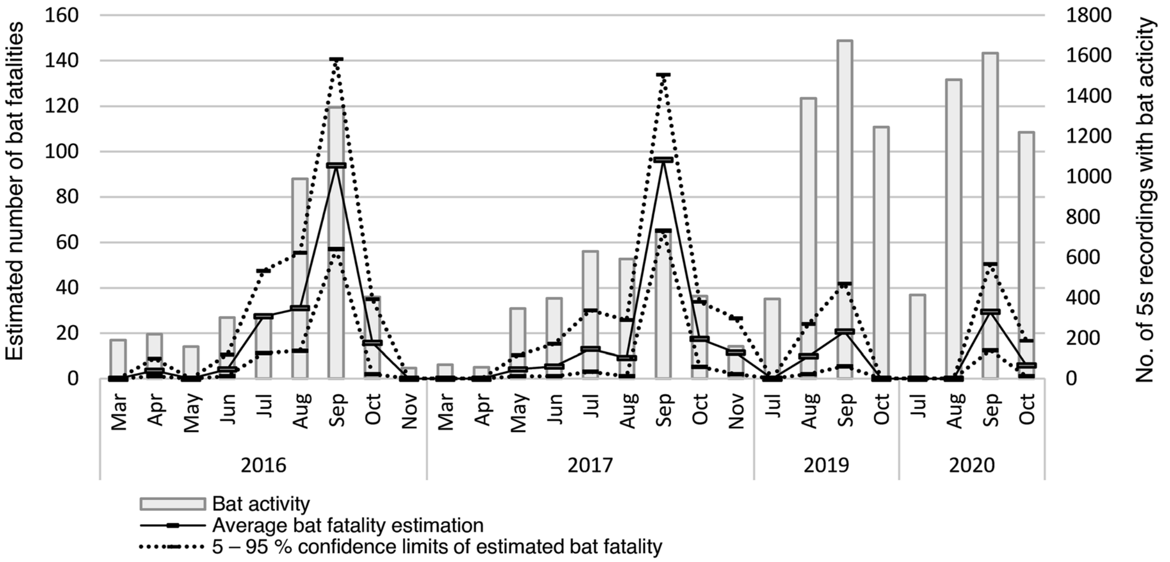

Figure 3: Monthly bat fatality estimation at Rudine wind farm (average and 5–95% confidence intervals; left y-axis) and monthly bat activity recorded at weather mast (right y-axis), both before (2016–2017) and after (2019–2020) the implementation of mitigation measures.

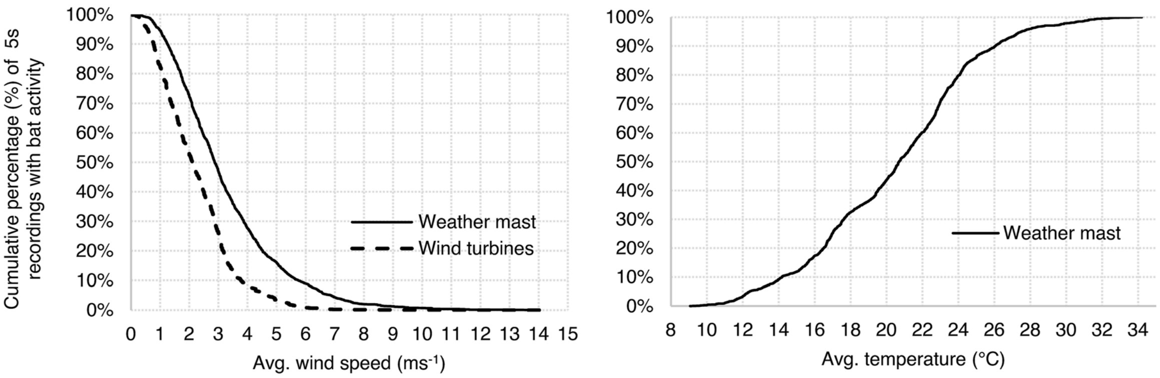

Figure 4: Cumulative percentage of bat activity (raw data) at Rudine wind farm from weather mast and four wind turbines based on averaged 10 min values of wind speed (ms^{-1}) and temperature (°C).

during the rest of the monitoring period, mostly during the first part of the night. This includes the entire period of the highest collision risk. Most 5 s recordings referred to *Tadarida teniotis* (47%), phonic group *Eptesicus/Nyctalus/ Vespertilio* including *Nyctalus noctula* (29%), and *H. savii/P. kuhlii/nathusii* (22%). Other species including *Pipistrellus pygmaeus, Pipistrellus pipistrellus, Miniopterus schreibersii* along with phonic groups *Myotis blythii/myotis, T. teniotis/ Nyctalus lasiopterus,* genera *Plecotus* and *Myotis* were detected occasionally (2%). 53% of the activity at the weather mast and 48% at WTs was detected before midnight.

3.3 Bat activity in relation to weather conditions

Both activity datasets, from the weather mast and WTs, show a similar trend of relation to wind speed (Figure 4). Analysis of bat activity from the weather mast showed that 98.0% of hours with recorded bat activity occurred when the temperature was higher than 11 °C, while 97.5% of the time bat activity was recorded when there was no precipitation (Table 3).

3.4 Mitigation measures design

Mitigation measures were implemented each night from sunset to sunrise at eight out of 12 WTs. Proposed CWS values ranged from 5.0 to 6.5 ms^{-1} (Table 4), defined as the tolerance threshold of wind speed above which it occurs less than 1.0% of total bat activity for each 30 day period before and after midnight (Figure 5). The implementation of CWS thresholds determined for the period from 16th September to 15th October was prolonged until 31st October due to potential annual variations in the timing of seasonal migrations.

4 Discussion

The estimated number of bat fatalities suggests the importance of conservation of bat fauna at Rudine WF at local and regional scale. Bat carcasses of 11 bat species were detected, out of 20 bat species present at wind farm location based on previous surveys (Rnjak et al. 2015) and case study results. Implemented mitigation measures significantly reduced the number of bat fatalities, despite an increase in bat activity observed by bioacoustic monitoring at the same time. They still lead to occasional bat fatalities as expected, partially also due to detection range of ultrasonic microphones, acoustic shadow produced by the nacelle, criteria for triggering a recording by ultrasound detectors, software tools used for noise filtering, etc. (Voigt et al. 2021). Even with these known limitations of acoustic monitoring, this study showed that it is possible to obtain enough sample data to produce effective mitigation measures. In addition, carcass searches provided valuable data in designing and testing the mitigation scheme. Potential advantages of limiting the searches to roads and pads were already suggested by Maurer et al. (2020), provided that a sufficient sample size is gathered, with access roads positioned in different directions. These advantages were also observed in our case study, allowing more thorough searches close to wind turbines, which resulted in higher searchers efficiency in areas where the highest share of bat carcasses is expected. On the other hand, the use of control wind turbines to test the mitigation measures was assessed as an inappropriate method in this case, due to the relatively small number of wind turbines, with both temporal and spatial high variability in number of found carcasses.

Study results at Rudine WF indicate that the immediate wind farm area is used by local populations, as well as bats during seasonal migrations and mating period. The highest

Table 3: Number of hours according to (A) average hourly air temperature and (B) total hourly precipitation both in relation with bat activity (*N* 5 s recordings per hour) recorded at weather mast.

(A) Number of hours						
Temperature (°C)	**For 1 5 s recordings/h**	**For 2 5 s recordings/h**	**For 3–5 5 s recordings/h**	**For 6–10 5 s recordings/h**	**For >10 5 s recordings/h**	**% of the time with recorded bat activity**
7–8	0	0	0	0	0	0.0
8–9	0	0	0	0	0	0.0
9–10	2	0	0	0	0	0.3
10–11	4	1	5	0	0	1.7
11–12	14	6	8	2	1	5.2
12–13	4	3	7	2	1	2.9
13–14	8	3	3	1	0	2.5
14–15	7	2	9	1	0	3.2
15–20	74	50	62	49	9	41.3
20–25	35	29	34	25	16	23.5
>25	21	23	38	24	8	19.3

(B) Number of hours						
Precipitation (mm)	**For 1 5 s recordings/h**	**For 2 5 s recordings/h**	**For 3–5 5 s recordings/h**	**For 6–10 5 s recordings/h**	**For >10 5 s recordings/h**	**% of the time with recorded bat activity**
0	167	115	159	101	34	97.5
0–0.5	1	0	2	1	0	0.7
0.5–1	0	0	2	0	0	0.3
>1	1	2	3	2	1	1.5

Grey coloured areas: temperature and precipitation classes for which less than 5% of hours with bat activity was recorded.

Table 4: Curtailment regulation proposed at Rudine wind farm.

Wind turbines	**Period**	**Critical wind speed (ms^{-1})**	
		Sunset-midnight	**Midnight-sunrise**
8 out of 12	15th July–15th August	5.5	5.0
	16th August–15th September	6.5	6.5
	16th September–31st October	5.0	5.5

collision risk period was defined from 15th July based on the findings during the case study and at other wind farms in Croatia (Rnjak, unpublished). It corresponds to the expected arrival of young bats, which are still inexperienced flyers and therefore at greater risk of collision. Similar findings were recorded at other wind farms in the Mediterranean region (Sánchez-Navarro et al. 2020). As stated by Rodrigues et al. (2015) effective, adequate and sustainable measures should be designed on a case-by-case basis since bat activity, wind tolerance, and correlation to other weather conditions may differ significantly between sites (Arnett et al. 2010). However, our study confirms previous results which often indicate wind speed thresholds of 5.0–6.5 ms^{-1} for effectively reducing mortality rates (Arnett et al. 2011; Măntoiu et al. 2020). In another wind farm location in Croatia (Rnjak et al. 2021) critical wind speed thresholds ranged from 1.5 to 5.0 ms^{-1}, with the total reduction by 86% of the estimated bat fatalities using blade feathering and increasing cut-in speed when necessary.

The decrease of bat activity during rainfall detected at the study site is a common observation in bat surveys possibly due to the low presence of insects as available prey, constraints in flight due to interference with echolocation, and increased flight metabolism (Barros et al. 2014; Voigt et al. 2011). The relation of bat activity and temperature found in this study was also accordant to the often-recommended threshold between 10 °C and 11 °C (e.g., NatureScot et al. 2021), although some other studies at wind farms in Europe detected threshold values around 15 °C (Amorim et al. 2012; Behr et al. 2015). All this suggests that production losses can be reduced by avoiding general thresholds offered by blanket curtailment, while still enabling a significant reduction in bat fatalities.

The method described in this study could be considered as a minimum standard for post-construction monitoring projects and can be used at other wind farms as a practical and accessible tool. The question remains whether this method would be more effective than detailed algorithms developed for other parts of Europe (e.g., Behr et al. 2018; Topwind 2019), which should be experimentally tested within a more detailed study. Efforts can be made for its

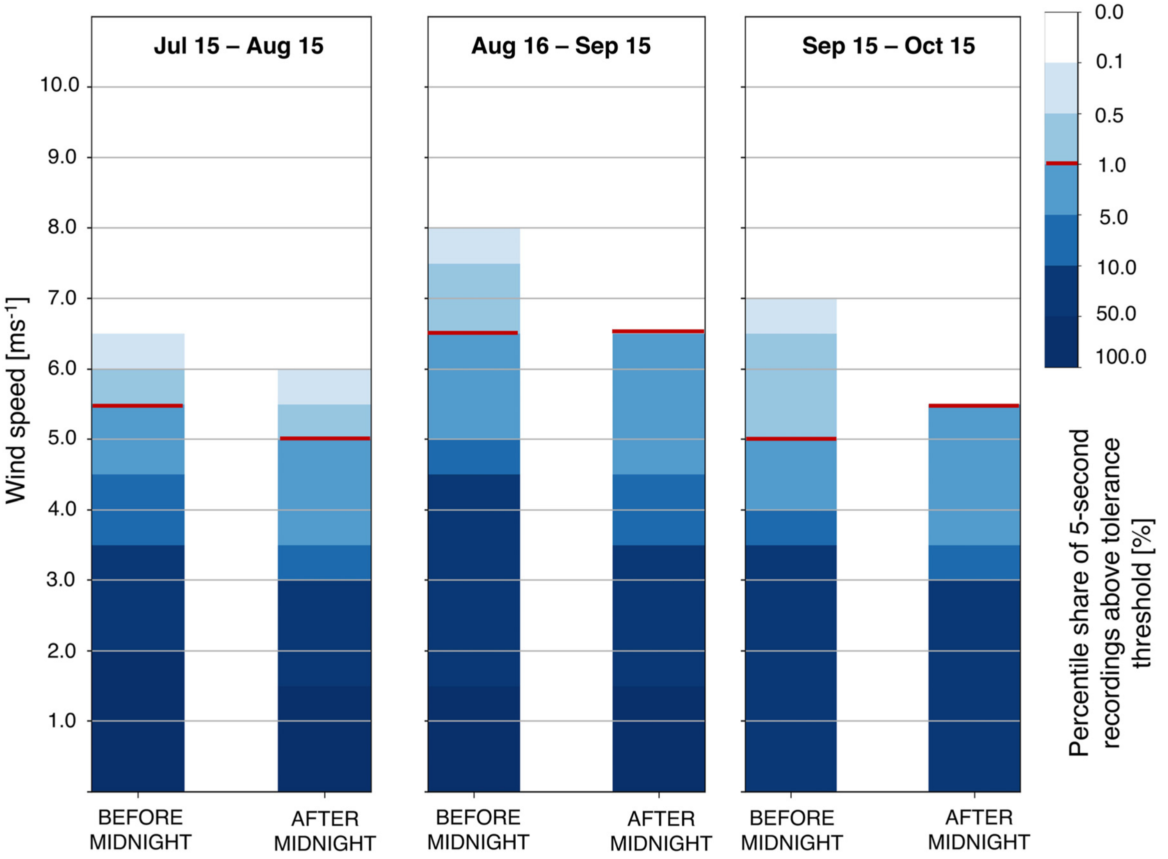

Figure 5: Percentile share of 10 min intervals with recorded bat activity at Rudine wind farm above the tolerance threshold (more than two 5 s recordings in 10 min) distributed in relation to corresponding 0.5 ms^{-1} intervals of averaged 10 min wind speed values per 30 day intervals (red line: threshold for 99.0% of bat activity).

further improvements. Additional microphones at wind turbines could increase the probability of detecting bats (Voigt et al. 2021). The implementation of species detectability coefficients should be considered in the future as suggested by Barataud (2015), and their adaptation in terms of different ultrasound detectors and microphones currently available. Defining regional reference values of bat activity could help indicate high collision risk, which could serve as a basis for recognizing the need to implement mitigation measures even without data collected through carcass searches (Coronado et al. 2021; Roemer et al. 2017). Further development in this area should also be directed towards the application of models based on artificial intelligence to predict bat activity in terms of actual meteorological conditions and testing the implemented measures on larger data sets obtained by carcass searches.

Based on our results, further reduction in production losses at Rudine WF can be achieved by testing temperature and precipitation thresholds for which mitigation measures are not considered necessary. This study undoubtedly shows that clearly defined criteria based on site-specific collected data can be an important part of mitigation measure scheme. They allow further adjustments of specific conditions and criteria depending on the target level of bat mortality reduction. It is important to note that in Croatia bat population sizes are not known (MZOE; HAOP 2018) and an acceptable level of bat mortality during wind farm operation is not defined. Number of found bat carcasses often cannot be compared between studies which differ in methodology used, while most estimation models vary due to different levels of uncertainty and bias (Péron 2018). This is also the case for a number of European countries where implementation of mitigation measures often depends on the goodwill of wind farm stakeholders, in absence of adequate post-construction monitoring and mitigation methods (EUROBATS 2017). It is crucial for conservation of bat populations along with further development of wind energy to invest in all efforts possible to provide sustainable and species-conservation-friendly mechanisms.

Research ethics: All activities regarding handling with strictly protected bat species were in accordance with the Permission for bat (Chiroptera) research issued by the competent Ministry of the Republic of Croatia.

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Author contributions: Authors approved submission of this manuscript and are responsible for its content. Dina Rnjak managed the project and was in charge of overall planning and implementation, survey design and data analysis. Together with Magdalena Janeš she participated in field surveys and took the lead in writing the manuscript. Magdalena Janeš also performed estimations of number of bat carcasses, while Josip Križan performed the numerical calculations of bat activity in relation to weather conditions. Oleg Antonić provided critical feedback and helped to shape the research, analysis and manuscript.

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