RESEARCH PAPER

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Long-term impact on the breeding birds of a semi-offshore island-based wind farm in Åland, Northern Baltic Sea

Långsiktig påverkan på åländska häckfåglar av en kustnära, havsbaserad vindkraftspark

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BREEDING BIRD POPULATIONS were monitored at a wind farm in the Båtskär area of the southern Åland archipelago in 2006–2017. The area is situated in the outer archipelago and comprises four islands with six wind turbines in total. The wind turbines began operating in autumn 2007. An environmental impact assessment for the area was conducted in 2002. A control area called Stenarna, located 22 km NW of Båtskär, was used for comparison. The Båtskär area annually recorded 850–1,050 pairs of breeding birds. Four species showed significantly decreasing trends in Båtskär, namely the Common Eider *Somateria mollissima*, Lesser Black-backed Gull *Larus fuscus*, Herring Gull *Larus argentatus*, and Black Guillemot *Cepphus grylle*. In Stenarna, only the Common Eider significantly decreased over the same period. The Arctic Tern *Sterna paradisaea* increased in both areas, while the Velvet Scoter *Melanitta fusca*, Red-breasted Merganser *Mergus serrator*, Common Gull *Larus canus*, Rock Pipit *Anthus petrosus*, and White Wagtail *Motacilla alba* increased in Stenarna, the control area. The Herring Gull population decline is unlikely to be related to the wind farm. However, the proximity of a wind turbine to a breeding colony of the Lesser Black-backed Gull has most likely contributed to its decline. The reason for the Black Guillemot decline in Båtskär is unknown. The decline of Common Eider in both areas may be connected to increasing predation from White-tailed Eagles *Haliaeetus albicilla*. Some species, such as the House Martin *Delichon urbicum* and auks, have

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benefitted from the wind farm construction. They can utilize new microhabitats created by the construction, while other species, such as the Common Eider, gain protection against predation because of human activities.

Keywords: Baltic Sea | archipelago | wind energy | wind farm | population trends | breeding | Laridae | Anatidae

Introduction

High man-made structures, e.g. wind turbines, pose risks of collision, disturbance, and habitat loss for birds, and these structures may negatively affect populations (Drewitt & Langston 2006, Hüppop *et al.* 2006, de Lucas *et al.* 2007, Stewart *et al.* 2007, Krijgsveld *et al.* 2009, Furness *et al.* 2013, Rydell *et al.* 2017). Large soaring birds of prey are known to be vulnerable, but other bird species also migrate along coastal routes and breed in coastal areas where wind turbines are often installed. In addition to the soaring birds of prey, gulls and terns have been shown to collide with wind turbines and other high constructions (Drewitt & Langston 2006). On the other hand, some waterbirds and terns avoid wind turbines and change their flight routes when passing turbines (Desholm & Kahlert 2005, Harwood *et al.* 2017, Rydell *et al.* 2017).

The effects of wind power production on birds have mainly been studied in North America and Europe. Studies have dealt with birds of prey (de Lucas *et al.* 2008, Carwin *et al.* 2011), breeding birds on farmland (Pearce-Higgins 2009), and wintering birds (Larsen & Guillemette 2007, Devereaux 2008). Many studies have focused on bird collisions (Desholm *et al.* 2006, Hüppop *et al.* 2006, Petersen *et al.* 2006, Drewitt & Langston 2008, Loss *et al.* 2013). The effects on coastal breeding terns have been studied in Belgium (collisions; Everaert & Stienen 2007) and Britain (foraging area, avoidance; Perrow *et al.* 2006, Harwood *et al.* 2017). The effects of building offshore wind farms on bird migration have been studied in the Baltic Sea region (Petterson 2005, Petersen *et al.* 2006).

Desholm (2006) presents a model to examine various species' sensitivity to increased migration mortality due to collisions with wind farms. The model is based on observations of migratory bird numbers, wind farm avoidance, and flight routes within the wind farm stratified by bird species. Model data were collected from Nysted offshore wind park, Denmark. Although knowledge of wind power impacts on birds is increasing, local conditions may result in very different effects to local and migrating bird populations. The selection of wind turbine sites should include economic and ecological aspects (Haaren & Fthenakis 2011), and the cumulative impacts of several wind farms should be assessed (Carrete *et al.* 2009, Masden *et al.* 2010). All available information on the risks of wind power to birds is valuable in these decision-making processes.

During the last decades, wind power has been built increasingly on land, shores, and large islands, but the recent trend is to build more parks offshore. Constructing semi-offshore wind farms on small islands and islets is rare. The demanding icy conditions of the northern Baltic Sea make offshore parks difficult and expensive to build.

We previously reported the results from the first years of monitoring at Båtskär wind farm (Tanskanen 2012). The aim of our current study is to present the long-term effects of wind turbines on the breeding archipelago bird fauna in a semi-offshore wind farm in Åland, the northern Baltic Sea.

Material and methods

STUDY AREA

The study area and methods are described previously in Tanskanen (2012), and here we present a short summary. The wind farm in Båtskär consists of six Enercon E-70 2.3 MW units, with a hub height of 64 m and a rotor diameter of 70 m (Figure 1). Wind farm construction began in autumn 2006, and the wind turbines began operating in autumn 2007. The Båtskär area consists of a group of five small islands and islets at the edge of the open sea, south of Åland in the Baltic Sea (59°57.736' N 19°57.384' E; Figure 2). Two shipping routes restrict the area, one in the north and one in the east. Both routes are used daily by passenger and cargo ships (Figure 3). The smallest islet Österbådan

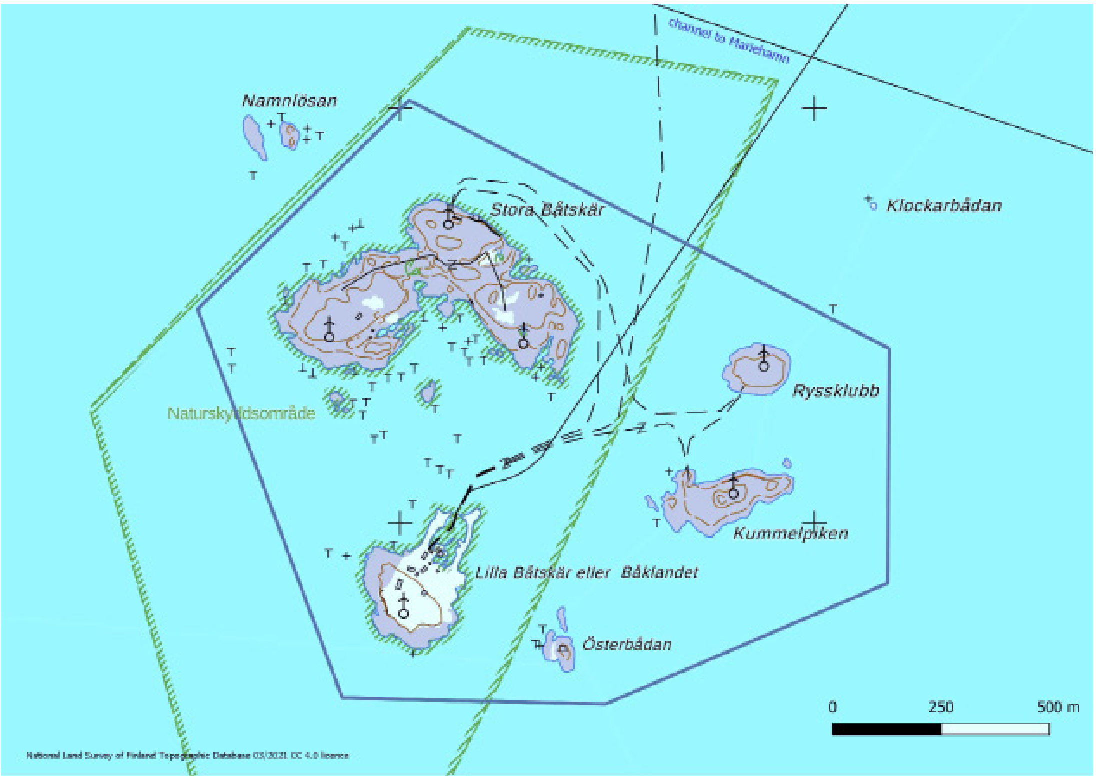

FIGURE 1. Map of Båtskär, Åland, Northern Baltic Sea. The blue line delineates the study area. Wind turbine locations indicated with ♁. — *Karta över Båtskär, Åland, norra Östersjön. Den blåa linjen avgränsar inventeringsområdet. Placering av vindkraftverk indikeras av ♁.*

(0.5 ha) is swept over by waves during storms and has no breeding birds. Two small islets, Ryssklubben (1.5 ha) and Kummelpiken (3.1 ha), consist of open rock, ground vegetation, and small bushes in sheltered places. Kummelpiken has a stone field on its southern side, and Ryssklubben has a small mire. Both islets have a wind turbine.

Lilla Båtskär (5.1 ha) has been heavily exploited by humans. The island has a sheltered harbour with substantial breakwaters and a few service buildings, a large main building used to host the pilot station at the highest spot on the island, and a 33-m high mine tower. Most of the island has been altered by humans and has gravel fields and blasted stone rock with some vegetation, bushes, and single trees. Lilla Båtskär has one wind turbine placed south of the mine tower.

Stora Båtskär (15.3 ha) has higher cliffs and deeper shores on the northern side compared to the southern side, which has sheltered bays and low cliffs. There are small skerries in the sound between Lilla and Stora Båtskär. Stora Båtskär has small temporary ponds that partly dry out during hot summer periods. There are large areas of mire and moor vegetation. Sheltered areas hold birches *Betula pendula* and *B. pubescens*, common alders *Alnus glutinosa*, and rowans *Sorbus aucuparia*. Three wind turbines are located on the island: one at the east end, one in the west, and one on the high cliff in the centre.

Stenarna (Figure 4), a group of six islands and islets 22 km NW of Båtskär (Figure 2), was used as a control area. It is similar to Båtskär, with small rocky islands and only a few trees. It is also at the edge of the open sea, just like Båtskär, but no commercial vessel traffic passes through the boating route east of the area. Stenarna experiences a lower level of disturbance from boating etc. than Båtskär, and the islands are further apart from each other. There are no buildings or harbour in the Stenarna area.

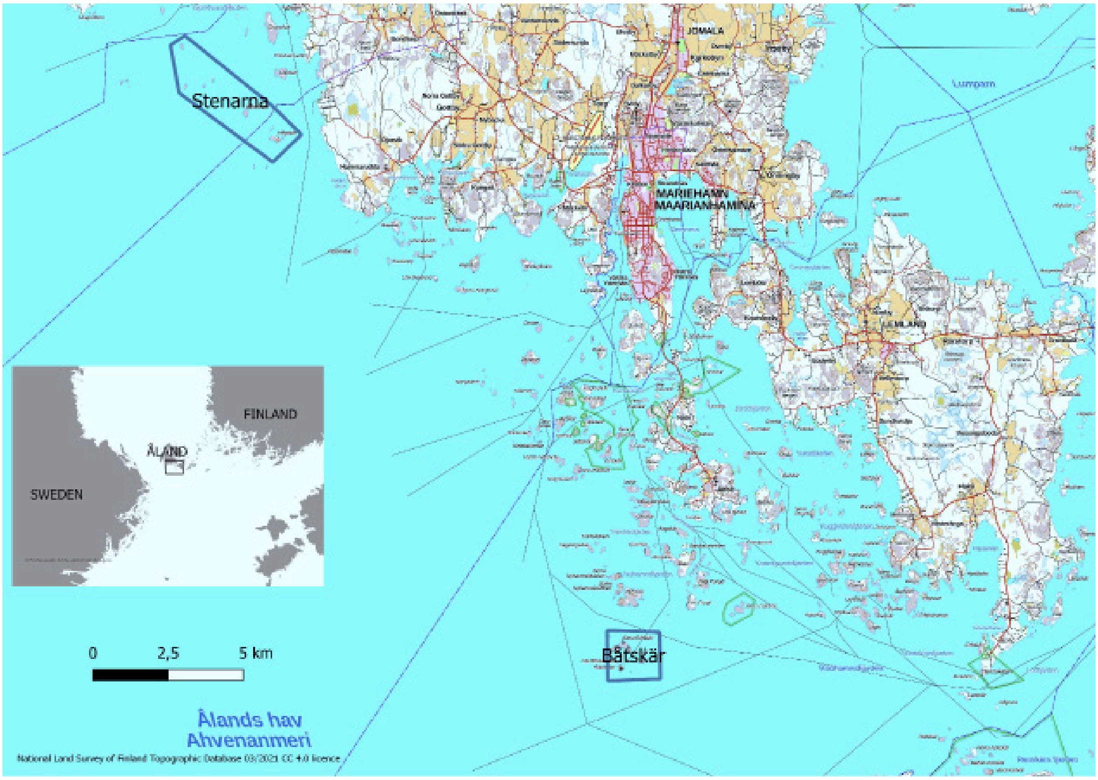

FIGURE 2. Map of southern Åland, Northern Baltic Sea. Study areas are marked with blue borders. The location and area of the main map are indicated with a black rectangle in the insert map.
— Karta över södra Åland. Inventeringsområdena är avgränsade i blått. I den inlagda kartan visas huvudkartans område med svart rektangel.

FIGURE 3. View of Stora Båtskär towards the south from a car ferry, in the background Lilla Båtskär with a mine tower.
— Vyn mot söder från färjan. Bakom farleden är Stora Båtskär och i bakgunden syns Lilla Båtskär med gruvtornet.

We performed bird surveys three times each summer: in early May, June, and July. The method was adapted from Hildén *et al.* (1991), i.e. counting adults, young birds, and nests where possible. The only exception to the Hildén *et al.* (1991) method was that, for each survey, birds were counted with a spotting scope and binoculars from the roof of the mine tower at Lilla Båtskär early in the morning. The number of breeding pairs for each species is the largest number recorded at one time over the three surveys: the number of observed adults divided by two, and the number of nests, breeding territories, or observed broods. Breeding pair numbers for 2002 were obtained from the EIA report (Anon. 2002). The Båtskär area was surveyed in 2002 and in 2006–2017. Stenarna (control) was surveyed in 2006 and 2009–2017.

Linear models (lm) and generalized linear models (glm) with log-transformed number of pairs with Poisson distribution were used to examine the population trends for all species that averaged three or more pairs during the survey period in the area (16 species in Båtskär, 13 in Stenarna; bolded in Tables 1 and 2). A linear regression was separately applied to the whole timespan (2002–2017, marked with blue) for the Båtskär area and separately for the wind farm operation period (2008–2017, marked with red). Šidák correction for a significance level of 0.05 resulted in 16 or 13 tested species, with a corrected level of 0.003 (Šidák 1967). The significance was drawn from the lowest p-value of two models (Stenarna) or three models (Båtskär): linear regression (total time and operation for Båtskär) and the glm p-value. The Shannon index was calculated for each year for both areas for all species. Analyses were performed with R 4.1.1 (R Core Team 2021).

Results

The total number of breeding pairs in Båtskär varied from 807 to 1,047 during the survey period of 2002–2017 (Table 1). The number of breeding species varied

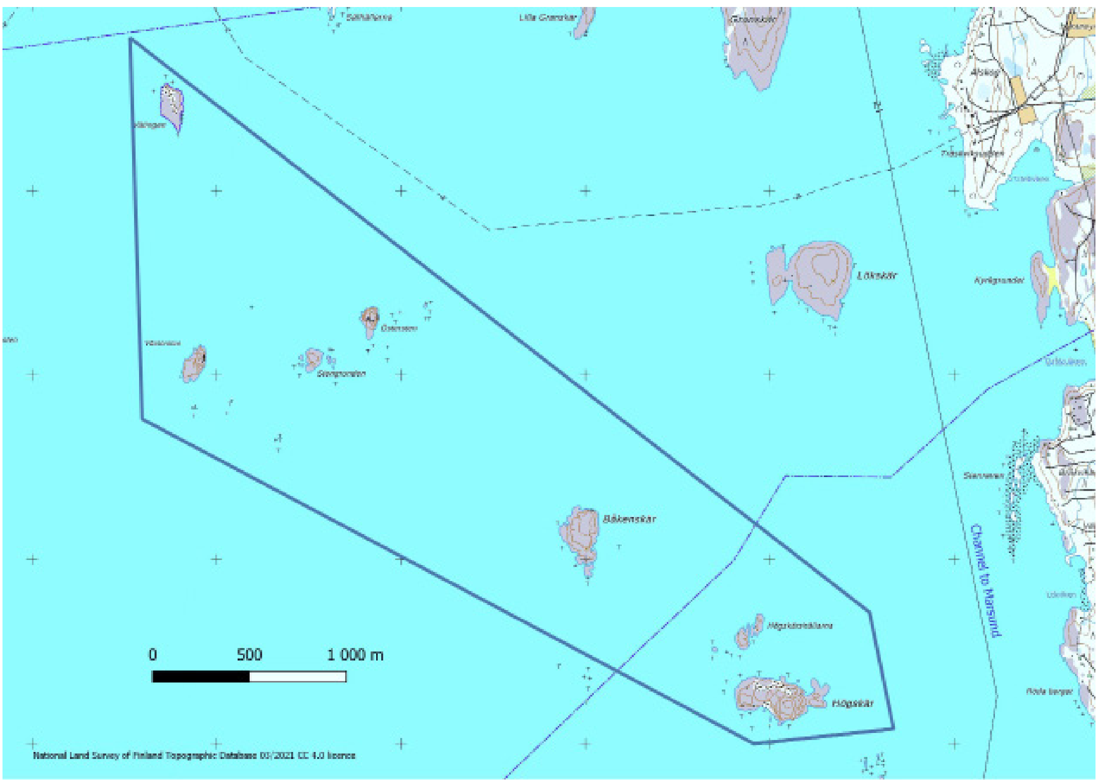

FIGURE 4. Map of Stenarna. The blue line delineates the study area. — *Karta över Stenarna. Den blåa linjen avgränsar inventeringsområdet.*

TABLE 1. The annual number of breeding bird pairs at Båtskär wind farm. The three most abundant species (Common Eider *Somateria mollissima*, Black Guillemot *Cepphus grylle*, and Razorbill *Alca torda*) comprise 63–78% of all breeding pairs. The composition of bird assemblages has remained fairly stable, as the number of breeding species and pairs, the number of species with five or more pairs, and the Shannon index have not changed notably during the follow-up years. The years during which the wind farm has been in operation are marked in bold font and demarcated with a vertical line. Species for which population trends have been analysed (Figure 5) are indicated by Y (yes) in the trend column.
— Årligt antal häckande fågelpar i Båtskärsområdet. De tre vanligaste arterna (ejder Somateria mollissima*, tobisgrissla* Cepphus grylle *och tordmule* Alca torda*) utgör 63–78% av alla häckande par. Fågelfaunas struktur har varit ganska stabil: antalet häckande arter och par, antalet arter med minst fem par och Shannon-index har inte ändrats markant under uppföljningen. De år som vindkraftverken har varit i bruk är i tabellen avgränsade med en vertikal linje och markerade med fetstil. Arter vars populationstrender analyserats (figur 5) är markerade med Y (yes) i trendkolumnen.*

Species *Art*			Year (N breeding pairs) *År (antal häckande par)*													Trend
English name *Engelskt namn*	Swedish name *Svenskt namn*	Scientfic name *Vetenskapligt namn*	2002	2006	2007	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	
Canada Goose	kanadagås	*Branta canadensis*	0	0	0	1	1	0	1	0	2	0	0	0	0	
Greylag Goose	grågås	*Anser anser*	3	2	1	3	1	1	4	2	2	1	2	1	0	
Mute Swan	knölsvan	*Cygnus olor*	1	0	1	1	1	1	1	1	2	1	1	1	0	
Common Shelduck	gravand	*Tadorna tadorna*	0	0	0	1	0	0	0	0	0	0	0	0	0	
Northern Shoveler	skedand	*Anas clypeata*	1	0	0	0	0	0	0	0	0	0	0	0	0	
Mallard	gräsand	*Anas platyrhynchos*	6	2	2	2	1	2	0	0	5	4	3	1	1	
Tufted Duck	vigg	*Aythya fuligula*	10	2	2	3	2	1	4	3	7	6	6	3	3	Y
Common Eider	ejder	*Somateria mollissima*	200	211	212	198	188	193	229	233	203	140	130	119	117	Y
Velvet Scoter	svärta	*Melanitta fusca*	9	5	6	6	6	9	11	6	15	12	10	12	25	Y
Red-breasted Merganser	småskrake	*Mergus serrator*	0	0	1	4	2	3	2	4	4	4	5	5	4	
Common Merganser	storskrake	*Mergus merganser*	2	10	8	5	12	6	9	10	13	11	8	9	9	Y
Black Grouse	orre	*Tetrao tetrix*	1	1	1	0	1	1	1	0	1	0	0	0	1	
Eurasian Oystercatcher	strandskata	*Haematopus ostralegus*	3	4	1	3	3	1	4	4	4	6	3	4	5	Y
Common Ringed Plover	större strand-pipare	*Charadrius hiaticula*	1	1	1	0	0	0	0	1	2	4	3	3	4	
Ruddy Turnstone	roskarl	*Arenaria interpres*	5	3	2	2	2	2	2	2	2	2	1	1	2	
Common Redshank	rödbena	*Tringa totanus*	1	1	1	1	0	1	0	1	1	2	1	1	2	
Common Gull	fiskmås	*Larus canus*	116	51	60	61	62	62	81	99	91	79	83	82	83	Y
Great Black-backed Gull	havstrut	*Larus marinus*	4	2	1	1	1	1	1	1	2	1	1	1	1	
Herring Gull	gråtrut	*Larus argentatus*	55	18	19	22	19	12	10	11	10	8	11	5	4	Y

TABLE 1 continued *fortsatt.*

Species *Art*			Year (N breeding pairs) *År (antal häckande par)*													Trend
English name *Engelskt namn*	Swedish name *Svenskt namn*	Scientfic name *Vetenskapligt namn*	2002	2006	2007	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	
Lesser Black-backed Gull	silltrut	*Larus fuscus*	49	47	37	40	30	28	26	25	26	25	16	26	21	Y
Arctic Tern	silvertärna	*Sterna paradisaea*	51	37	35	28	15	24	68	69	75	65	42	95	92	Y
Parasitic Jaeger	kustlabb	*Stercorarius parasiticus*	1	1	1	0	0	0	0	0	0	0	0	0	0	
Razorbill	tordmule	*Alca torda*	165	210	196	195	175	149	190	182	162	190	161	215	195	Y
Black Guillemot	tobisgrissla	*Cepphus grylle*	337	355	398	352	333	307	333	290	339	287	280	229	204	Y
Eurasian Eagle-owl	berguv	*Bubo bubo*	0	0	0	0	0	0	0	0	0	1	1	0	0	
Hooded Crow	kråka	*Corvus corone cornix*	3	4	4	3	2	3	2	4	6	3	3	2	2	Y
Barn Swallow	ladusvala	*Hirundo rustica*	4	10	16	10	9	7	4	5	6	3	4	5	4	Y
Common House Martin	hussvala	*Delichon urbicum*	7	19	18	18	17	17	18	20	18	21	17	19	17	Y
Eurasian Blackcap	svarthätta	*Sylvia atricapilla*	0	0	0	0	0	0	0	0	0	1	0	0	0	
Lesser Whitethroat	ärtsångare	*Sylvia curruca*	1	0	0	1	1	3	0	1	3	3	1	3	2	
Common Whitethroat	törnsångare	*Sylvia communis*	2	2	3	3	3	0	1	1	5	5	3	1	1	
Northern Wheatear	stenskvätta	*Oenanthe oenanthe*	1	4	4	2	2	2	4	4	2	3	3	4	4	Y
White Wagtail	sädesärla	*Motacilla alba*	5	4	4	5	5	7	6	6	7	8	5	6	8	Y
Rock Pipit	skärpiplärka	*Anthus petrosus*	3	3	2	2	4	1	0	4	3	3	2	2	5	(Y)
Common Chaffinch	bofink	*Fringilla coelebs*	0	0	0	0	0	0	1	0	0	0	1	0	0	
N breeding pairs (total) *häckande par (totalt)*			1,047	1,009	1,037	973	898	844	1,013	989	1,018	899	807	855	816	
N breeding species *häckande arter*			29	26	28	28	27	26	25	26	29	29	29	27	26	
N breeding species with ≥5 pairs *häckande arter med ≥5 par*			13	11	11	12	12	12	11	12	16	14	13	13	12	
Shannon index			2.05	1.91	1.87	1.92	1.89	1.89	1.92	1.98	2.07	2.09	2.02	2.06	2.13	

between 25 and 29. Black Guillemot *Cepphus grylle* (204–398 pairs), Common Eider *Somateria mollissima* (117–233 pairs), and Razorbill *Alca torda* (149–215 pairs) were the most abundant species. Common Gull *Larus canus* was the most abundant gull (51–116 pairs), and the Arctic Tern *Sterna paradisaea* (15–95 pairs) was the only tern breeding in the area. The most common passerines were House Martin *Delichon urbicum* (7–21 pairs) and Barn Swallow *Hirundo rustica* (3–16 pairs).

Stenarna housed 19–23 species of breeding birds, with Black Guillemot (120–158 pairs), Arctic Tern (50–117 pairs), Common Eider (7–61 pairs), and Common Gull (24–58 pairs; Table 2) being the most common species.

In Båtskär, Black Guillemots mainly bred on the stony breakwaters of the Lilla Båtskär harbour, and also, to some extent, on man-made landing places on the other islands. Most of the Common Eiders bred on Stora Båtskär and increasingly also on Lilla Båtskär. Razorbills utilized both man-made landing places with large stone blocks and natural gorges and stone fields. Arctic Terns bred mainly on open rock but also on service road gravel fields. Common Gulls bred mostly close to Arctic Tern colonies on the open rock with some vegetation.

In Stenarna, Black Guillemots bred mostly on Västersten in natural gorges, Arctic Terns bred on many islands on the open rock and stone fields, and Common Gulls close to Arctic Tern colonies, just as in Båtskär.

Four species decreased significantly in Båtskär for the whole study period 2002–2017: Common Eider (lm: $b=-6.4$, $P<0.012$; glm: $\beta=-0.13$, $p<0.001$), Lesser Black-backed Gull *Larus fuscus* (lm: $b=-2.1$, $P<0.001$; glm: $\beta=-0.31$, $p<0.001$), Herring Gull *L. argentatus* (lm: $b=-2.6$, $p<0.001$; glm: $\beta=-0.70$, $p<0.001$), and Black Guillemot (lm: $b=-9.6$, $p=0.001$; glm: $\beta=-0.12$, $p<0.001$; Figure 5). The Arctic Tern was the only significantly increasing species (lm: $b=3.75$, $p<0.021$; glm: $\beta=0.31$, $p<0.001$). The linear trend for breeding pair numbers during wind farm operation (2008–2017) is shown in Figure 5 with red lines and figures. Black Guillemot ($b=-13.84$, $p=0.001$) and Herring Gull ($b=-1.65$, $p=0.001$) showed significant decreases during wind farm operation.

The Common Eider decreased significantly in Stenarna (lm: $b=-4.5$, $p=0.001$, glm: $\beta=-0.51$, $p<0.001$), whereas six species increased: Velvet Scoter *Melanitta fusca* (lm: $b=0.95$, $p=0.01$, glm: $\beta=1.44$, $p<0.001$), Red-breasted Merganser *Mergus serrator* (lm: $b=0.64$, $p=0.02$, glm: $\beta=1.59$, $p=0.003$), Common Gull (lm: $b=2.46$, $p=0.01$, glm: $\beta=0.24$, $p=0.003$) Arctic Tern (lm: $b=5.52$, $p=0.004$, glm: $\beta=0.29$, $p<0.001$), Rock Pipit *Anthus petrosus* (lm: $b=0.44$, $p=0.002$, glm: $\beta=0.37$, $p=0.12$), and White Wagtail *Motacilla alba* (lm: $b=0.32$, $p=0.002$, glm: $\beta=0.19$, $p=0.33$).

TABLE 2. The annual numbers of breeding bird pairs in Stenarna. Species for which population trends have been analysed (Figure 5) are indicated by Y (yes) in the trend column.
— Årligt antal häckande fågelpar i Stenarna. Arter vars populationstrender analyserats (figur 5) är markerade med Y (yes) i trendkolumnen.

Species *Art*			Year (N breeding pairs) *År (antal häckande par)*										Trend
English name *Engelskt namn*	Swedish name *Svenskt namn*	Scientfic name *Vetenskapligt namn*	2002	2009	2010	2011	2012	2013	2014	2015	2016	2017	
Barnacle Goose	vitkindad gås	*Branta leucopsis*	0	0	0	0	0	1	0	0	0	0	
Greylag Goose	grågås	*Anser anser*	0	1	0	0	0	1	0	0	0	0	
Mute Swan	knölsvan	*Cygnus olor*	0	2	1	1	1	0	1	1	1	1	
Northern Shoveler	skedand	*Anas clypeata*	0	0	0	0	0	0	0	0	1	0	
Mallard	gräsand	*Anas platyrhynchos*	0	2	1	1	1	1	3	4	4	2	
Tufted Duck	vigg	*Aythya fuligula*	7	1	4	1	8	8	6	8	8	3	Y
Common Eider	ejder	*Somateria mollissima*	61	40	28	54	30	35	17	14	7	15	Y
Velvet Scoter	svärta	*Melanitta fusca*	2	0	0	0	8	4	10	6	7	11	Y

TABLE 2 continued *fortsatt.*

Species *Art*			Year (N breeding pairs) *År (antal häckande par)*										Trend
English name *Engelskt namn*	Swedish name *Svenskt namn*	Scientfic name *Vetenskapligt namn*	2002	2009	2010	2011	2012	2013	2014	2015	2016	2017	
Red-breasted Merganser	småskrake	*Mergus serrator*	0	2	2	0	5	4	1	9	6	6	Y
Common Merganser	storskrake	*Mergus merganser*	2	0	1	2	0	5	4	3	5	5	
Eurasian Oystercatcher	strandskata	*Haematopus ostralegus*	3	4	4	3	3	4	5	3	5	4	Y
Common Ringed Plover	större strandpipare	*Charadrius hiaticula*	1	2	3	3	4	3	5	5	6	6	Y
Ruddy Turnstone	roskarl	*Arenaria interpres*	4	3	4	4	6	2	3	3	2	4	
Common Sandpiper	drillsnäppa	*Actitis hypoleucus*	0	0	0	0	0	1	1	0	0	0	
Common Redshank	rödbena	*Tringa totanus*	2	2	3	1	1	1	1	4	2	5	
Common Gull	fiskmås	*Larus canus*	37	24	36	29	49	43	58	54	50	52	Y
Great Black-backed Gull	havstrut	*Larus marinus*	2	2	2	1	1	1	5	2	1	1	
Herring Gull	gråtrut	*Larus argentatus*	7	17	8	11	11	16	10	8	11	9	Y
Arctic Tern	silvertärna	*Sterna paradisaea*	63	77	50	103	103	83	104	116	110	117	Y
Parasitic Jaeger	kustlabb	*Stercorarius parasiticus*	2	2	3	3	3	4	4	4	3	3	Y
Razorbill	tordmule	*Alca torda*	1	0	0	1	1	2	2	1	0	0	
Black Guillemot	tobisgrissla	*Cepphus grylle*	152	151	156	120	149	154	134	150	158	153	Y
Hooded Crow	kråka	*Corvus corone cornix*	1	2	2	1	1	1	1	2	1	3	
Lesser Whitethroat	ärtsångare	*Sylvia curruca*	0	0	2	0	0	0	0	1	1	0	
Common Whitethroat	törnsångare	*Sylvia communis*	0	0	0	0	0	0	2	3	1	0	
Northern Wheatear	stenskvätta	*Oenanthe oenanthe*	3	1	2	4	1	1	5	3	4	4	
White Wagtail	sädesärla	*Motacilla alba*	6	6	5	6	7	8	8	8	8	9	Y
Rock Pipit	skärpiplärka	*Anthus petrosus*	4	4	3	4	5	7	7	7	8	7	Y
N breeding pairs (total) *häckande par (totalt)*			360	345	320	353	398	390	397	419	409	420	
N breeding species *häckande arter*			19	20	21	20	21	24	23	23	23	21	
N breeding species with ≥5 pairs *häckande arter med ≥5 par*			7	6	6	6	11	9	13	11	13	12	
Shannon index			1.8	1.78	1.81	1.82	1.9	1.98	2.05	2	1.94	1.95	

Avifauna composition changed in both areas, as shown by the Shannon index, which increased towards the end of the study period, being 2.13 in Båtskär and 1.95 in Stenarna in 2017. The number of species with five or more breeding pairs per year varied between 11 and 17 during the study period in Båtskär, and between 6 and 13 in Stenarna. The total number of breeding pairs declined in Båtskär (lm: b=−14.31, p=0.007, glm: β=−0.07, p<0.001) and increased in Stenarna (lm: b=8.12, p=0.005, glm: β=0.08, p=0.001).

Discussion

This study investigates the effects of a semi-offshore wind farm, Båtskär, on local breeding archipelago bird populations from two years prior to ten years after construction. A control area, Stenarna, was used to compare changes in the wind farm area with an unaltered archipelago. Breeding numbers of Common Eider, Herring Gull, Lesser Black-backed Gull, and Black Guillemot decreased in the wind farm area, whereas Arctic Tern numbers increased. In the control

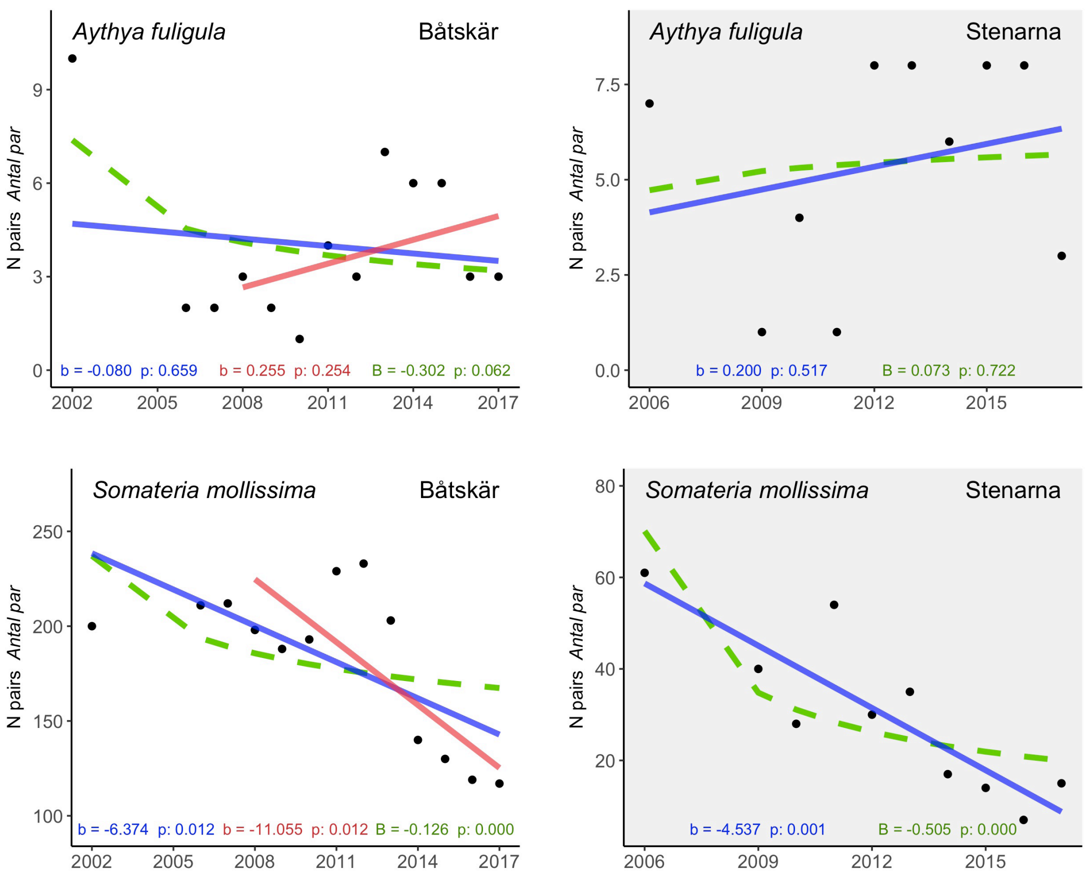

FIGURE 5 (six pages). Linear and GLM log-linear trends for species having three or more pairs on average during the follow-up (see Tables 1–2) and additionaly for Rock Pipit *Anhus petrosus* in Båtskär (just under three pairs) as comparison to the trend in Stenarna. Green dotted curves show the glm-fitted estimate of the population. β and p-values are in green. Blue lines show the linear trend, slope (change in number of pairs per year), and the p-value. Red lines show the linear trend for Båtskär during operation 2008–2017. Population trends for the study area Båtskär are drawn with white background while those for the control area Stenarna are drawn with grey background, for facilitated distinction.
— (sex sidor). Linjära samt log-linjära GLM-trender för arter med tre eller fler par i genomsnitt under uppföljningen (se tabell 1–2) samt för skärpiplärka Anthus petrosus vid Båtskär (just under tre par), som jämförelse med trenden vid Stenarna. Gröna prickade kurvor visar GLM-skattningen av populationen. β- och p-värdena är markerade med grönt. Blåa linjer visar linjär trend och lutning (ändring i antal par) samt p-värde. För Båtskär är den linjära trenden under drift 2008–2017 markerad med rött. Populationstrender för studieområdet Båtskär visas med vit bakgrund och för kontrollområdet Stenarna med grå bakgrund, för lättare särskiljning.

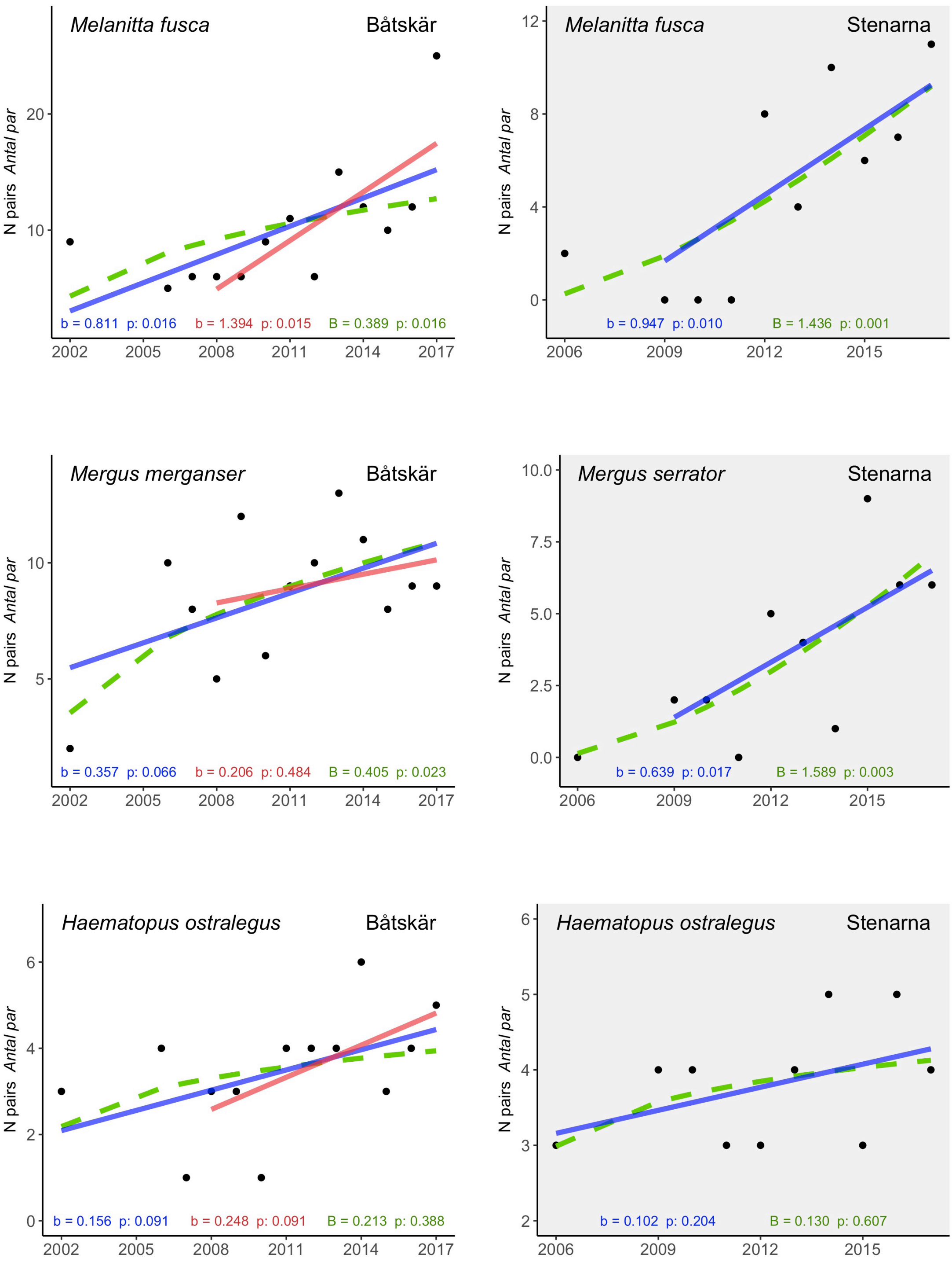

FIGURE 5 continued *fortsatt.*

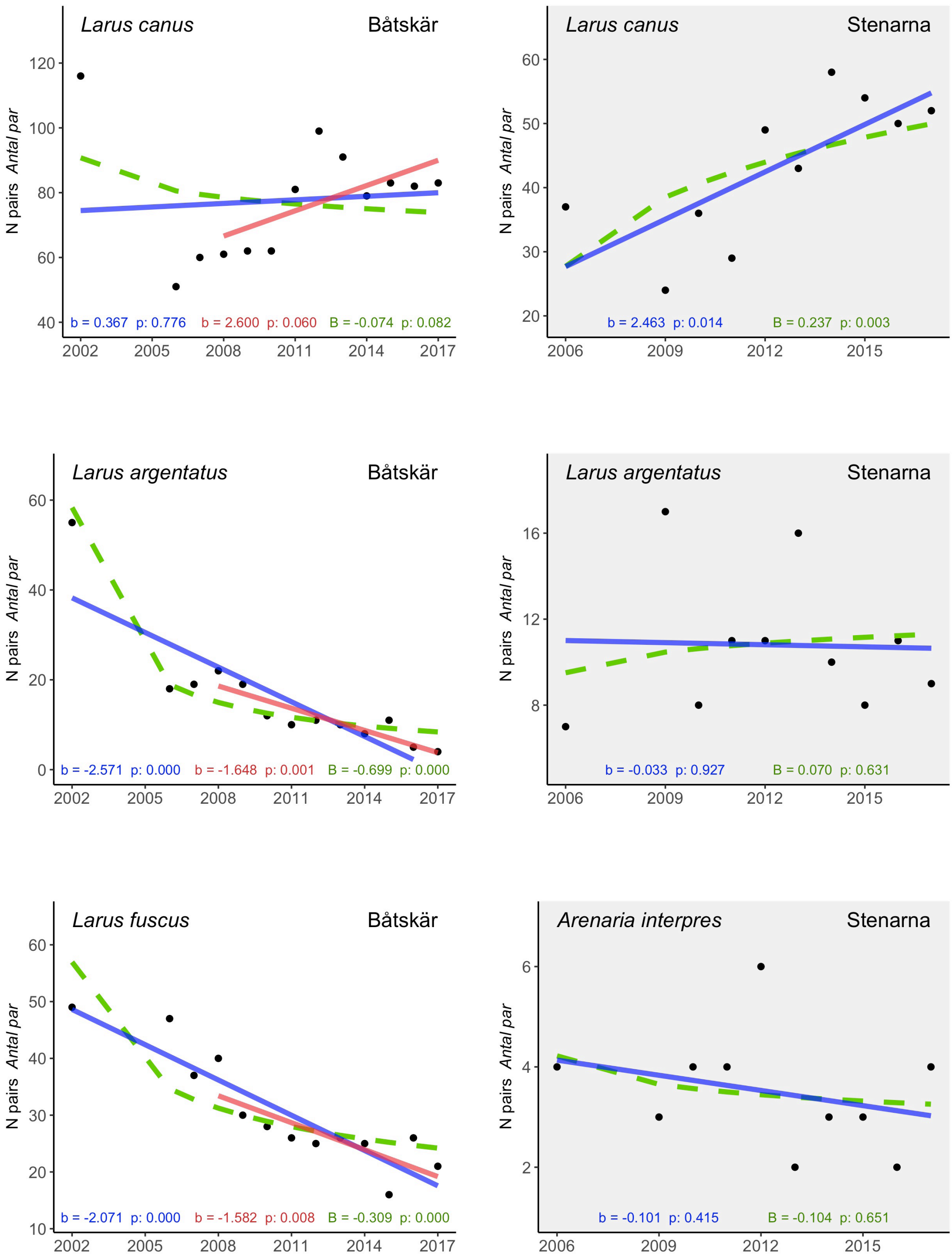

FIGURE 5 continued *fortsatt.*

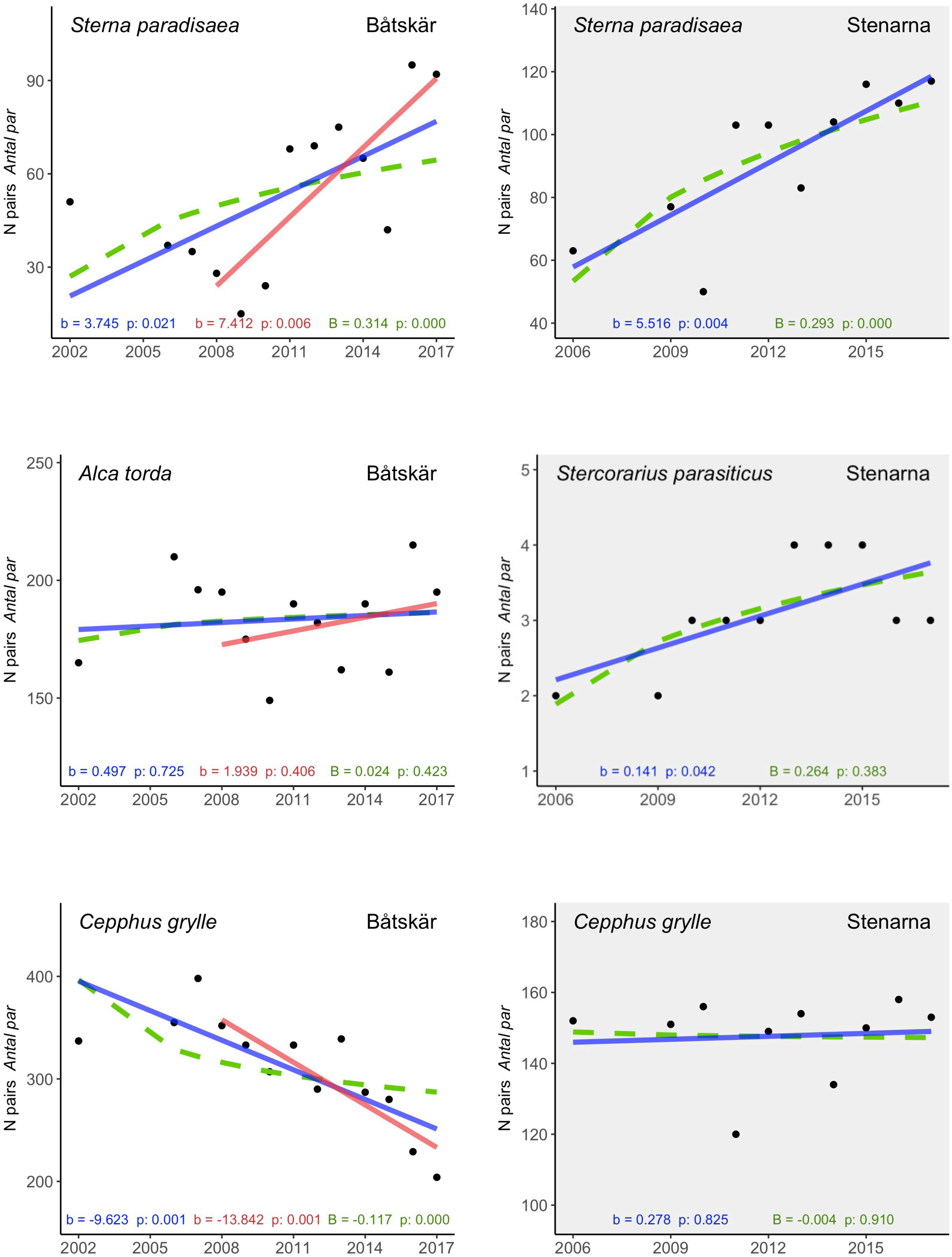

FIGURE 5 continued *fortsatt.*

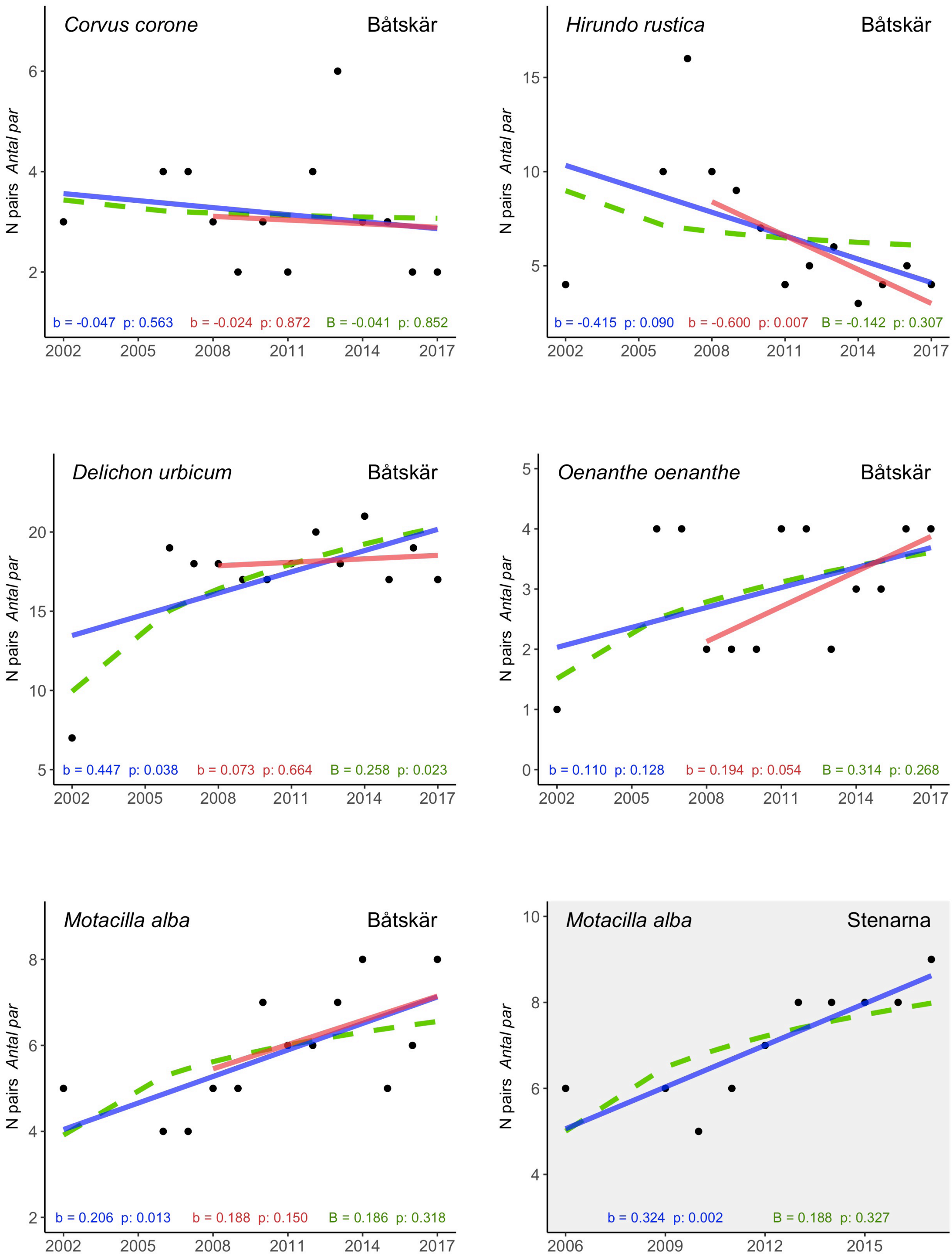

FIGURE 5 continued *fortsatt.*

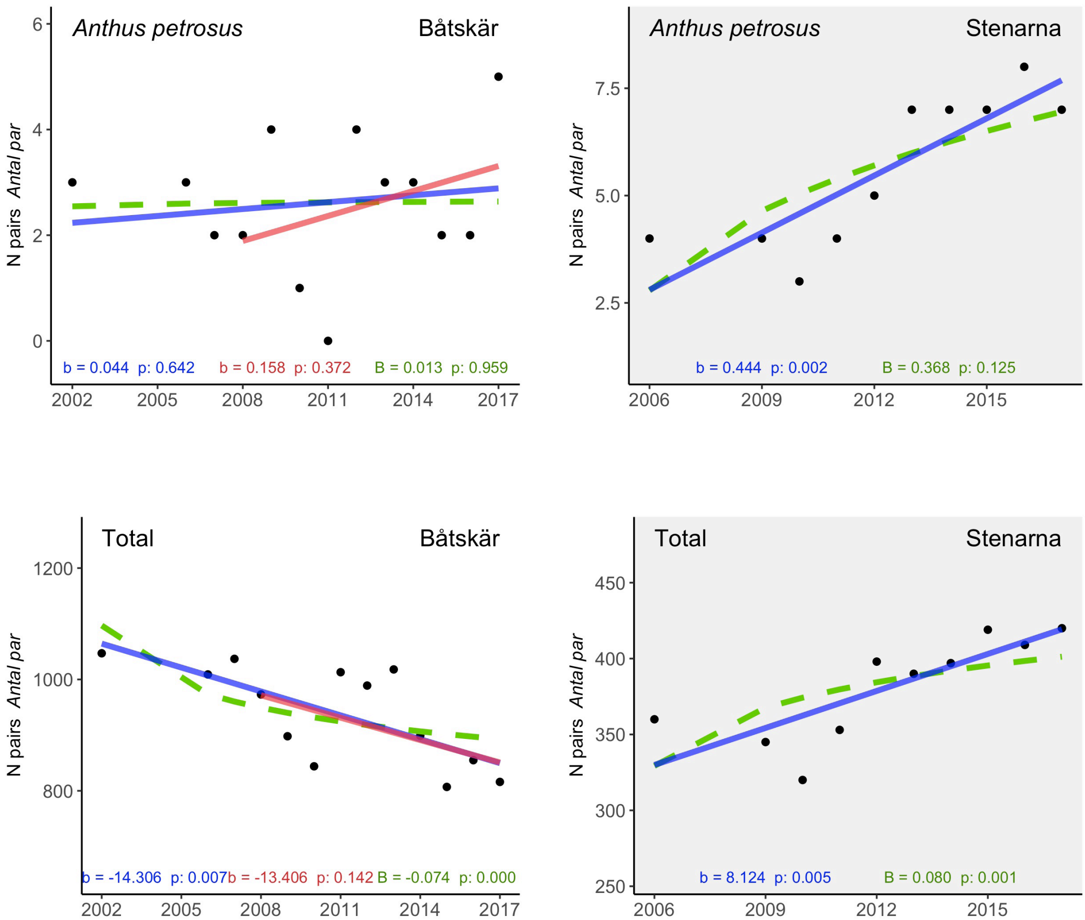

FIGURE 5 continued *fortsatt.*

area, Common Eider decreased significantly, and six species increased significantly. The total number of breeding birds increased in the control area (Stenarna) but decreased in Båtskär. The number of breeding pairs in Båtskär remained low during 2014–2017, but the linear trend for total breeding pair numbers was similar during the whole time period (2002–2017) compared with the operation period (2008–2017). We observed some variation between species in this time period comparison, but only Tufted Duck *Aythya fuligula* showed a trend change, from decreasing to increasing. The trends for total follow-up time and operation time were quite similar for most species. As the period prior to operation only included three years of observations (2002, 2006–2007), it was not meaningful to separately estimate the linear trend for this period.

The composition of avian fauna changed in both areas, the Shannon index increased, and many infrequent species increased their numbers while the numbers of some common species, such as the Common Eider, decreased. In contrast to the early-breeding Common Eider, Velvet Scoters increased their numbers, and the same trend appeared for both *Merganser* species in both areas, although the increase was not significant. The total number of breeding species did not change in either area despite some small variation.

The decline of the Herring Gull colony in Båtskär may be related to closure of the last rubbish dump site in Åland on New Year 2006/2007. Remains of human food packages were commonly found in the gull colony in 2006, but no signs of human waste utilization were observed in the colony at later times. The large-scale elimination of Herring Gulls from rubbish dumps on the Finnish mainland may be another reason for the Båtskär colony decline, as it may have decreased the number of new gull recruits in Åland. Systematic elimination of Herring Gulls has led to a clear decreasing population trend for example in the Gulf of Finland (Hario *et al.* 2009, Hario & Rintala 2014).

The Lesser Black-backed Gull colony was close to the wind turbine on Kummelpiken islet, and the colony did not change its location due to wind turbine construction. Before construction, the closest nests were only a few metres from the future maintenance road. Construction took place outside the breeding season, and in 2007 the breeding pairs therefore had to choose whether to breed on the previous site, move within the island, or move to another location. We observed two strong declines, one by 21% in 2007 and another by 25% two years later. The first decline may have been caused by breeding pairs being forced to leave the area for better breeding places due to habitat loss, and the second decline may be due to lower reproductive success of pairs due to disturbance (Salas *et al.* 2020). Since 2010, the number of pairs have varied, but no declining trend has been observed.

The Black Guillemot population size decreased in 2016 and 2017 in Båtskär, and Common Eiders have decreased since 2014. These two common species are the main cause of the 100-pair overall drop in Båtskär since 2014, although the Arctic Tern has compensated for this decrease in the overall number of breeding pairs in the area. The reason for the Black Guillemot decline remains unknown, and their breeding sites in Båtskär did not change during the decline. In contrast, Black Guillemots in Stenarna increased, which is the opposite result to the generally declining trend of this species in Finland (Hario & Rintala 2014, Lehikoinen *et al.* 2019). In Stenarna, the Arctic Tern has increased from its lowest number of 50 pairs in 2010 to 117 in 2017, and this number is the key factor in the observed overall increase in breeding pair numbers in the area.

Disturbance and habitat loss may have caused the decline of the Lesser Black-backed Gull, a species recently classified as endangered in Finland (Lehikoinen *et al.* 2019). Two other large gull species, the Herring Gull and Great Black-backed Gull *Larus marinus*, are both classified as vulnerable because of declining populations (Lehikoinen *et al.* 2019). The Arctic Tern population increase in both areas may be explained by good breeding success in previous years, as the trends were comparable in both areas. Arctic Tern colonies also change sites fairly readily, and colonies move to new places as a consequence of predation, disturbance, or other reasons. Predation caused by the White-tailed Eagle *Haliaeetus albicilla* occurs in both areas and is partly behind the Common Eider decline. Remnants of consumed incubating Common Eider females have been found in the proximity of buildings and wind turbines, and predation events have been observed during surveys close to wind turbines. The Common Eider has nearly disappeared from Stenarna and breeds close to houses and other construction in Båtskär. The presence of human activities provides some protection against predation. The Eurasian Eagle-Owl *Bubo bubo* is another bird of prey breeding in Båtskär, and according to carcass observations it also exploits the local breeding waterfowl. During this survey period, we observed no predatory mammals, such as Red Foxes *Vulpes vulpes* or American Minks *Mustela vison*, in either area.

Wind turbine construction changes the breeding habitat of several bird species. At Båtskär wind farm, no buffer zones were applied around bird breeding sites (Rydell *et al.* 2017) and wind turbines were placed on sites close to existing colonies (Anon 2002), which destroyed some breeding habitat. On the other hand, gravel and sand were spread next to the turbines and onto the maintenance roads, which were utilized by terns and certain wader species for breeding, likely contributing to increases in their populations. The Working Group of German State Bird Conservancies (2014) has recommended leaving a distance of at least 1,000 metres between wind turbines and colony-breeding terns or gulls. In our study area, the shortest distance between a colony and a wind turbine is only some tens of metres, and all seabird colonies are closer than 1,000 metres to the nearest wind turbine.

Wind turbines may increase the mortality of avian predators, such as the White-tailed Eagle (Heuck *et al.* 2019), which may benefit other species. The use and maintenance of power plants increase the presence of people on the islands, which may negatively affect the most sensitive species. Human presence may expel predators while other species (Hentati-Sundberg *et al.* 2021), such as the Common Eider, may benefit from it.

Environmental authorities and ornithologists have debated whether migratory birds avoid wind turbines and whether breeding birds become used to them. The numbers of breeding pairs of certain species may recover during the operational phase of the wind farm after having initially declined during the construction phase (Pearce-Higgins *et al.* 2012). Various bird groups also exhibit large differences in sensitivity in their responses to wind power plants, with some species declining while others do not, and certain species even increasing (Stewart *et al.* 2007, Pearce-Higgins *et al.* 2012, Niemuth *et al.* 2013, Hötker 2017). In our study area, bird populations appear to tolerate wind turbines fairly well, with few species having declined, some having increased, and species diversity having remained the same.

The wind turbines in our study area are situated on small islands with breeding birds. In practice, to avoid disturbance caused by turbines, the birds must either move to another area or tolerate the disturbance and remain breeding in the area that may have partly lost its quality for successful breeding. Long-lived birds may also exhibit lags in breeding site changes, as they may use the breeding success from previous years to guide their site selection process (Robert *et al.* 2014).

Conclusions

Our study shows that constructing wind power close to bird colonies does not systematically incur negative impacts on the local breeding avian fauna. The total number of breeding pairs decreased in the Båtskär area and increased in the Stenarna control area, but many species showed similar trends in both areas. Changes in local populations appear to mainly reflect changes in wider areas rather than local conditions. Only the Lesser Black-backed Gull population seems to have suffered from direct negative impact due to the construction of this wind farm. It is possible that other species have been negatively impacted by wind power, but their population declines have occurred years after operation began, and it is therefore difficult to estimate the mechanisms behind these declines.

The construction of this wind farm has also created new microhabitats such as gravel roads, stony landing places, and renovated old houses. These have benefitted at least auks, Common Eiders, Barn Swallows, and House Martins. A coin always has two sides, and careful planning can increase positive effects while diminishing negative ones. Long-lasting follow-up studies are needed to discern any long-term effects of wind power production.

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Svensk sammanfattning

Den häckande fågelfaunan inventerades i Båtskärs vindkraftspark i Ålands yttre skärgård mellan 2006 och 2017. Området består av fyra holmar på vilka det årligen häckar 850–1050 par fåglar. Området har också undersökts år 2002 för en miljökonsekvensbeskrivning. Ett jämförelseområde, Stenarna, 22 km nordväst från Båtskär, inventerades 2006 samt 2009–2017. Där häckar det 320–420 fågelpar årligen.

Fyra fågelarter har uppvisat signifikant minskning i Båtskärsområdet: ejder *Somateria mollissima*, silltrut *Larus fuscus*, gråtrut *L. argentatus* samt tobisgrissla *Cepphus grylle*. Ejder hade minskat i jämförelseområdet Stenarna, medan sex arter ökat i antal. Orsaken till gråtrutens minskning är sannolikt stängningen av Mariehamns soptipp i Ödanböle, Jomala, och avlivande av trutar vid flera soptippar på det finländska fastlandet. Orsaken till silltrutens nedgång är troligen byggandet av vindkraftverk vid silltrutskolonin. Möjligen har en del trutar lämnat kolonin efter att bygget startade och vindkraftverket togs i bruk, men sedan dess har stammen varit ganska stabil. Orsaken till minskningen av tobisgrissla är okänd. I Stenarna har ejderstammen drabbats av predationstryck från havsörn *Haliaeetus albicilla*, men vårjakt av ejder har också pågått i området.

En del arter har gynnats av byggandet, till exempel hussvala *Delichon urbicum*, ladusvala *Hirundo rustica*, ejder och tordmule *Alca torda*. Dessa arter utnyttjar de nya omgivningarna, som grusfält, stenpirar och renoverade byggnader, samt skyddet som människans närvaro ger. Som helhet har byggandet av vindkraftparken haft både för- och nackdelar för den häckande fågelfaunan.

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