ESTIMATING STREAKED SHEARWATER *CALONECTRIS LEUCOMELAS* ABUNDANCE IN THE REPUBLIC OF KOREA USING AUTOMATED ACOUSTIC RECORDERS

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ABSTRACT

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Traditional methods to assess population size in seabirds are applicable only to species that nest in visible locations, leaving cryptic nocturnal, burrow-nesting seabirds underrepresented in typical long-term population monitoring programs. Alternative methods to count burrow-nesting birds, however, are extremely labor-intensive and therefore are applicable only to small and possibly unrepresentative areas, and may have negative effects on burrow-nesting populations. We suggest the use of automatic acoustic recorders as a possible survey technique to overcome logistic difficulties of research of seabirds on remote islands in the Republic of Korea, where funding for ecological research is extremely limited but where globally important seabird colonies exist. In this study, we used automated acoustic recorders to model the relationship between call activity and known abundance of the Streaked Shearwater *Calonectris leucomelas* at sites on Sasu Island, the largest breeding colony that exists in Korea, supplemented by data from the closely related Cory's Shearwater *C. borealis*. Based on a positive relationship between breeding burrow density and call activity, we cautiously estimated the population size of the Streaked Shearwaters to be 95–278 pairs at another breeding colony on Chilbal Island. Although this method may not be precise enough to estimate the exact population size of a seabird species at a location, it can provide coarse estimates that can be used to track relative changes over time.

Key words: automated acoustic recorder, breeding bird abundance, call activity, *Calonectris leucomelas*, population estimate, Streaked Shearwater, Korea, passive acoustic monitoring

INTRODUCTION

Traditional methods to assess population size and trends in seabirds include point counts and area visual searches (Walsh *et al*. 1995). These methods are applicable only in species whose nests are visible, leaving cryptic, nocturnal, burrow-nesting seabirds underrepresented in typical long-term monitoring programs (Schumann *et al*. 2013). In order to assess the status of the latter seabirds, some studies have involved burrow searches and nighttime vocalization playback combined with mist netting. These methods, however, are extremely labor-intensive and, therefore, are applicable to small and possibly unrepresentative areas, and they may have negative effects on burrow-nesting populations (e.g., Bowman *et al*. 1994, Rodway *et al*. 1996, Carey 2009).

In recent years, technological innovations have given researchers an alternative method to assess the presence and population size of nocturnal, burrow-nesting seabirds: acoustic recorders. The use of automated acoustic recorders is becoming more common in assessments of numbers of marine mammals (Johnson *et al*. 2009), anurans (Brauer *et al*. 2016), and birds (Buxton & Jones 2012, Buxton *et al*. 2013, Borker *et al*. 2014, Zwart *et al*. 2014, Pérez-Granados *et al*. 2019). These devices are weatherproof sound recording devices that can be programmed to record bird sounds at pre-determined times of day or for months at a time at remote, difficult-to-access sites, such as remote islands. They are particularly useful where nocturnal, burrow-nesting seabirds breed, by utilizing a passive means of recording (e.g., Buxton *et al*. 2013, Oppel *et al*. 2014). In this passive manner, the automated technology avoids the negative impacts on wildlife reported in traditional surveying methods and facilitates a comprehensive and possibly more representative survey coverage, with less physical effort in the field for the burrow-nesting populations. Devices can be installed in any area of interest and can be pre-programmed to record at customized intervals. This reduces the cost of sampling because no field crew is required during the recording period (Williams *et al*. 2010, Buxton & Jones 2012, Buxton *et al*. 2013). Importantly, these automated sensors also allow for simultaneous, complementary surveying at multiple sites (Borker *et al*. 2014). Therefore, once the biases and assumptions are quantified, the use of automated acoustic recorders is a cost-effective and practical method of monitoring burrow-nesting seabird colonies.

The Streaked Shearwater *Calonectris leucomelas* is a medium-sized seabird in the order Procellariiformes, with most breeding sites located in eastern Asia. Although obtaining quantified information has been problematic, this species may be decreasing in population size through its entire range in response to the introduction of alien mammals to breeding islands (Oka 2004, Jones *et al*. 2008, Dias *et* *al*. 2019). Indeed, Norway rats *Rattus norvegicus* in the Republic of Korea (hereafter Korea) affect the survival and reproductive success of island-nesting seabirds. For example, on Sasu Island, a small, forested island off the south coast, rats depredate upwards of 80% of eggs and chicks in some years (Lee & Yoo 2002, Nam *et al*. 2004, Nam *et al*. 2014, Nam & Yoo 2017). It has become clear that eradication projects are a powerful way to improve the conservation status of affected seabird species (Howald *et al*. 2007, Jones *et al*. 2016, Brooke *et al*. 2018). However, to justify the expenditure of funds for an eradication project, knowledge of the seabird breeding populations that exist on these islands, and the ability to monitor their numbers, must be in place (Holmes *et al*. 2019). In this regard, the population sizes of Streaked Shearwaters on the Korean islands are almost completely unknown.

Here, we discuss the application of a cost-effective technique that will allow the simultaneous and continuous monitoring of Streaked Shearwater colonies on remote Korean islands, providing a means to estimate their breeding bird abundance and assess changes in populations over time. To do this, we developed a model that can be used to estimate the breeding abundance of Streaked Shearwaters on islands of unknown status using automated acoustic recorders. To this end, we first determined the relationship between vocal activity and breeding Streaked Shearwater abundance via quantifying the call activity at sites of known density of active burrows. We then used this relationship to estimate abundance on a remote and inaccessible island for which no information was available about Streaked Shearwater population size.

METHODS

Study species

The Streaked Shearwater breeds on the islands of eastern Asia, predominantly off Japan (Ochi *et al*. 2010, Yamamoto *et al*. 2010, Sugawa *et al*. 2014), with smaller colonies around the coast of Korea (Kuroda 1923, Park & Won 1993, Hart *et al*. 2015) on the Chinese island of Qingdao in the northern Yellow Sea (Cui 1994),

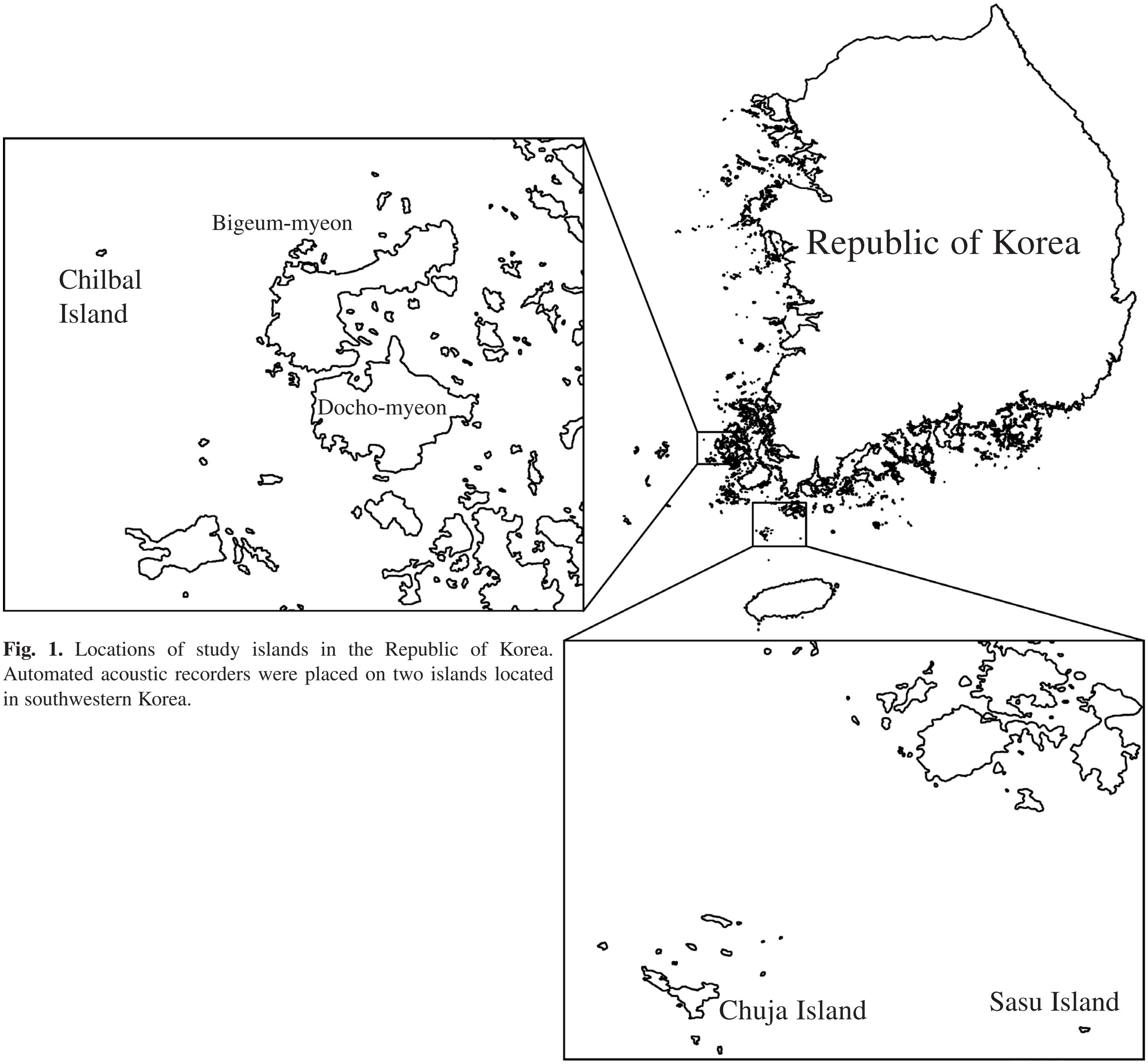

Fig. 1. Locations of study islands in the Republic of Korea. Automated acoustic recorders were placed on two islands located in southwestern Korea.

on the Pescadores Islands off Taiwan, and on the eastern Russian island of Karamzina (Oka 2004).

Body size and vocalizations of male and female Streaked Shearwaters are sexually dimorphic. Males are generally larger and have a high-pitched whistle-like call, while females are slightly smaller and have low-pitched "honking" calls (Shirai *et al.* 2013, Arima *et al*. 2014). They arrive at their breeding grounds in early March, the first to arrive awaiting the arrival of their mate; they generally return to the same breeding burrow as the previous year (KBN unpubl. data). Burrows range from 50 cm to > 2 m in depth and are usually dug into soft soil of a hillside (Lee *et al*. 2002). In mid to late June, females lay a single egg (Nam *et al*. 2008), which is incubated until hatching around mid-August; subsequently, the chick fledges in late October (Nam *et al.* 2014). Adults generally cease visitation about two weeks prior to the fledging of their independent chicks.

Study sites

Sasu Island (33°55′12″N, 126°37′48″E), 0.138 km^2 in area, is located between the Korean Peninsula and Jeju Island; it is forested and has a peak elevation of ~80 m (Figs. 1, 2A). The island's perimeter consists mainly of steep cliffs while the interior slopes gently, with hills covered in soft soil created from fallen leaf litter, which is ideal for shearwater burrowing. The dominant seabird species is the Streaked Shearwater, thought to number around 16 000 breeding pairs (KBN, unpubl. data). Non-native Norway rats are present and are known to play a significant role in Streaked Shearwater egg failures (Nam *et al*. 2014).

Chilbal Island (34°47′24″N, 125°47′24″E), 0.036 km^2 in area, is located ~50 km from the southwestern coast of Korea and is covered predominantly by the sedge *Carex boottiana* along with sparse woody vegetation (Park & Won 1993; Figs. 1, 2B). Its highest elevation is 105 m, and its shoreline consists almost entirely of steep cliffs, amongst which many seabirds nest. There are no permanent human residents on the island; however, there is a lighthouse, and people visit the island infrequently. Chilbal Island is free of introduced mammals and is therefore an important breeding site for Swinhoe's Storm Petrel *Hydrobates monorhis*, of which there are 7 000–13 000 breeding pairs (Taoka *et al*. 1989, Lee 2010). Streaked Shearwaters breed on the island, but their abundance is unknown because of the inaccessible nature of the island's topography.

Acoustic recording and deployment protocol

We recorded the call activity of Streaked Shearwaters using automated acoustic recorders deployed on Sasu Island during the

Fig. 2. The typical habitat seen at Sasu (A) and Chilbal (B) islands. Sasu Island is densely forested with soft soil, while Chilbal Island is made up of steep, granite cliffs and is dominated by the grass *Carex boottiana*.

2014 breeding season (where Streaked Shearwater abundance was known), and on Chilbal Island during the 2015 breeding season (where shearwater abundance was to be estimated).

We used Songmeter SM2+ (Wildlife Acoustics Inc., Maynard, MA, USA), also used in several other related projects (i.e., Borker *et al*. 2014; Oppel *et al*. 2014). These devices are waterproof and their recording schedule is customizable, thus making them perfect for use on remote seabird islands. The units can accurately capture vocalizations up to 50 m from the device (Buxton *et al*. 2013, Oppel *et al*. 2014).

Songmeters were placed at four locations, of differing shearwater density, at least 150 m apart on Sasu Island on 27 June 2014 (Table 1). The substrate was excellent for burrowing in two plots (A, B), but at the other two plots (C, D) the shallow soil was mixed with rocks, which limited the number of burrows. The sites were chosen to represent a range of burrow densities and to cover most of the breeding habitat on Sasu Island, without overlap of recordings. Due to the positioning of the recorders in forests, they were protected from strong winds which can render recordings inaudible. As a result, all recorders produced files that had very clear audio and produced spectrograms from which Streaked Shearwater calls were easily recognizable. No recordings had to be discarded due to inaudibility from strong winds or other noise.

On Chilbal Island, single recorders were placed on the south (plot E), west (plot F), and north (plot G) slopes, at least 100 m apart, on 01 June 2015; due to the island's small size, these three recorders were capable of recording the vocalizations of nearly the entire island without overlap (Table 1). Given the lack of trees, we expected many recordings to be inaudible because of strong winds. Therefore, we applied soft wind screens to each microphone. In addition, we placed recorders behind large boulders to function as wind breaks. Consequently, only a small number of recordings on fewer than five nights were unusable.

On both islands, recorders were placed as far from the ocean as possible to reduce wave noise interference. We set the sample rate at 16 kHz and microphones at a gain of +42.0 dB. Devices were attached to plywood bases screwed to a wooden post 1 m in length that was inserted in the ground. To provide additional stability, large rocks were placed around the base of the post. We tested whether we were able to detect experimental noises and human voices at similar distances and with equal probability in recordings from Chilbal as compared to recordings from Sasu. We found no major differences in the ability to capture sound between the two islands.

Procellariiform seabirds attend nests mostly continuously during the incubation period, with mates trading duties (Ojowski *et al*. 2001). After hatching, nest attendance of adult Streaked Shearwaters becomes less predictable (Ochi *et al*. 2010), and call activity during this time may not accurately reflect that of the true population size. Therefore, to ensure the highest and most accurate colony attendance for the purpose of modeling, recorders on Sasu and Chilbal islands were set on the same nightly recording schedule during the incubation period (except plot E, see below). Recording on Sasu and Chilbal islands commenced at 23h00 on a 1-min on, 9-min off schedule and stopped at 03h00 the following day, giving 24 1-min recordings per night. Plot E on Chilbal Island recorded from 23h00 to 03h00 but on a 2-min on, 28-min off schedule. Recording for Sasu Island started on 24 June 2014 and ended on 31 July 2014 (*n* = 152 device nights, 60.8 h of recordings). For Chilbal Island during the 2015 breeding season, recorders operated on slightly different schedules due to technical issues and the remote location of the island. Plot E ran 26 June 2015–02 July 2015 (*n* = 7 device nights around new moon); plot F ran 26 June 2015–20 July 2015 (*n* = 25 device nights); plot G ran 26 June 2015–12 July 2015 and 20 July 2015–31 July 2015 (*n* = 29 device nights). The recording schedule for devices on plots F and G included all stages of a lunar cycle.

Acoustic data analysis

Acoustic data were analyzed using Song Scope 4.1.3A (Wildlife Acoustics Inc.). Originally, we attempted to use an automated detection algorithm in Song Scope (Buxton *et al*. 2013, Oppel *et al*. 2014), but due to the high overlap of Streaked Shearwater calls at densely inhabited sites on Sasu Island, and the overlap of Streaked Shearwater calls with Swinhoe's Storm Petrels on Chilbal Island, the software yielded high rates of false positives and negatives. Therefore, we decided to manually quantify calls by visually observing spectrograms. In some cases, we listened to the respective audio to ensure correct identification and quantification.

We defined a call as any repeating syllable in a Streaked Shearwater vocalization. While male and female calls can be easily distinguished, we counted the total number of calls of both sexes combined in each 1-min recording. Because call activity of nocturnal seabirds is known to vary widely from night to night due to a number of environmental factors (Granadeiro *et al*. 2009, Bretagnolle *et al*.

TABLE 1

Nocturnal call activity of Streaked Shearwaters *Calonectris leucomelas* at study sites on Sasu and Chilbal islands, monitored using automated acoustic recorders during the 2014 and 2015 breeding seasons, respectively

Study site	Recording plot	Coordinates	Total recording time (min)	Total number of calls	Mean number of calls/min
Sasu Island	A	33°55′14.7″N, 126°38′27.0″E	840	93 219	110.975
	B	33°55′13.7″N, 126°38′22.8″E	744	45 940	61.747
	C	33°55′12.9″N, 126°38′18.6″E	836	39 334	47.050
	D	33°55′13.5″N, 126°38′14.8″E	816	21 835	26.759
Chilbal Island	E	34°47′15.5″N, 125°47′19.1″E	42	274	6.523
	F	34°47′15.3″N, 125°47′14.9″E	515	2 646	5.137
	G	34°47′18.3″N, 125°47′17.0″E	760	836	1.100

2012), the instantaneous call rate during any given 1-min recording can vary by orders of magnitude. The main benefit of long-term automated recording is the regular and consistent recording over different phases of the incubation cycle, the nocturnal cycle, and across moon phases, thus overcoming the known variation in Procellariform attendance patterns and calling rates. Therefore, we took an average of all recordings during incubation for each site and used the average number of calls per min to calibrate the relationship between nest density and vocal activity.

Breeding burrow assessment

Under the assumption that song meter units are capable of recording identifiable vocalizations up to 50 m away (Buxton *et al*. 2013, Oppel *et al*. 2014), in order to estimate the number of Streaked Shearwaters in the area surrounding each recorder, we searched for occupied burrows within 50 m of the device on Sasu Island (Table 2). Because searching for all burrows in the entire 50 m radius was logistically infeasible, we established 10 randomly dispersed sampling quadrats (dimension: 10 × 10 m) within the 50-m radius around each recorder. Streaked Shearwater burrows regularly exceed 2 m in length and often require excavation to check status, an effort that is time-consuming and stressful for occupants. This, coupled with limits to our permitted access to Sasu Island, necessitated that we use an active breeding pair occupancy rate derived from previous work of 82.6% (Nam *et al*. 2014). We averaged the estimated number of breeding burrows/m^2 across all 10 quadrats and multiplied this average density by the total area of each recording zone (7853.98 m^2) to obtain an estimate of actively breeding Streaked Shearwaters around each recording unit.

Estimating the breeding population size

To estimate breeding bird abundance on Chilbal Island based on calling activity, we needed to understand the relationship between call activity and abundance at each recorder site on Sasu Island. In order to add to the four recording sites on Sasu Island and make our model more robust, we included information on the call activity and number of nests in 11 plots in colonies of the closely related Cory's Shearwater *Calonectris borealis* among the Azores Islands, using the same recording schedule as Sasu Island (Oppel *et al*. 2014; Appendix 1, available on the website). Both species display behavioural similarities, including comparable call behaviour (Bretagnolle & Lequette 1990, Rabouam *et al*. 2000, Arima *et al*. 2014). The calls of both Cory's and Streaked shearwaters are roughly 1–2 s long, strung together in near continuous vocalizations with gaps of 0–1 s between syllables, and appear to vary more between sexes in each species than among the two species (Bretagnolle & Lequette 1990, Arima *et al*. 2014).

We averaged the number of calls/min over the entire recording period per recording site. We then related this index of vocal activity against *Calonectris* shearwater nest density using a generalized linear model (GLM), with 'species × calling rate' as an interaction term to allow for species-specific calling rates; models without species-specific calling rates were inferior in preliminary explorations (Table 3). This interaction also accounts for the fact that Cory's Shearwater density was lower and was not extrapolated based on occupancy rate from sampling quadrats. Cory's Shearwater density was determined by inspecting all available breeding burrows and was fully enumerated in a 50-m radius around recorders (Oppel *et al.* 2014).

With the average nocturnal call rate for Chilbal Island known for each site, we applied the model produced in the previous step to these data and estimated the number of breeding burrows at each of the three recording sites. We produced an estimate along with 95% confidence intervals, and all statistical analyses were carried out with R version 4.0.0 (R Core Team 2020).

RESULTS

Nocturnal call activity

In total, 3236 1-min recordings were collected at the four recording sites on Sasu Island and a total of 200328 Streaked Shearwater calls were identified. The number of calls per min ranged 0–357, and the average number of calls varied 26.759–110.975 among the four sites (Table 1).

On Chilbal Island, a total of 1317 min of recordings were collected and a total of 3756 Streaked Shearwater calls were identified across the three recording sites. The number of calls per min ranged 0–50, and the average number of calls at each site ranged 1.100–6.523 (Table 1).

Breeding burrow density

The number of burrows in each of the 10 sample quadrats varied very little within each of the four recording sites on Sasu Island,

TABLE 2

The estimation of active burrows of Streaked Shearwaters *Calonectris leucomelas* at four recording plots on Sasu Island, Republic of Korea, during the incubation period, 2014

Plot[a]	Number of burrows in 10 quadrats[b]	Number of estimated active burrows[c] in 10 quadrats	Active burrow density (No. of burrows/m^2 ± SD)	Total number of estimated active burrows in a recording plot
A	600	496	0.50 ± 0.08	3 927
B	385	318	0.32 ± 0.11	2 513
C	106	88	0.09 ± 0.05	707
D	140	116	0.12 ± 0.09	942

[a] Each plot area was 7853.98m^2

[b] All quadrats were 10 × 10 m

[c] A burrow occupancy rate of 0.826 was applied to estimated total burrows to estimate active burrows.

TABLE 3
Candidate models describing breeding bird abundance (number of active breeding burrows) of Streaked Shearwaters *Calonectris leucomelas* in relation to the average nightly call activity (Mean_calls_min) and *Calonectris* species.

	Model 1			Model 2			Model 3[a]		
Predictors	**Incidence rate ratios**	**Confidence interval**	***P***	**Incidence rate ratios**	**Confidence interval**	***P***	**Incidence rate ratios**	**Confidence interval**	***P***
(Intercept)	1.03	0.90–1.19	0.637	2.14	1.81–2.52	**<0.001**	14.66	11.09–18.88	**<0.001**
Mean_calls_min [log]	5.90	5.71–6.10	**<0.001**	3.08	2.94–3.22	**<0.001**	1.44	1.30–1.61	**<0.001**
Species [Streaked Shearwater]				8.89	7.81–10.15	**<0.001**	0.91	0.66–1.29	0.604
Mean_calls_min [log] × Species [Streaked Shearwater]							2.32	2.06–2.60	**<0.001**
R^2		0.89			0.95			0.96	
Akaike Information Criterion		2454.5			1116.4			981.8	

[a] Model 3 was used to estimate breeding bird abundance on Chilbal Island.

but there were large differences across sites (Table 2). Plot A had the highest number of burrows within the quadrats and, thus, the highest mean density of breeding burrows (0.50 ± 0.08 nests/m^2), followed by plot B (0.32 ± 0.11 nests/m^2). Substantially lower density existed in the remaining two plots (Table 2).

Estimating breeding population size

We found a positive relationship between average nocturnal call rate of *Calonectris* shearwaters and the number of active breeding burrows within a 50-m radius (R^2 = 0.96, $P < 0.001$; Fig. 3). By applying the fitted regression equation to call activity data from Chilbal Island, we estimated the Streaked Shearwater population on Chilbal Island (Table 4). Average call activity ranged 0–50 calls per min and resulted in a total estimate of 208–278 Streaked Shearwater pairs (95–13 pairs excluding plot E) breeding on Chilbal Island in 2015 (Table 4). Call activity at plots F and G decreased as the recording period progressed, coinciding with increasing moon illumination. Because the recorder at plot E operated only during the dark, new phase of the moon, it is likely that the call activity recorded there was higher than it would have been if averaged over the full lunar cycle. Therefore, the higher average mean calling rate extrapolated from plot E may overestimate the abundance of Streaked Shearwaters.

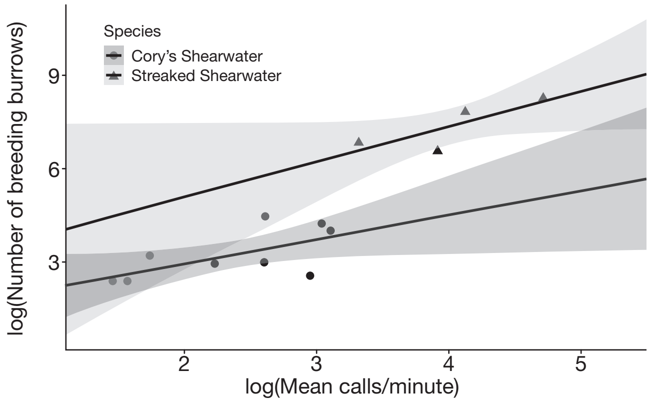

Fig. 3. The relationship between breeding burrow abundance and the calling rate of two *Calonectris* species. The total number of active burrows within a 50-m radius of the automated acoustic recorders is represented by breeding burrows in this figure (solid line = fitted regression line based on a generalised linear model with a species × calling rate interaction term; shaded area = 95% confidence intervals).

DISCUSSION

Chilbal Island is a breeding colony primarily for Swinhoe's Storm Petrels (Park & Won 1993, Lee 2010), as well as a small number of Streaked Shearwaters. Based on acoustic recordings, we cautiously suggest that 90–280 pairs of Streaked Shearwaters may nest on this island, but this estimate is surrounded by considerable uncertainty. Nonetheless, our estimates of small numbers of Streaked Shearwaters are consistent with anecdotal accounts, which are solely based on opportunistic observations without detailed surveys (Kuroda 1923, Kang *et al*. 2008). Given the automated and repeatable approach to estimation that we provide, our data can be combined with future estimates for monitoring relative changes over time at small- and medium-sized colonies, where oversaturation of recorders is not an issue.

Although Sasu Island is only about three times larger, it had 20–100 more calls/min and a larger nest density than Chilbal Island. This is simply due to the limited nesting habitat on Chilbal Island, much of which is covered by the grass *Carex boottiana*. The roots of this grass make burrowing very difficult for Streaked Shearwaters, thus reducing the availability of suitable burrowing soil. On the other hand, the much smaller Swinhoe's Storm Petrel

TABLE 4
Estimated number of breeding burrows of Streaked Shearwaters *Calonectris leucomelas* on three recording sites at Chilbal Island based on call activity

Recording plot	Mean number of calls/min	Estimated number of breeding burrows (95% Confidence Interval)
E	6.523	129 (113–147)
F	5.137	96 (83–112)
G	1.100	15 (12–19)

can more easily navigate the roots to produce a burrow, making it the dominant species on Chilbal Island.

Ideally, the quantification of data captured by automated acoustic recorders would use algorithms in an entirely automatic process. This would significantly reduce processing time and allow for thousands of hours of recordings to be captured and analyzed, thus providing the most accurate estimate of island call activity. While there has been a lot of progress in the effectiveness of such algorithms since the time of this study (Stowell *et al*. 2019, Priyadarshani *et al*. 2020, Wright *et al*. 2020), most studies deal only with small numbers of calling individuals within the area of the recorders and thus do not face the problem of overlapping calls, which complicates automatic detection and enumeration (Orben *et al*. 2019, Arneill *et al*. 2020). On Sasu Island, however, the shearwater call rates at some sites are > 100 per min, which leads to significant overlap of calls. This causes high rates of false positives and negatives in the spectrogram analysis of some automatic detection software (Buxton & Jones 2012). Similarly, because of the high rate of Swinhoe's Storm Petrel calls on Chilbal Island, it is possible that the calls of a different species could mask the calls of Streaked Shearwaters, causing Streaked Shearwater calls to be underestimated. These two factors, unfortunately, prevent the use of automatic detection software in its current form on Sasu and Chilbal islands.

We presumed that the vocalizations that we quantified reflected the breeding population of Streaked Shearwaters in this area based on our assumption that the proportion of vocalizations coming from non-breeding individuals was similar across sites. Because non-breeding individuals in some shearwaters have higher levels of call activity than breeders (James 1985, Arneill *et al*. 2020), we acknowledge that if a larger proportion of non-breeders was present on Chilbal, or if there was high non-breeder movement around the colony (Arneill *et al*. 2020), these birds may have inflated our assessment of population size on Chilbal Island. Additionally, we assumed that the difference in surface vegetation (Sasu = forested; Chilbal = grass-only) would not affect the audio capturing ability of the recorders. In field tests, only heavy rain and wind were found to alter audio recording quality within the 50-m recording zone, and both islands had nearly identical detection rates for experimental recordings.

We acknowledge that our small sample size is a limiting factor for extrapolating our results, and that the small sample size and resulting uncertainty are therefore the key weakness of the study. To overcome the small sample size of Korean colonies, we included data from a closely related species. However, these two species' datasets did not overlap in either call activity or number of breeding burrows and were based on a slightly different assessment of nest abundance around sound recorders. Hence, we were unable to ascertain whether the differences we found between the two studies were solely due to population size or whether other confounding aspects may have affected vocalization characteristics at low densities (Fig. 3). Therefore, our model would benefit from the inclusion of additional Streaked Shearwater colonies with small, known populations to allow for overlap of those variables and thus allow us to better assess model quality. Given that Chilbal Island is logistically challenging and, therefore, we cannot perform a physical population estimate to validate our predictions, other breeding colonies of Streaked Shearwaters, such as Hwa Island and Gugul Island (Hart *et al*. 2015), would serve as ideal sites, as they host relatively smaller, easily accessible populations.

Our goal in this study was to establish an automated technique for efficiently and effectively surveying a nocturnal, burrow-nesting seabird on islands around the Korean Peninsula, especially those on which inaccessible terrain prevents traditional surveying methods. Our approach provided the first full-island survey of Streaked Shearwaters on Chilbal Island, and its application seems promising. This method may not precisely estimate the population size breeding on an island, but it offers a repeatable method that can be used to quantify relative changes in species numbers over time in response to introduced species removal or other factors. When considering that nearly all Korean Streaked Shearwater colonies of unknown status exist on small islands with no other nocturnally vocalizing species (Hart *et al*. 2015), we believe these automated acoustic recorders and associated recognition software could work well as a low-cost, user-friendly survey technique. Their use would fill in the vital information gaps at these remote areas for Streaked Shearwaters and other nocturnal, burrow-nesting seabirds.

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